MECHANICAL TESTING

UNDERSTANDING THE BASICS

The results of tests commonly used to measure the properties of heat treated parts provide information about how well design requirements are met. Test data also can help ID production problems before they become critical.

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Mechanical testing deals with the response of metals to applied forces. Considered in this article are the common testing techniques related to the mechanical failure of metals. These include tension (tensile and transverse rupture), torsion, hardness, fatigue, creep and stress-rupture, and impact tests. Residual stress and statistical analysis of mechanical property data are also briefly covered.

Tension Testing

Tensile, transverse rupture, and other tension tests are widely used to provide basic design information on the strength of materials and as acceptance tests for the specification of materials. The basic parameters used to determine the stress-strain behavior of a metal are its tensile strength (ultimate tensile strength), yield strength (tensile yield strength) and yield point, elongation (or percent elongation), and reduction in area. The first three are strength properties; the other two, measures of ductility.

Tensile tests are designed to "pull" a specimen to failure (Fig. 1). The destructive test measures the force and stretch of a material during testing. The test plots "stress" versus "strain" (Fig. 2). Stress is the (applied) load divided by the cross-sectional area of the test specimen at its center. Strain is the change in a dimension divided by the original dimension, and is measured over the central portion of the specimen length (where the cross section is constant).

As the specimen is stretched, the load required to induce each level of strain is measured. When the load is first applied the tensile specimen stretches in proportion to the applied load. If the load is removed during

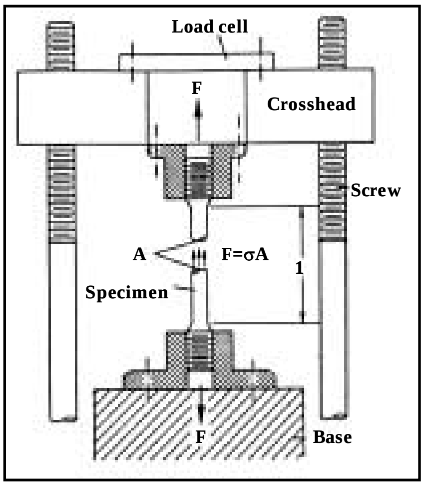

Fig. 1 — Typical tensile tester: a screw-driven electromechanical system. (Ref. 1)

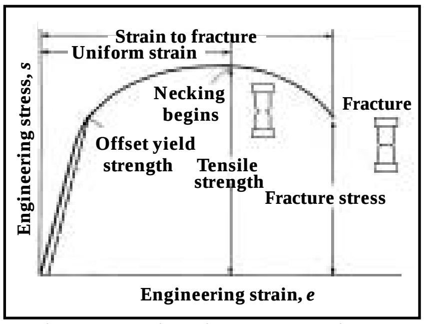

Fig. 2 — Engineering stress-strain curve. Intersection of the dashed line with the curve determines the offset yield strength. (Ref. 2)

this portion of the test, the specimen will return to its original length. This is called elastic deformation. The proportionality between the stress and strain is the elastic modulus (modulus of elasticity or Young's modulus). The modulus of elasticity is determined by the binding forces of the atoms and since these forces cannot be changed without changing the basic nature of the material, it follows that this is one of the most structure insensitive mechanical properties.

With continued loading and stretching, the tensile specimen permanently deforms, exhibiting plastic deformation. The yield strength is the stress at which the specimen shifts from elastic (recoverable) stretching to plastic (permanent) deformation. By standard convention,

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the reported yield strength corresponds to a plastic strain of 0.2% (where observable deformation has taken place)

Tensile strength is the highest stress encountered in the tensile test. For many steels this corresponds to the stress at fracture. For very ductile steels, the stress at fracture is lower than the tensile strength. For very brittle steels, the yield strength is the same as the tensile strength (and fracture strength).

A common measure of ductility is the elongation (given as total stretch to failure divided by the initial specimen-center test length, or gage length). Elongation is a dimensionless number, expressed as a percentage. Another measure of ductility is reduction in area, also dimensionless and expressed as a percentage. Reduction in area is a measure of the change in cross sectional area at the point of failure (change in area divided by the original area).

The transverse rupture test is a strength test designed for low-ductility materials, including carbides and powder metallurgy (P/M) materials. This destructive test involves bending rather than pulling of the specimen. Maximum load, specimen dimensions, and test time are used to calculate the stress needed to cause failure. A typical transverse rupture strength is 1.5 to 2 times the tensile strength

Torsion Testing

Torsion testing is used to determine such properties as modulus of elasticity in shear, torsional yield strength, and modulus of rupture. Any part subject to torsional loading in service, such as shafts and axles, should be torsion tested.

Torsion testers (Fig. 3) consist of a twisting head, with a chuck for gripping the specimen and for applying the twisting moment, and a weighing head, which grips the other end of the specimen and measures the twisting moment, or torque. Deformation of the specimen is monitored by a twist measuring device called a troptometer.

A torsion test specimen typically has a circular cross section (the simplest geometry for calculation of stress). Since the shear stress in the elastic range varies linearly from zero at the center of the specimen to a maximum at the surface, it is frequently desirable to test a thin-wall tubular specimen. This results in a nearly uniform shear stress over the cross section.

Torsion test results can be used to validate or expand on the information gleaned from tensile testing. Torsion testing provides a more fundamental measure of the plasticity of a material than does tension testing. It directly yields a shear stress-shear strain curve. In torsion, the critical shear stress for plastic flow is reached before the critical normal stress for fracture; while in tension, the critical normal stress is reached before the critical shear stress.

Hardness Testing

Among mechanical testing equipment, heat treaters probably are most familiar with the hardness tester. Almost every shop has either a Rockwell-scale or Rockwell superficial-scale tester. The Rockwell scales are those most often used for ferrous materials. Many shops also have Brinell and microhardness or microindentation hardness testers. These and other indentation hardness tests are compared in Table 1.

In general, hardness usually implies a resistance to deformation. For a metal, the property is a measure of its resistance to permanent or plastic deformation. Hardness measuring methods can be sorted into three general types, depending upon the manner in which the tests are conducted: scratch hardness, indentation hardness, and rebound, or dy-

Test	Indenter(s)	Indent: Diagonal or diameter
Brinell	Ball indenter, 10 mm (0.4 in.) or 2.5 mm (0.1 in.) in diameter	1–7 mm (0.04–0.28 in.)
Rockwell	120° diamond cone, 1.6–13 mm (1/16–1/2 in.)	0.1–1.5 mm (0.004–0.06 in.)
Rockwell superficial	As for Rockwell	0.1–0.7 mm (0.004–0.03 in.)
Vickers	136° diamond pyramid	Measure diagonal, not diameter
Micro-hardness	136° diamond indenter or a Knoop indenter	40 μm (0.16 micro-in.)
Ultrasonic	136° diamond pyramid	15–50 μm (0.06–0.2 micro-in.)

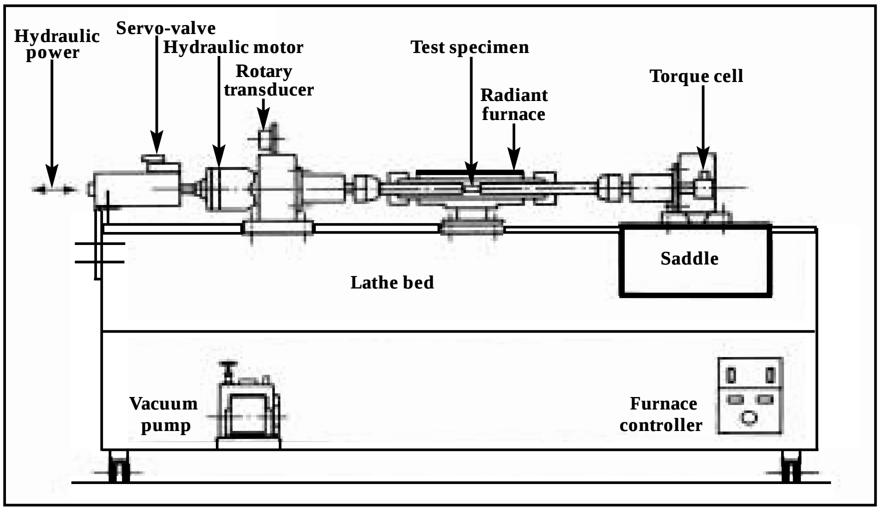

Fig. 3 — Typical torsion tester: a servo-controlled, hot torsion machine mounted on a lathe bed. Shafts and axles are among the parts that should be torsion tested. (Ref. 3)

Table 1 - Comparison of indentation hardness tests (Ref. 4)

Depth[1]	Load(s)	Method of measurement	Surface preparation	Tests per hour	Applications	Remarks
Up to 0.3 mm (0.01 in.) and 1 mm (0.04 in.), respectively, with 2.5 mm (0.1 in.) and 10 mm (0.4 in.) in diameter balls	3000 kgf for ferrous metals; down to 100 kgf for soft metals	Measure diameter of indent under microscope; read hardness from tables	Specially ground area for measurements of diameter	50 with diameter measurements	Large forged and cast parts	Damage to specimen minimized by use of lightly loaded ball indenter; indent will then be less than a Rockwell indent
25–375 µm (0.1–1.48 micro-in.)	Major, 60–150 kgf; Minor, 10 kgf	Read hardness directly from meter or digital display	No preparation necessary on many surfaces	300 manually, 900 automatically	Forgings, castings, roughly machined parts	Measure depth of penetration, not diameter
10–110 µm (0.04–0.43 micro-in.)	Major, 15–45 kgf; Minor, 3 kgf	As for Rockwell	Machined surface, ground	As for Rockwell	Critical surfaces of finished parts	A surface test of case hardening and annealing
30–100 µm (0.12–0.4 micro-in.)	1–120 kgf	Measure indent with low-power microscope; read hardness from tables	Smooth clean surface, symmetrical if not flat	Up to 180	Fine finished surfaces, thin specimens	Small indent but high local stresses
1–4 µm (0.004–0.016 micro-in.)	1 gf–1 kgf	Measure indent with low-power microscope; read hardness from tables	Polished surface	Up to 60	Surface layers, thin stock, down to 200 µm (0.008 in.)	Laboratory test used on brittle materials or microstructural constituents
4–18 µm (0.016–0.07 micro-in.)	800 gf	Direct readout onto meter or digital display	Surface better than 1.2 µm (0.004 micro-in.) for accurate work; otherwise, up to 3 µm (0.012 micro-in.)	1200 (limited by speed at which operator can read display)	Thin stock and finished surfaces in any position	Calibration for Young's modulus necessary; 100% testing of finished parts; completely nondestructive

1.The minimum material thickness for a test is usually taken to be 10 times the indent depth.

namic, hardness. Only indentation hardness is of major engineering interest for metals.

A part is usually hardness tested after heat treating, and the value obtained is an indication of the effectiveness of the treatment. A test tip (indenter) of defined configuration is pressed into the surface of the specimen using a constant, predetermined force. The tip deforms the steel such that a high hardness corresponds to a small impression or indent. The hardness value is a function of the size of the indent (Brinell and Vickers) or the depth of penetration by the indenter (Rockwell).

Fatigue Testing

Fatigue is a measure of the stress that a material can withstand repeatedly without failure. A fatigue failure is particularly catastrophic because it occurs without warning. Three basic factors are necessary to cause a fatigue failure: a maximum tensile stress of sufficiently high value, a large enough variation or fluctuation in the applied stress, and a suffi-

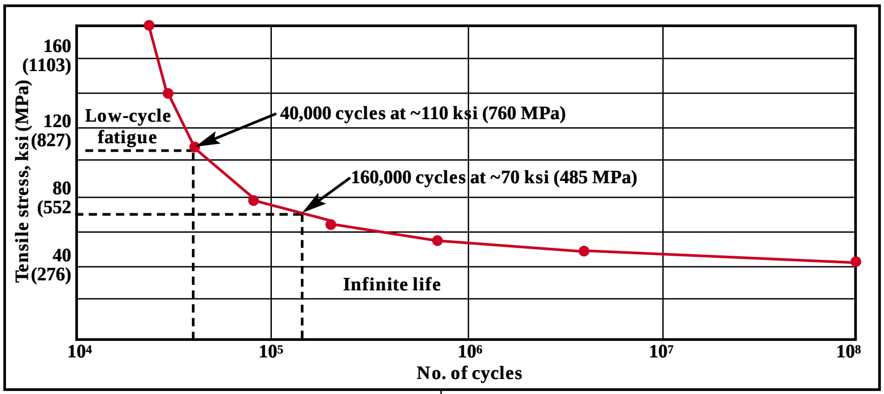

Fig. 4 — Typical S-N (stress vs. load cycles) curve. A linear reduction in applied stress results in an exponential improvement in fatigue life. (Ref. 5)

ciently large number of cycles of the applied stress.

The basic method of presenting engineering fatigue data is by means of the S-N curve (Fig. 4) that shows how the life of the specimen, expressed in number of cycles to failure

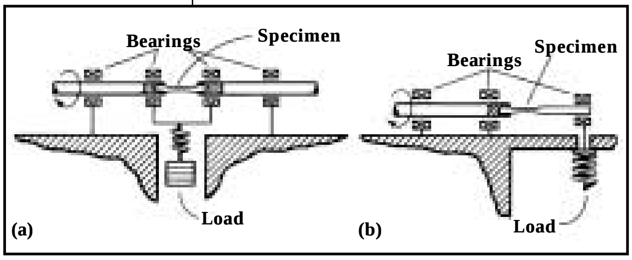

Fig. 5 — Schematics of rotating-beam fatigue testing machines. (a) Four-point loading R.R. Moore testing machine. (b) Cantilever loading machine. (Ref. 6)

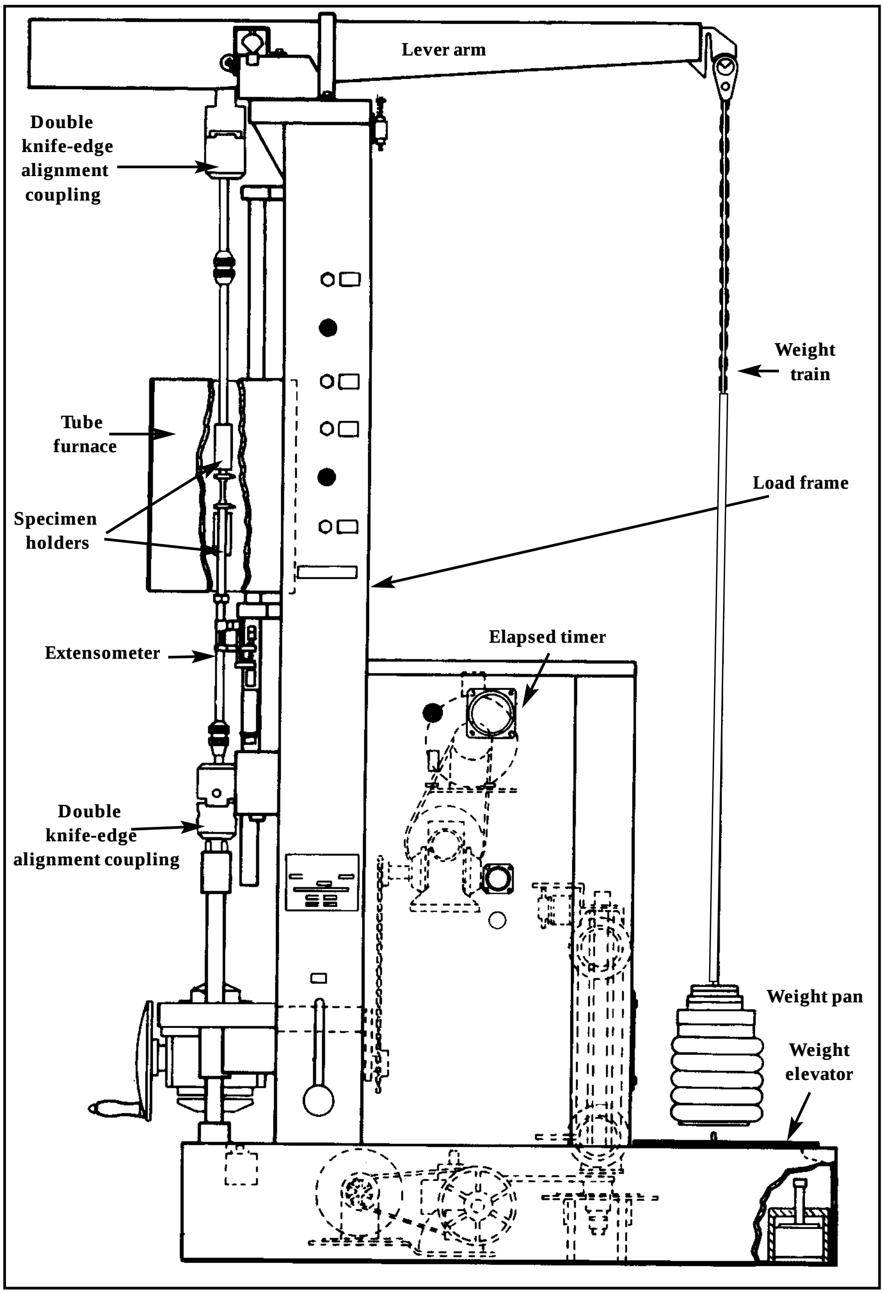

Fig. 6 — Schematic of a test stand used for creep and stress-rupture testing. (Ref. 7)

(N) depends on the maximum applied stress (S). This particular graph shows that a linear reduction in applied stress results in an exponential improvement in fatigue life. Thus, a 35% reduction in stress — from 110 ksi (760 MPa) to 70 ksi (485 MPa) — results in a 400% improvement in fatigue life — from 40,000 cycles to 160,000 cycles. Additional reductions in stress result in significantly more fatigue life enhancement.

Fatigue testing equipment (Fig. 5) is usually designed to induce cyclic loading and unloading to a known (peak) stress and measure the number of such cycles to failure of the specimen. Variants of the test include tensile, bending, and rotating. The average stress at which a steel can withstand 10 million loading cycles without failure is reported as the fatigue strength (also called the endurance limit). As stress increases, the number of cycles to specimen failure decreases.

Fatigue failures are a combination of crack initiation and crack growth (propagation). Sophisticated design equations are available to predict component life under cyclic loading conditions. Fatigue strength is always less than yield strength, and is often 30 to 50% of tensile strength.

Fatigue strength is significantly reduced by the introduction of a stress raiser (stress concentrator) such as a keyway, screw thread, fillet, press fit, or hole, many of which are present in most structural parts. One of the best ways to minimize fatigue failures is to reduce as much as possible the number of stress raisers via careful design and proper heat treatment.

Creep and Stress-Rupture Testing

It's often necessary to consider the effects of service temperature on the life of a heat treated part. Since the mobility of atoms increases rapidly with temperature, diffusion-controlled processes can have a very significant effect on high-temperature mechanical properties. The effect of long-term exposure to these environments is a critical design consideration. Thus, successful use of these parts requires knowledge of how their strength varies with time at high temperatures.

Creep and stress-rupture tests are used to evaluate the performance of materials for elevated-temperature service. The creep test measures the dimensional changes that occur in a specimen during exposure to high temperature, while the stress-rupture test measures the effect of temperature on the specimen's long-time load-bearing characteristics. The test stand shown in Fig. 6 can be used for both creep and stress-rupture testing. Other tests measure special properties such as thermal shock resistance and stress relaxation.

Note that creep and stress-rupture data also play important roles in the heat treating industry. For example, when selecting high-temperature alloys for furnace interior components or heat treating fixtures, a good measure of the reliability of a candidate alloy, or as a comparison of the expected performance of several different alloys, is "1% creep in 10,000 hours" data at the intended service temperature.

Impact Testing

Brittle fracture is catastrophic, and factors that contribute to it include: triaxial stress, such as exists at a notch or stress raiser; low temperature; and a high strain rate or rapid rate of loading. All three do not have to be present at the same time.

Impact tests are designed to determine a toughness value, which indicates the susceptibility of a material to brittle fracture (tougher materials are less susceptible). Notched-bar impact tests are used most often. These tests detect differences between materials that are not revealed by a torsion test.

Notched Charpy and Izod specimens are considered the standards for impact testing. Charpy "bars" have a square cross section and a "V" or "keyhole" notch at the center of their length. The Charpy bar is struck at its center by the impact load to ensure failure at that point, which results in a lower toughness value (reflecting a more conservative design parameter). Izod specimens have either circular or square cross sections and contain a "V" notch near one end. The specimen is clamped at the end with the notch and then struck by the impact load at the opposite end.

The most common test machine for measuring toughness, or impact resistance, involves a swinging pendulum, with a test specimen positioned at the bottom of the pendulum swing (Fig. 7). A specimen of a tough material requires considerable energy for failure, consuming much of the pendulum's kinetic energy. Consequently, the pendulum will not swing very high after breaking the specimen. If the specimen has low toughness, then the pendulum will end its swing considerably higher after fracture.

Toughness defined: The toughness of a material is a measure of its ability to absorb energy in the plastic range. The ability to withstand occasional stresses above the yield stress without fracturing is particularly desirable in certain applications; for example, freight car couplings, gears, chains, and crane hooks. Toughness may be visualized as the total area under the stress-strain curve. This area is an indication of the amount of work per unit volume that can be done to the material without causing it to rupture.

An example is shown in Fig. 8, stress-strain curves for high- and low-toughness materials. The high-carbon spring steel has a higher yield strength and tensile strength than the medium-carbon structural steel. However, the structural steel is more ductile and has a greater total elongation. The total area under the structural steel's stress-strain curve also is greater, which means it is the tougher of the two materials. Therefore, toughness encompasses both strength and ductility.

Data scatter: Results of tests using notched impact bars are subject to considerable scatter, particularly in the region of the ductile-to-brittle transition temperature. (There actually are two distinct temperatures in this region: the ductility transition temperature, which is related to the material's fracture initiation tendencies, and the fracture transition temperature, which is related to crack propagation.) The transition temperature owes its existence to the way in which resistance to shear and cleavage change with temperature. Temperature has a strong effect on basic flow and fracture properties. For metals, the yield stress (flow stress) increases with decreasing temperature. Above the transition temperature, the flow stress is reached before the fracture stress; below it, the fracture stress is reached first. The relative values of these two properties determine whether the fracture will be ductile or brittle.

Most of the scatter in impact test data is due to local variations in the properties of the steel, while some is due to the difficulty of preparing perfectly repeatable notches. In general, the reported value of the transition temperature is based on an amount of transition energy absorbed, a change in the appearance of the specimen fracture surface, or a transition in ductility.

Note that a slow-bend test is sometimes used to determine the transi-

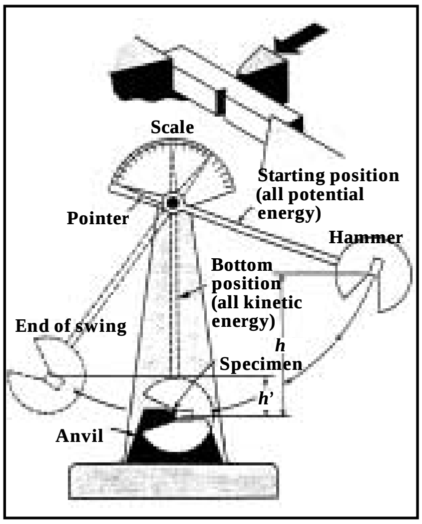

Fig. 7 — Standard impact testing apparatus. (Ref. 8)

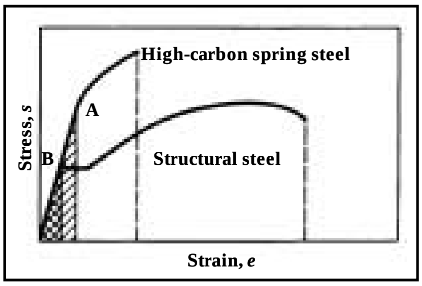

Fig. 8 — Comparison of stress-strain curves for high- and low-toughness steels. Cross-hatched regions represent the modulus of resilience (U_R) of the two materials. U_R is determined by measuring the area under the stress-strain curve up to the elastic limit of the material (point A for the spring steel; point B, the structural steel). (Ref. 9)

tion temperature. A biaxial stress state is produced during bending of an unnotched beam (having a width much greater than its thickness). This test represents a severity intermediate between that of the tension test and the notched impact test.

Residual Stress

Heat treaters deal with issues of residual stress every day. These are the stresses that exist in a material when it is free from external forces. They also are sometimes referred to as internal or locked-in stresses.

Residual stresses are produced whenever a material undergoes a nonuniform plastic deformation. In quenching (hardening), for example, a temperature differential between the rapidly cooling surface and the slower cooling core produces a mismatch of strain. The residual stress pattern that results is a combination of the thermal volume changes and those resulting from the transformation of austenite to martensite.

Residual stresses are responsible for warping and dimensional instability of heat treated parts. They also can influence how a material reacts to externally applied stresses.

Statistical Methods

There are at least three reasons why a working knowledge of statistics is needed in mechanical testing.

• Mechanical properties are structure-sensitive, so they frequently exhibit considerable variability or scatter. This makes statistical techniques useful, and often necessary, for determining the precision of the measurements and enabling valid conclusions to be drawn from test data.

• Statistical methods can assist in designing experiments to provide the maximum amount of information at minimum cost.

• Statistical methods (which are based on probability theory) can be used to help explain certain problems or phenomena such as the size effect in brittle fracture and fatigue.

Heat treaters use statistical methods daily. For example, control charts and linear regression analysis are useful everyday tools, while design of experiments and frequency distribution techniques are invaluable to the design engineer.

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