TUNGSTEN BEHAVIOUR AT HIGH TEMPERATURE AND HIGH STRESS*

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Abstract

Recently reported results on the behaviour of the tungsten under conditions expected in the Neutrino Factory target have strengthened the case for a solid target option for the Neutrino Factory. This paper gives a description of the measurements of the surface motion of tungsten wires, stressed by a pulsed current, using a Laser Doppler Vibrometer in order to measure tungsten properties at high temperature and high stress. The experimental results have been compared with modelling results, and the results of previous lifetime tests have been confirmed.

INTRODUCTION

The magnitude of thermal stress on the target is the main issue for solid target option for the Neutrino Factory. In order to make thermal shock measurements on tantalum and tungsten samples it would be best to do a lifetime test on a real size target in a proton beam over several years. However, beams of the required power are not readily available for any length of time. Hence, it was decided to pass a fast, high current pulse through a thin wire made of the candidate materials [1]. This paper concentrates on measurements of wire surface motion during the pulsing using a laser interferometry technique. The main goal of the experiment is to measure tungsten properties as a function of applied stress and temperature, as well as to check the modelling results and, hopefully, to confirm the results of previous lifetime tests [2].

EXPERIMENTAL SETUP

A thin wire is necessary to allow the current to diffuse into the centre of the wire in a sufficiently short time for the shock to be effective. For tungsten, the wire cannot be greater than ~ 0.75 mm in diameter. A power supply for the ISIS [3] kicker magnets is being used, supplying a maximum of 60 kV and 9200 A at up to 50 Hz in a pulse which rises in 100 ns and is ~ 800 ns long. The wires, of $3 - 5$ cm length, are supported in a vacuum chamber to avoid oxidation. One end of the wire is firmly clamped, while the other end is allowed to expand freely through a pair of graphite (or copper) conductors that lightly clamp the wire. The wire is operated at temperatures from 300 to 2500 K by adjusting the pulse repetition rate. The wire temperature is measured by a manually operated optical pyrometer.

The shape of the current pulse is shown in Fig. 1 (dotted line). After the first pulse ($\sim 1\mu$s long) there is a series of reflections that last up to 5μs.
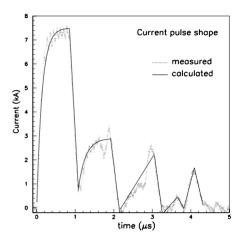

Figure 1: Measured and calculated (see text) waveform of the current pulse used in the experiment.

In order to calculate energy density and temperature rise across the wire an analytic current penetration formula was used [4]. The idea of this procedure was to obtain a good fit of the measured current pulse shape. That formula and the results of measurements of the voltage waveform were used to obtain the current density $j(r, t)$ distribution across the wire (and the current waveform) as a function of time. It is seen in Fig. 1 that the calculated current (full line) is very close to the measured current waveform (dotted line). After confirming that analytic current penetration formula describes nicely the experimental results, we have used it to produce the input needed for LS-DYNA [5] calculations: the temperature rise across the wire (proportional to the integral of the j^2) and the Lorenz force from the magnetic field produced by the current passing through wire. In the LS-DYNA calculations, the geometry of cylindrical wire was meshed with a 3D element type 164 (LS-DYNA Explicit Solid) or corresponding 2D element type. The empirical 'Temperature Dependent Bilinear Isotropic Model' was used as the material model. This is a model that uses two temperature-dependent slopes to represent the experimental data on the material stress-strain curve. A single point Laser Doppler Vibrometer (LDV) from Polytec [6] has been used for measurements of the wire's longitudinal and radial surface oscillations. The measurement system

consists of the optical sensor head OFV-534 which is connected with the OFV-5000 vibrometer controller. The sensor head consists of a laser source, an interferometer and a photo-detector. The most important parts of the vibrometer controller are the decoder units. There is a wide range of available decoders and we have used three different units to cover the complete range of amplitudes and frequencies of the wire vibrations.

RESULTS

We have performed an extensive set of measurements of longitudinal wire oscillations but only the measurements of radial oscillations have been used for the material characterization at high temperatures. This is because the longitudinal vibrations are the results of the non-homogeneous temperature distribution along the wire so it is difficult to say what the relevant temperature is. It is important to note that we have used two LDV decoder units for this set of measurements, and that they utilise completely different measurements techniques.
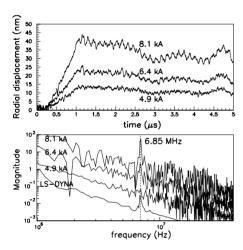

Figure 2: (Top) Radial displacement of the 0.5 mm wire as a function of applied current. (Bottom) Corresponding frequency spectra and the result of LS-DYNA prediction.

First data were taken with a DD-300 displacement decoder. Fig. 2 (top) shows radial displacements of the 0.5 mm diameter tungsten wire as a function of time and applied current, as well as the fact that displacement increases with increasing current (as expected), one can see that high frequency oscillations are much more prominent for higher current values. This can be seen in Fig. 2 (bottom), together with almost perfect agreement between the measured frequency (6.85 MHz) and LS-DYNA prediction. It must be noted here that the frequency spectra lie on top of each other but they have been separated in Fig. 2 by scaling in order to show the rise of the 6.85 MHz line with increasing current. The measured radial frequency f can be used to extract the value of Young's modulus of tungsten using the

formula [7]:

$$E = \frac{(2\pi f)^2 r^2 \rho}{\zeta^2} \cdot \frac{(1+\nu)(1-2\nu)}{(1-\nu)}, \qquad (1)$$

where r is the wire radius, ρ is the density, ν is Poisson's ratio for tungsten and ζ is the root of the following Bessel function [7]:

$$\zeta J_0(\zeta) - \frac{(1-2\nu)}{(1-\nu)} J_1(\zeta) = 0. \qquad (2)$$

Unfortunately, the amplitude range of the DD-300 decoder unit (± 75 nm) was a limiting factor for high temperature measurements.

Tungsten Properties at High Temperature and High Stress

The VD-05 velocity decoder unit has been found to be much better suited for the high temperature measurements. High temperature measurements are the most important goal of this study because this places the material sample under high thermal stress conditions as expected at the Neutrino Factory. We have tested wires of different sizes, and the radial velocity of the 0.38 mm diameter wire is shown in Fig. 3 (bottom, dotted line). The wire in this case was stressed well above the Neutrino Factory level. The equivalent stress here was calculated to be 560 MPa while at the Neutrino Factory we expect ~ 300 MPa. The LS-DYNA result (full line) nicely follows the experimental data.
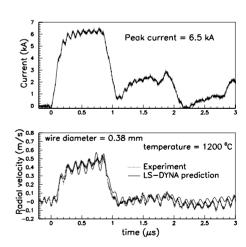

Figure 3: (Top) The current pulse shape for 6.5 kA peak current; (Bottom) Radial velocity of the 0.38 mm diameter tungsten wire at 1200 ^{0}C.

This is also illustrated in Fig. 4 where the comparison is shown between the measured and calculated radial frequency spectra (only the region of interest is plotted). The difference between experiment and simulation is at the level of a fraction of a percent, which is additional proof of
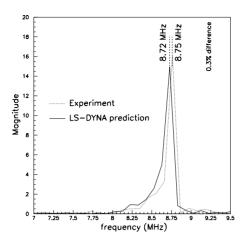
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Figure 4: Measured and simulated characteristic frequency of radial vibrations of the 0.38 mm diameter wire measured at 1200 ^{0}C.

the quality of both the experimental method and simulation procedure.

Fig. 5 shows the comparison between our experimental results (filled circles) and existing data [8]. The line in Fig. 5 represents the result of a fit to the results obtained in previous so-called dynamic measurements [8]. One can see that our measurements show that Young's modulus of tungsten remains high at high temperatures and high stresses.
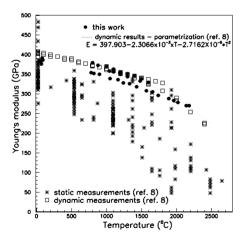

Figure 5: Comparison between our experimental results and previous results [8] on tungsten Young's modulus.

When discussing measured tungsten properties as a function of temperature, it should be noted that results depend on a set of parameters that define the material behaviour (electrical conductivity, coefficient of thermal expansion, etc ...). All of these are temperature dependent. However, if we choose the characteristic frequency as a measured observable we reduce this multi-parameter phase space to only three degrees of freedom: modulus of elas-

ticity, density and Poisson's ratio. The Poisson's ratio and tungsten density depend on temperature relatively weakly and definitely more weakly than the Young's modulus. As a result, we have chosen the Young's modulus to be the variable which represents the change of tungsten behaviour with temperature. Also, Young's modulus is directly related to applied stress which is additional important information needed for the interpretation of our results. Our measurements of tungsten material properties were dynamic and with relatively high strain-rates. The significant difference compared to the static measurements (see Fig. 5) should be noted. From the point of view of the Neutrino Factory solid target concept, it is important that we have tested our tungsten samples under conditions as close as possible to those expected at the Neutrino Factory. We have induced the same level of shock and operated the wire in the same temperature region. Also, the wire vibrations in our experiment lie in the frequency region from tens of kHz up to tens of MHz. Dimensions of a single Neutrino Factory tungsten target are planed to be $\sim$ 2 cm in diameter and 20 cm in length, and it will vibrate dominantly in the frequency region around 10 kHz, so here too we have quite a good match. As a result, we also expect to see that tungsten's modulus of elasticity remains high under the Neutrino Factory conditions.

CONCLUSIONS

We have performed an extensive set of measurements of the surface displacement and velocity of tungsten wires at high temperature and high stress. Stress was induced by passing a fast, high current pulse through a thin wire and radial and longitudinal motion of the sample were measured by a Laser Doppler Vibrometer. The wire was operated at temperatures of $300 - 2500$ K by adjusting the pulse repetition rate. In doing so we have tried to simulate the conditions (high stress and temperature) expected at the Neutrino Factory. The most important result of this study is that Young's modulus of tungsten remains high at high temperature and high stress. The experimental results have been compared with modelling results and we have found that they agree very well. This means that the results of previous lifetime tests have been confirmed.

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