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Mechanical Properties Testing for Metal Parts Made via Additive Manufacturing: A Review of the State of the Art of Mechanical Property Testing

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INTRODUCTION

Background

This National Institute of Standards and Technology Internal Report (NISTIR) is the first in a series of planned reports from the National Institute of Standards and Technology's (NIST) Engineering Laboratory project titled *Materials Standards for Additive Manufacturing*.[1] This project provides the measurement science for the additive manufacturing industry to measure material properties in a standardized way. Currently there are no consensus-based standards in this area, except for those pertaining to terminology and data file formats. This project, in conjunction with NIST's *Fundamental Measurement Science for Additive Processes* project,[2] will provide the technical foundation and documentary standards development necessary to develop new consensus-based standards. This will be done via ASTM-International's (hereafter referred to as 'ASTM') Committee F42 on Additive Manufacturing Technologies and the newly formed International Organization for Standardization (ISO) TC261 committee on Additive Manufacturing.

Determining the properties of the powder used for metal-based additive manufacturing, as well as the properties of the resulting bulk metal material, is a necessary condition for industry to be able to confidently select powder and produce consistent parts with known and predictable properties. By 2014, the project team will develop and deliver enhanced measurement techniques that support new, standardized methods for quantifying the material properties of both the powders used for additive manufacturing and the resulting manufactured products.

The project's research plan includes assessments of the current state-of-the-art testing methods for determining properties of both bulk metal materials, which is the focus of this report, and raw metal powder, which will be reported on in mid-2012. These methods will then be evaluated for applicability and enhanced for use on additively manufactured parts and raw additive powder. NIST's new Direct Metal Laser Sintering (DMLS) machine will be used to make parts, and these new methods will be rigorously implemented. Using these enhanced methods, the sensitivity of part material properties to variations in initial powder properties will be determined. This is a critical step necessary for determination of scopes of relevant material standards for additive manufacturing and for the production of additive manufacturing parts with consistent properties.

Scope

In order to perform this state-of-the-art assessment of bulk metal material property measurements in a rational and reasonable way, the focus was on existing consensus-based standards. Careful scoping of existing standards was first performed to ensure that the assessment was both representative of the

[1] http://www.nist.gov/el/isd/sbm/matstandaddmanu.cfm
[2] http://www.nist.gov/el/isd/sbm/fundmeasursci.cfm

state-of-the-art, and at the same time not unwieldy. To do this, three criteria were applied to determine which standards should be included in this assessment:

- Metals – Only standardized methods for measuring the mechanical properties of metal parts were included. Mechanical property measurements for non-metals such as polymers or ceramics were excluded.
- Bulk Mechanical Properties – Only standardized methods for measuring bulk properties were included. Mechanical property measurements of extremely localized properties, such as those obtained by micro-indentation methods, were excluded. This criterion does not preclude most standardized hardness tests, because the results of these tests are reflective of the bulk properties of the specimen.
- Focus on International Standards – This was done in order to make the assessment practical. A cursory review of standards from the major Standards Development Organizations showed that the ASTM-International and the International Organization for Standardization mechanical standards are representative of all the pertinent standardized mechanical testing methods.

In addition, care was taken to ensure that both all of the mechanical testing characteristics required by the MMPDS[3] and the characteristics typically reported by the additive manufacturing original equipment suppliers were included in the assessment. The MMPDS includes both required tests (tensile, compression, shear, bearing, moduli) and recommended tests (tests at elevated temperatures, fatigue, fracture toughness, crack growth [1].) *EOS* – a German producer of additive manufacturing machines with a significant market presence in the U.S. – reports tensile strength, yield point, hardness, and fatigue strength for their materials [2]. The criteria above were applied to a total of 86 standards – 58 ASTM and 29 ISO – covering the measurement of material properties.

The following is organized into two sections: (1) deformation properties (where the tests attempt to quantify how a material will yield or deform) and (2) failure properties (where the tests attempt to quantify the potential for the component to rupture or fail.) Deformation property tests include tension, compression, bearing, modulus, and hardness tests. Failure property tests include fatigue, fracture toughness, and crack growth tests. Within each of these general test classifications the most general test is first described, followed by modified tests that have testing features or parameters that make them distinct from the most general test.

[3] The MMPDS is the Metallic Materials Properties Database and Standardization. This database replaced MIL-HDBK-5 and is the preeminent source for aerospace component design allowables. See http:// http://projects.battelle.org/mmpds/ for further information.

DEFORMATION PROPERTIES

General Description

One criterion for the selection of engineering materials for particular applications is how those materials behave when subjected to forces, since parts made from those materials will typically be subjected to forces while in service. This is particularly true for parts and structures used in the aerospace and biomedical industry.

If a material is subjected to a static or very slowly changing stress and that stress is applied uniformly over a cross section of that material, then the resulting deformation behavior can be characterized by a simple stress-strain test. The stress can be applied in several different ways relative to the sample including tension (stretching), compression (squeezing), shear (sliding), and torsion (twisting.) The applied stress causes a certain amount of displacement, or strain, in the test specimen. The graphical representation of the amount of strain (on the abscissa) resulting from the applied stress (on the ordinate) is referred to as a stress-strain diagram.

For most metals that are stressed in tension at low levels, the stress and strain are proportional to each other and the constant of proportionality is Young's Modulus [3]. This type of low-level stress where this proportionality is maintained is called elastic deformation. Under elastic deformation the material returns to its original configuration after the stress is removed. For some materials the initial elastic portion of the stress-strain relationship is not linear; in these cases the tangent (the slope of the stress-strain curve at a specified value of stress) and/or secant modulus (the slope of a line drawn between the origin and a given point on the stress-strain curve) is used.

Above a certain level of strain most metal materials no longer strain elastically, and non-recoverable (i.e., the material does not return to its original configuration when the stress is released) plastic deformation occurs. A subset of these exhibit yield-point phenomena, where the stress-strain curve drops precipitously from the end-point of the elastic deformation (called the upper yield point), and then remains nearly constant for further increasing strain (called the lower yield point) before again gradually increasing for further increases in strain [3]. If the strain is continued to even higher levels most materials eventually fail via rupturing.

Indentation tests, which measure the resistance of a material to plastic deformation, are also included here. These types of measures use a specified load and loading condition to force a small indenter into the material surface. The size of the indent is then measured, from which the material hardness can be computed. Since different hardness tests employ different indenters with different sizes and geometries, the resulting hardness value applies only to the particular test being used. Hence hardness measurements are mostly relative in nature [3, 4].

Properties Measured

Deformation property tests, which include tension, compression, modulus, and hardness tests, provide the measured material properties listed below. Definitions for many of these terms can be found in Appendix A.

Stress-Strain Diagram	Poisson's Ratio
Torque-Twist Diagram	Tangent Modulus
Yield Strength	Secant Modulus
Yield Point	Chord Modulus
Tensile Strength	Brinell Hardness Number
Rupture Strength	Rockwell Hardness Number
Upper Yield Strength	Knoop Hardness Number
Lower Yield Strength	Vickers Hardness Number
Compressive Strength	Scleroscope Hardness Number
Bearing Strength	Webster Hardness
Ductility	Indentation Hardness
Young's Modulus	Indentation Modulus
Shear Modulus	Elasto-plastic Hardness

Specific Tests

<u>Tension Tests</u>

ASTM E8 [5] is the basic method for uniaxial tension testing of metals at room temperatures (10 °C – 38 °C). ISO 6892-1 [6] is the equivalent ISO test and includes additional test sample geometries such as sheet and wire. Both methods give the material's measured yield and tensile strengths. ASTM E21 [7] and ISO 6892-2 [8] provide methods for tension test of metals at elevated temperatures (above 38 °C.) ISO 15579 is similar to ASTM E8 and ISO 6892-1 but provides guidance for testing at low temperatures, between 10 °C and -196 °C [9]. Guidance for tension testing of metals at cryogenic temperatures (less than -196 °C) is covered in ASTM E1450 [10] and ISO 19819 [11].

ASTM also has two metal material tension tests, ASTM E292 [12], and ASTM E740 [13] , that are similar to E8, except that the samples are first prepared with a notch or surface-crack before subjecting them to tension. ASTM E292 is explicitly performed at elevated temperatures. These tests provide the test material's rupture strength (E292) or metal plate yield strength (E740.)

Finally, there are two ISO standards, ISO 26203 [14] and ISO 26203 [15], that describe testing of metal sheet material at high-strain rates (10^{-2} s^{-1} to 10^{3} s^{-1} and higher), such as the testing of sheet metal for automotive bodies. There do not appear to be any equivalent standards in ASTM.

Compression Tests

ASTM E9 [16] is the basic method for uniaxial compression testing of metallic samples at room temperatures. ASTM standard practice E209 [17] is the same test performed at elevated and uniform temperatures, up to and beyond 538 °C. There do not appear to be equivalent test standards in ISO.

Bearing Tests

ASTM E238 appears to be the only ASTM or ISO method for pin-type bearing tests [18], which determines the bearing yield strength and bearing strength for a rectangular metal specimen containing a hole for a bearing pin. The load on the bearing pin is increased at a rate of 0.05 bearing-strain per minute and a plot of the bearing pin load versus bearing deformation is made. From this data the bearing yield strength and bearing strength are determined.

Modulus Tests

ASTM E111 is the basic method for conducting modulus tests [19]; it builds on the test methods specified in ASTM E8 for tension and E9 for compression by providing additional guidance on the number of required trials, specimen preparation, and test temperatures. It also defines how to determine the Young's, Tangent, and Chord modulus values from the tension and compression test data. ASTM E111 includes guidance for modulus measurements at both high and low temperatures. ASTM E143 provides the basic method for measuring the shear modulus at room temperature [20]. Both of the E143 and E111 methods involve subjecting the test specimens to macroscopic tension, compression, or twisting.

Alternatively, dynamic methods that employ more microscopic deformations may be employed. ASTM E1875 describes a vibrational method that induces a sonic resonance throughout the entire sample, using a variable-frequency audio oscillator to generate a sinusoidal signal and a power-amplified transducer to convert that signal into a mechanical driving vibration [21]. A suspension-coupling system supports the test specimen and another transducer detects the mechanical vibration in the sample. If both the flexural mode and torsional mechanical resonances of the specimen are measureable, and if the geometry and mass are known, then the Young's and Shear modulus and Poisson's Ratio can be determined. This method includes guidance for making measurements made at room, elevated, and very low temperatures, across the range -195 °C to 1200 °C. ASTM E1876 is similar, and is also a micro-scale deformation method; however this test uses a more localized elastic excitation, typically generated by an impulse tool [22]. Both E1875 and E1876 methods give the dynamic Young's and Shear Moduli and Poisson's Ratio. With careful experiments, ultrasonic nondestructive testing techniques, which are similar conceptually to E1876, can measure the various dynamic moduli and Poisson's Ratio of a suitably-sized metal material with a measurement uncertainty of better than 1 % (k=2) [23].

Hardness Tests

Hardness tests give a general indication of the strength of a material and its resistance to deformation [3]. Hardness is not a fundamental material property, however, due to the wide variety of indenters and a material's resistance to indentation being dependant on the size and geometry of the indenter and the applied load [3, 4]. Hence it is difficult to make quantified comparisons between material tests made with different indenters. ASTM E140 [24] does provide approximate conversions of the hardness values measured with different types of indenters.

ASTM E10 [25] and ISO 6506-1 [26] provide guidance for hardness tests of metal samples using Brinell indenters, which are spherical in shape, at room temperatures (10 °C to 35 °C). ASTM E18 [27] and ISO 6508 [28] provide the same for Rockwell (either tungsten carbide balls (Rockwell B) or diamond spheroconical indenters (Rockwell C) hardness tests, also at room temperatures. Knoop and Vickers indentation tests are covered in ASTM E384 [29] and ISO 4545-1 [30] (for Knoop) and ISO 6507-1 [31] for Knoop and Vickers, respectively. Both Knoop and Vickers indenters are pyramidal in shape, but with different face angles.

The above methods all involve the application of a static (or quasi-static) load. ASTM E448 [32] describes a Scleroscope Hardness measurement, which is a dynamic measurement. For this test an indenter is dropped from a height above the metal test sample, and the magnitude of the rebound height is used to determine the hardness. ISO 14577-1 is also an elastic method, and measures both the plastic and elastic deformation of the metal material during application of the indenter, in order to compute the indentation modulus and the elasto-plastic hardness [33].

Four ASTM standards also provide guidance on three hand-held instrument methods which are useful in production environments for quality control purposes. These include the Webster [34] and Barcol Indentation Hardness [35] (both of which are not as sensitive to material properties as Rockwell or Brinell), and the Rockwell B-Scale Hardness, which is measured using a Newage Instrument [36]. All three of these portable methods are only standardized in ASTM for use on aluminum materials. ASTM E110 also includes portable hardness testers [37].

Finally, ISO Technical Report 29381 [38] summarizes the state of the art in deriving bulk material tensile properties from the indentation response of the material. It describes three techniques: representative stress-strain, inverse finite element analysis methods, and the use of neural networks. However, all of these techniques assume a test piece that is free of residual stresses.

FAILURE PROPERTIES

General Description

Part failure is an undesirable aspect of in-service parts that is difficult to predict. A number of mostly qualitative tests have been devised to determine a part's or material's resistance to failure under cyclical stress or impacts. These include impact tests and cyclical stress tests, which are often made on specimens that include pre-made cracks. These types of tests are also useful for materials that don't strain well and rupture quickly under applied stress, thus making them problematic for deformation testing.

Properties Measured

Failure property tests, which include fatigue, fracture toughness, and crack growth tests, provide the measured material properties listed below. Definitions for many of these terms can be found in Appendix A.

Number of Cycles to Failure
Stress/Strain Ranges
Strain Ratio
Fatigue Crack Growth Rates as a Function of Stress-Intensity Factor Range (ΔK)
Fatigue Life
Tensile and Compressive Stresses as a Function of Number of Fatigue Cycles
Representative Cycles of Mechanical Strain Versus Stress/Temperature
Plane-Strain Fracture Toughness
Fracture Toughness
Plain-Strain Crack-Arrest Fracture Toughness
Crack-Tip Opening displacement
Absorbed Impact Energy
Specimen Residual Strength
Creep Crack Growth Rate
Threshold Stress Intensity Factor
Crack Resistance Curve

Specific Tests

<u>Fatigue</u>

In basic fatigue tests a test specimen is subjected to cyclical stresses (e.g., tension and compression) until the specimen fails. ASTM E466 is the basic ASTM method for room-temperature fatigue testing of metals [39] and ISO 1099 is the equivalent ISO standard test method [40], although 1099 includes guidance on performing the tests at higher temperatures. ISO 1099 provides a quantitative measure of the fatigue life, while E466 just determines whether a part will fail for a given set of material and testing conditions, such as material composition, geometry, and surface condition. The basic test subjects either un-notched or pre-notched specimens to a constant amplitude periodic axial force. ASTM E606 [41] is similar to E466, but is strain-controlled instead of force-controlled fatigue, and provides guidance on determining the fatigue life, similar to ISO 1099. In addition, E606 determines the cyclic stresses and strains at any time during the tests.

ASTM E647 is a fatigue test that measures the rate of crack growth in a specimen [42] and determines the rate as a function of the stress-intensity factor range (ΔK). The method uses cyclic loading of notched specimens that have been pre-cracked. The crack size is measured as a function of the number of fatigue cycles, and the crack growth rates are expressed in terms of ΔK, which is calculated from linear stress analysis. ISO 12108 is the equivalent ISO test [43].

ASTM E2368 is a practice for strain-controlled thermomechanical fatigue testing, which occurs when a uniform temperature and strain field over the specimen are simultaneously varied and independently controlled [44]. ISO 12111 is the equivalent ISO test method [45]. ASTM E2714 is the ASTM test method for creep-fatigue testing [46]. This test determines deformation and crack formation or crack nucleation as a result of constant-amplitude strain-controlled tests or constant-amplitude force-controlled tests (see ASTM E606, ASTM 466, ISO 12106, and ISO 1099.) These tests are typically done at elevated temperatures and involve sequential or simultaneous application of the loading conditions necessary to generate cyclical deformation or damage enhanced by creep deformation or damage. The distinction between E2714 and E466 is that E2714 involves much longer hold times. ISO 12111 is the equivalent ISO test method for strain-controlled thermomechanical fatigue testing [45].

ASTM E2760 is the ASTM test method for creep-fatigue crack growth testing [47]. E2760 covers fatigue cycling with long loading/unloading rates and/or hold times. This causes creep deformation in the pre-cracked crack tip and the creep deformation is then responsible for enhanced crack growth during each loading cycle.

ASTM E2789 is the ASTM guide for fretting fatigue testing [48]. E466 is still the basic method, but E2789 provides guidance for fatigue testing of small amplitude oscillatory tangential motion between two solid surfaces in contact. Fretting fatigue is generally characterized by a sharp decrease in fatigue life at the same stress level of a standard specimen. This decrease is due to the shortened time required to form a crack and the acceleration of the crack growth under the coupling of the fretting and bulk cyclical stresses and strains.

ISO 1143 measures the fatigue life of rotating bar bending fatigue testing [49]. This method uses metal samples with a circular cross-section, which are rotated and subjected to a bending moment. ISO 1352 is similar to ISO 1143 but is for torque-controlled fatigue testing [50]. ISO 12106 covers fatigue testing of metal samples where the axial-strain is controlled [51]. This is similar to ISO 1099 but is a low-cycle fatigue test that is performed until specimen failure. The standard has guidance on performing the test at both low and high temperatures.

Fracture toughness

The basic fracture toughness test subjects a pre-cracked specimen to strain, in an attempt to initiate crack growth and fracture the material. The ability of a material to resist this fracture is a measure of its fracture toughness. ASTM E399 [52] and E1820 [53] are the basic ASTM test methods for determining the linear-elastic plain-strain fracture toughness of metals. The E399 test is performed on metals under linear-elastic, plane-strain conditions using fatigue pre-cracked specimens that are subjected to a slowly increasing crack-displacement force. ISO 12737 [54] is the equivalent ISO test method of E399. In ASTM E1820 a precracked fatigue test specimen is loaded to induce either stable or unstable crack extensions. ISO 12135 [55] is the ISO equivalent of E1820, and ISO 22889 is similar, but provides guidance for specimens that are very small, and hence have size sensitivities [56]. ASTM B646 [57] is the standard practice for fracture toughness of aluminum alloys, and provides information supplementary to E399 on specimen size, analysis, and interpretation of results, especially for parts of varying thickness, when aluminum alloys are tested. ASTM B645 [58] is supplementary to both E399 and B646, and is the basic test method for plane-strain fracture toughness measurements of aluminum specimens. ASTM B909 [59] provides additional guidance for fracture toughness tests of aluminum where complete stress relief of the aluminum samples is not possible and ASTM E1304 covers plane-strain fracture toughness of metal materials that have a Chevron-shaped-notch [60].

ASTM E23 contains the standard methods for absorbed impact energy measurements of notched metal bars using both Charpy and Izod test methods [61]. These two methods have differences in the shape of the notches, the bar holding mechanisms, the impact locations, and the sample dimensions. ASTM E23 has detailed information about testing at different temperatures. ISO 148-1 is the equivalent ISO Charpy test [62] and in addition provides guidance on performing the test at elevated or decreased temperatures using liquid or gaseous mediums. ISO 14556 is similar to 148-1 but is for steel materials [63].

ASTM E1221 is the ASTM test method for determining the plane-strain crack-arrest fracture toughness of ferritic steels [64]. There does not appear to be an equivalent ISO test. ASTM E1290 [65] is the ASTM test method for crack-tip opening displacement (CTOD) fracture toughness measurements. This test determines the critical CTOD values, which are used to measured cleavage crack initiation toughness for materials that exhibit a change from ductile to brittle behavior with decreasing temperatures. Finally, ISO 27306 is a standard method of constraint loss correction of CTOD fracture toughness for fracture assessment of steel components [66]. Specifically, this method converts fracture toughness from laboratory specimens to the equivalent value for structural components. There does not appear to be an equivalent ASTM standard.

Crack Growth

In basic crack growth testing a pre-cracked specimen is subjected to stress, and the rate of growth of the crack(s) is measured. ASTM has four standards that cover crack growth testing. ASTM E740 [13] is the practice for fracture testing with surface-crack tension specimens. This practice covers the design, preparation, and testing of surface-crack specimens, and the test is performed with a continuously increasing force, and excludes cyclical and sustained loadings. This test determines the residual strength of specimens with semi-elliptical or circular-segment fatigue cracks. ASTM E1457 [67] is a test method for measurement of creep crack growth times in metal specimens. It determines the creep crack growth in metals at elevated temperatures using pre-cracked specimens that are subjected to static or quasi-static loading conditions. ASTM E1681 [68] is a test method for determining the threshold stress intensity factor for environmentally-assisted cracking of metallic materials, and requires an environmental chamber. Finally, ASTM E2472 [69] is a test method for determination of resistance to stable crack extension under low-constraint conditions, which occurs when the crack-length-to-thickness and uncracked-ligament-to-thickness ratios are greater than or equal to 4. This test is performed only under a slowly increasing remote applied displacement.

CONCLUSIONS AND NEXT STEPS

As mentioned in the introduction, this report is the first step of a longer process to develop standards appropriate for the testing of the mechanical properties of metal parts made via additive manufacturing. A future report will assess the practical applicability of the existing test methods and standards summarized in this report for use on additively-made metal parts. Nevertheless, some initial conclusions can be made.

First, this assessment shows that a large number of international, consensus-based standards covering a wide range of material mechanical properties already exists. This is fortunate because it means that the baseline technical development for these standard tests has already been done. These tests include the typical mechanical properties specified in the introduction for both the MMPDS and a typical additive parts manufacturer. The hope is that these existing tests can be used, in either their current or slightly modified forms, on metal additive parts.

However, given the way in which these parts are manufactured, supplementary guidance will have to accompany these tests. This will be necessary to account, for example, for the anisotropy and potential porosity that may be present in these parts. Users should not assume that specimens made via additive manufacturing processes are isotropic, and the influence of anisotropy and porosity on the results obtained with these tests will need to be determined. In addition, not all of the test specimens described in these standards are easily built with additive manufacturing; very thin test specimens for example will be problematic because the resulting residual stresses may warp the specimens. Finally, there is a strong need for a careful study of the sensitivity of the material properties to both the additive manufacturing build parameters and the properties of the initial powder.

The next step is to assess the state-of-the-art measurements for the properties of metal powders. The properties of interest include measurements of particulate size, powder chemical composition, powder viscosity, and powder particulate morphology. This will be reported on in mid-2012. Following that, the suitability of these existing measurements - both mechanical properties of metal parts and properties of metal powders - will be assessed for use in additive manufacturing.

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APPENDIX A: DEFINITIONS OF MATERIAL PROPERTY TERMS

Absorbed Impact Energy – In an Izod or Charpy test, the amount of energy required to fracture a material.

Bearing Strength – The maximum bearing stress which a material is capable of sustaining. [70]

Brinell Hardness Number – Result from indentation hardness test in which a number proportional to the quotient obtained by dividing the test force by the curved surface area of the indentation which is assumed to be spherical and of the diameter of the ball. [70]

Chord Modulus – The slope of the chord drawn between any two specified points on the stress-strain curve. [19]

Compressive Strength – The maximum compressive stress that a material is capable of sustaining. [70]

Crack-Tip Opening Displacement – The crack displacement resulting from the total deformation (elastic plus plastic) at variously defined locations near the original (prior to force application) crack tip. [71]

Creep Crack Growth Rate – The rate of crack extension caused by creep damage and expressed in terms of average crack extension per unit time. [71]

Ductility – The ability of a material to deform plastically before fracturing. [70]

Elasto-plastic Hardness – Hardness measured from the recorded time record of the force and displacement data of an indentation during plastic and elastic deformation.

Fatigue Cycle – One complete sequence of values of force (strain) that is repeated under constant amplitude loading (straining). [71]

Fatigue Life – The number of cycles of a specified character that a given specimen sustains before failure of a specified nature occurs. [71]

Fracture Toughness – A generic term for measures of resistance to extension of a crack. [71]

Indentation Hardness – The hardness as evaluated from measurements of area or depth of the indentation made by pressing a specific indenter into the surface of a material under specified static loading conditions. [70]

Indentation Modulus – Modulus measured from the recorded time record of the force and displacement data of an indentation during plastic and elastic deformation.

Knoop Hardness Number – A number related to the applied force and to the projected area of the permanent impression made by a rhombic-based pyramidal diamond indenter having included edge angles of 172° 30’ and 130° 0’. [70]

Lower Yield Strength – The minimum stress recorded during discontinuous yielding, ignoring transient effects. [70]

Plane-Strain Fracture Toughness – The crack-extension resistance under conditions of crack-tip plane strain in Mode I for slow rates of loading under predominately linear-elastic conditions and negligible plastic-zone adjustment. [71]

Poisson’s Ratio – The negative of the ratio of transverse strain to the corresponding axial strain resulting from an axial stress below the proportional limit of the material. [70]

Rockwell Hardness Number – A number derived from the net increase in the depth of indentation as the force on an indenter is increased from a specified preliminary test force to a specified total test force and then returned to the preliminary test force. [70]

Rupture Strength – The stress at which rupture (a failure that is accompanied by significant plastic deformation, often associated with creep failure) occurs. [3]

Scleroscope Hardness Number – A number related to the height of rebound of a diamond-tipped hammer dropped on a material being tested. [70]

Secant Modulus – On a stress-strain curve, the slope of a line between the origin and any specified stress. [3]

Shear Modulus (aka torsional modulus) – The ratio of shear stress to corresponding shear strain below the proportional limit. [70]

Strain Ratio – The ratio of width to thickness strain determined in the uniform elongation portion of a tension test. [72]

Stress-Intensity Factor – The magnitude of the mathematically ideal, crack-tip stress field for a particular mode in a homogeneous, linear-elastic body. [71]

Stress-Intensity Factor Range – In fatigue, the variation in the stress-intensity factor in a cycle. [71]

Stress-Strain Diagram (aka Stress-Strain Curve) – A diagram in which corresponding values of stress and strain are plotted against each other. Values of stress are usually plotted as ordinates and values of strain as abscissas. [70]

Tangent Modulus – The slope of the stress-strain curve at any specified stress or strain. [19]

Tensile Strength (aka Ultimate Tensile Strength) – The maximum tensile stress which a material is capable of sustaining. Tensile strength is calculated from the maximum force during a tension test carried to rupture and the original cross-sectional area of the specimen. [70]

Torque-Twist Diagram (aka Torque-Twist Curve) – In shear testing, a diagram in which corresponding values of torque and twist are plotted against each other. Values of torque are usually plotted as ordinates and values of twist as abscissas.

Upper Yield Strength – See *Yield Point*.

Vickers Hardness Number – A number related to the applied force and the surface area of the permanent impression made by a square-based pyramidal diamond indenter having included face angles of 136°. [70]

Webster Hardness – A hardness number measured by a Webster Hardness gauge. Webster Hardness gauges can measure a range of hardness that corresponds to 5 HRE to 110 HRE on the Rockwell hardness scale. [34]

Yield Point (aka Upper Yield Strength) – In a uniaxial test, the first stress maximum associated with discontinuous yielding at or near the onset of plastic deformation. [70]

Yield Strength – The engineering stress at which it is considered that plastic elongation of the material has commenced. [70]

Young's Modulus – The ratio of tensile or compressive stress to corresponding strain below the proportional limit of the material. [70]

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