

Tensile Test of Copper Fibers in Conformance with ASTM C1557 using Agilent UTM T150

Application Note

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Figure 1. The Agilent UTM T150.

Introduction

Fibers play an important role in various applications such as composites, textile, insulation, filtration, and even in biomedical tissue engineering. In recent years, there has been an increase in scientific interest towards ultrathin fibers for enhanced performance because of reduced defect concentration. Hence, measurement of mechanical properties of thin fibers is of utmost importance to the engineering community. Although mechanical behavior of large-diameter fibers is well documented, systematic mechanical characterization of thin fibers has been sparse, because measurement tools that conform to the requirements of international standards have not been widely available.

The Agilent UTM T150 (Figure 1) has been specifically designed to address the need to characterize mechanical behavior of thin fibers in conformance with the standard C1557-03 from ASTM International [1]. The UTM T150 has already been successfully utilized to characterize ultrathin polymeric fibers [2], spider silk [3-10], lyocell fibers [11], basalt glass fibers, tungsten wire and

polypropylene [12]. It offers the highest resolution in load and displacement up to 500 mN of load that makes the UTM T150 suitable for thin fibers with a wide range of properties.

The ASTM C1557 test method covers sample preparation and determination of tensile strength and Young's modulus at ambient temperature. It is valid for any fiber specimen with diameter up to 250 μm . To conform to the ASTM C1557-03 standard, the testing machine should be in conformance with standard practice ASTM E4, which specifies that the force measurement should be within $\pm 1\%$ at any force within the selected force range. The force transducer in the Agilent UTM T150 is calibrated using standard weights, which are NIST traceable. Hence, the uncertainties in force measurement for the complete force range are much smaller than 1%. The standard specifications for the Agilent UTM T150 are given in Table 1. The current application note demonstrates how the UTM T150 is used to determine the tensile strength and Young's modulus of thin copper (Cu) wire in conformance with the ASTM C1557-03.

| | |
|---|-------------------------------|
| Maximum Load | 500 mN (50.8 gm) |
| Load Resolution | 50 nN (5.1 μgm) |
| Maximum Actuating Transducer Displacement | ± 1 mm |
| Displacement Resolution | < 0.1 nm |
| Dynamic Displacement Resolution | < 0.001 nm |
| Maximum Crosshead Extension | 150 mm |
| Extension Resolution | 35 nm |
| Extension Rate | 0.5 $\mu\text{m/s}$ to 5 mm/s |

Table 1. Agilent UTM T150 specifications.

Theory

In a tensile test, the engineering stress in a fiber is defined as:

$$\sigma = \frac{F}{A_0} \quad (1)$$

where, F is the tensile force and A_0 is the original fiber cross-sectional area. The engineering strain of the fiber is defined as:

$$\epsilon = \frac{\Delta l}{l_0} \quad (2)$$

where, l_0 is the specimen gage length and Δl is the increase in gage length. The actual fiber elongation, Δl , can be calculated from;

$$\Delta l = \Delta L - C_S F \quad (3)$$

where, ΔL is the recorded cross-head displacement and C_S is the frame compliance. To conform to the ASTM C1557-03 standard test method, the frame compliance should be determined accurately. The detailed procedure for determination of frame compliance is outlined in the Agilent UTM T150 Users' Manual.

Once the tensile stress-strain curve is plotted, the Young's modulus, E , of the fiber is determined from the slope of the initial linear region.

At the point of failure, the tensile strength of a fiber is calculated by dividing the tensile force at the point of failure by the final cross-sectional area at fracture plane, A_f . ASTM C1557-03 recommends that the final cross-sectional area be measured directly by means of microscopy. However, an estimate of the final cross-sectional area is obtained by assuming a constant-volume deformation:

$$A_f = A_0 \left(\frac{l_0}{l_0 + \Delta l} \right) \quad (4)$$

Experimental Method

Sample Preparation

Thin Cu wire (48 AWG) was purchased from MWS Wire Industries, Westlake Village, CA. As fiber diameter is an important parameter to calculate the fiber cross-sectional area, and hence the tensile stress, the ASTM test method suggests using a scanning electron microscope (SEM) to determine diameters of thin fibers. The diameter of the Cu wire used in this study is measured to be $28.6 \pm 0.1 \mu\text{m}$, using the Agilent 8500 Field Emission SEM.

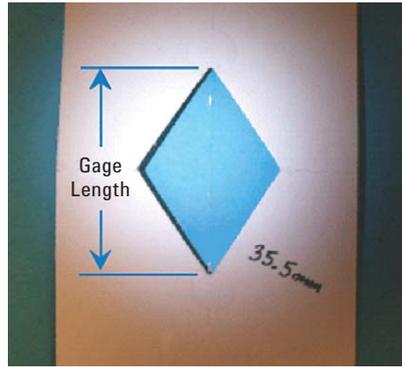


Figure 2. Single Cu wire mounted on a template made of card-stock.

The Cu wire is cut into small pieces and individual fibers are mounted on card templates, as shown in Figure 2. (Note: The ASTM standard suggests printing the mounting tab pattern on card-stock for consistent fiber length). The ends of the fibers are secured using cyanoacrylate. The gage length of the Cu wire specimen is measured between the two attached points (Figure 2) using a caliper (Mitutoyo Corporation, Japan). The card template with the fiber specimen are then mounted on the UTM T150 as shown in Figure 3. Note that although ASTM suggests a template design, the test method is valid for any gripping method as long as the grips are properly aligned with the line of tension. To address this requirement, the UTM T150 has an X-Y micropositioner (Figure 3). This prevents spurious bending strains and/or stress concentrations in the fiber. According to the ASTM standard the test results should be discarded if the fiber failure occurs at the grip or outside the gage section.

After each sample is mounted and aligned, the sides of the card-stock template are clipped to release the sample for testing (Figure 3). The Cu

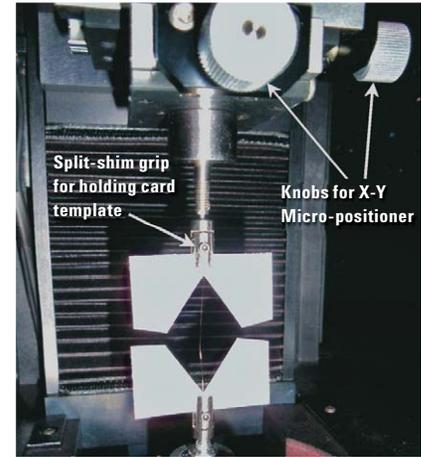


Figure 3. Single fiber sample (Cu wire) mounted in the UTM T150 using split-shim grips. The card template has been cut to release the sample for testing. Note the micropositioner attached to the top grip that ensures proper alignment of the fiber specimen.

wires are tested with a strain rate of $2 \times 10^{-3} \text{ s}^{-1}$. There is no particular reason behind selecting this strain rate, however it kept the time to failure (time from the start of loading to the fracture) within 30s, as specified in the ASTM C1557-03 standard test method. In case the time to failure exceeds 30s, the NanoSuite test method (see below) displays a warning message so that the strain rate can be modified accordingly.

Test Method

The quasi-static tensile test method, "UTM T150 ASTM C1557 Fiber Tensile Strength Modulus", has been designed to accommodate the required and post editable inputs mentioned in the ASTM C1557-03. Tables 2a and 2b show the required inputs and the post-test editable inputs, respectively. A detailed explanation of each input is given in the method documentation in NanoSuite. The method calculates the tensile strength as the failure force divided by

| a. Required Inputs | Units | b. Editable Inputs | Units |
|----------------------------|---------------|----------------------------|-----------------|
| Strain Rate | 1/s | Final Cross-sectional Area | μm^2 |
| Maximum Strain | mm/mm | Frame Stiffness Correction | N/m |
| Original Specimen Diameter | μm | Original Specimen Diameter | μm |
| Specimen Gage Length | mm | Specimen Gage Length | mm |
| Tension Trigger | μN | Slope Segment Length | % |
| Specimen Name | (String) | Specimen Name | (String) |

Table 2. (a) Required inputs, and (b) Inputs editable post-test in the NanoSuite test method conforming to ASTM C1557-03 standard.

| Results | Units |
|--------------------------------------|-----------------|
| Cross-head Displacement Rate | mm/s |
| Data Acquisition Rate | Hz |
| Final Cross-sectional Area | μm^2 |
| Force To Failure | mN |
| Original Specimen Diameter | μm |
| Specimen Gage Length | mm |
| Specimen Name | (String) |
| Strain Rate | 1/s |
| Tensile Strength Based on Final Area | MPa |
| Tension Trigger | μN |
| Time at Beginning of Experiment | (String) |
| Time To Fracture | s |
| Total Compliance | m/N |
| Young's Modulus | GPa |

Table 3. Results obtained from the Agilent NanoSuite test method for the UTM T150, in conformance with the ASTM C1557-03.

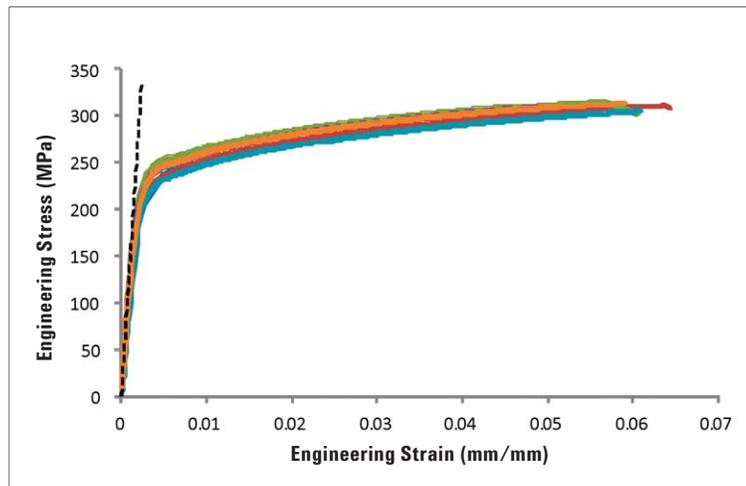


Figure 4. The engineering stress-strain curve for 6 Cu wire specimen tested using the UTM T150 in conformance with the ASTM C1557-03 standard test method. The dotted line delineates the elastic deformation.

the final fiber cross-sectional area as calculated from Eq. 4. However, if the user follows the recommendation of ASTM C1557-03 and directly measures the final cross-sectional area by means of microscopy, the user can edit the measurements in the cross sectional area post-test. This modification will recalculate the 'Tensile Strength Based on Final Area'. Table 3 is a summary of results reported by this NanoSuite test method, following the prescription of ASTM C1557-03. The NanoSuite test method also reports the total compliance for each measurement; this value may be used to determine the frame compliance following the procedure outlined in the UTM T150 Users' Manual.

Results and Discussion

Table 4 summarizes the results from 6 Cu wire specimens from the same spool. The engineering stress vs. engineering strain curves from the tensile tests are shown in Figure 4. Each curve clearly exhibits a linear-elastic regime (dotted line in Figure 4) followed by plastic yield and strain hardening prior to fracture. The consistency of the measured stress-strain values is evident from the good reproducibility of the linear-elastic region.

The slope measured from the linear-elastic regime of engineering stress-strain curves is the Young's modulus of the material. In the present study, the Young's modulus for Cu-wire is

measured to be 130 ± 5 GPa (Table 4), which is consistent with previously reported modulus values for Cu [13].

The tensile strength of the Cu-wire, measured from the quotient of force to failure and the final cross-sectional area, is 327 ± 6 MPa (Table 4), which is higher than the tensile strength calculated using the original cross-sectional area (310 ± 5 MPa). This behavior is expected because the fiber cross-sectional area decreases with increasing elongation to conserve the specimen volume. However, as mentioned above, the 'Final Cross-sectional Area' can be edited post-test and the software will recalculate the values for tensile strength based on

| Test # | Original Specimen Diameter (μm) | Final Cross-sectional Area (μm^2) | Specimen Gage Length (mm) | Force to Failure (mN) | Tensile Strength Based on Final Area (MPa) | Young's Modulus (GPa) |
|-----------|--|--|---------------------------|-----------------------|--|-----------------------|
| 1 | 28.600 | 609.670 | 38.200 | 194.638 | 319.251 | 130.736 |
| 2 | 28.600 | 604.062 | 39.800 | 200.060 | 331.191 | 134.489 |
| 3 | 28.600 | 607.938 | 36.200 | 202.820 | 333.620 | 136.739 |
| 4 | 28.600 | 612.095 | 35.100 | 198.866 | 324.894 | 127.783 |
| 5 | 28.600 | 605.582 | 35.200 | 195.889 | 323.473 | 121.818 |
| 6 | 28.600 | 606.665 | 38.100 | 201.377 | 331.941 | 127.541 |
| Mean | 28.600 | 607.669 | 37.100 | 198.942 | 327.395 | 129.851 |
| Std. Dev. | 0.000 | 2.899 | 1.893 | 3.165 | 5.688 | 5.364 |
| % COV | 0.00 | 0.48 | 5.10 | 1.59 | 1.74 | 4.13 |

Table 4. Summary of tensile test results from 6 copper wires.

the final area. The small amount of variation in the measured tensile strength may be due to the distribution of surface defects in the fiber.

Conclusions

The Agilent UTM T150 conforms to the specifications of ASTM C1557-03 standard test method. The Young's modulus and tensile strength of thin copper wire, as determined from the tensile tests using UTM T150 and the NanoSuite test method, agrees with the previously reported values.

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Significance

This application note demonstrates the integrity and reproducibility of test results from the Agilent UTM T150. The ASTM C1557-03 standard test method conformance not only provides confidence in the results but also helps in fundamental understanding of fiber behavior without any complication from the measurement technique. It shows great promise in the evaluation of tensile strength and Young's modulus of thin fibers at the research and development level.

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