A Guide to Laboratory Testing of Metal Products

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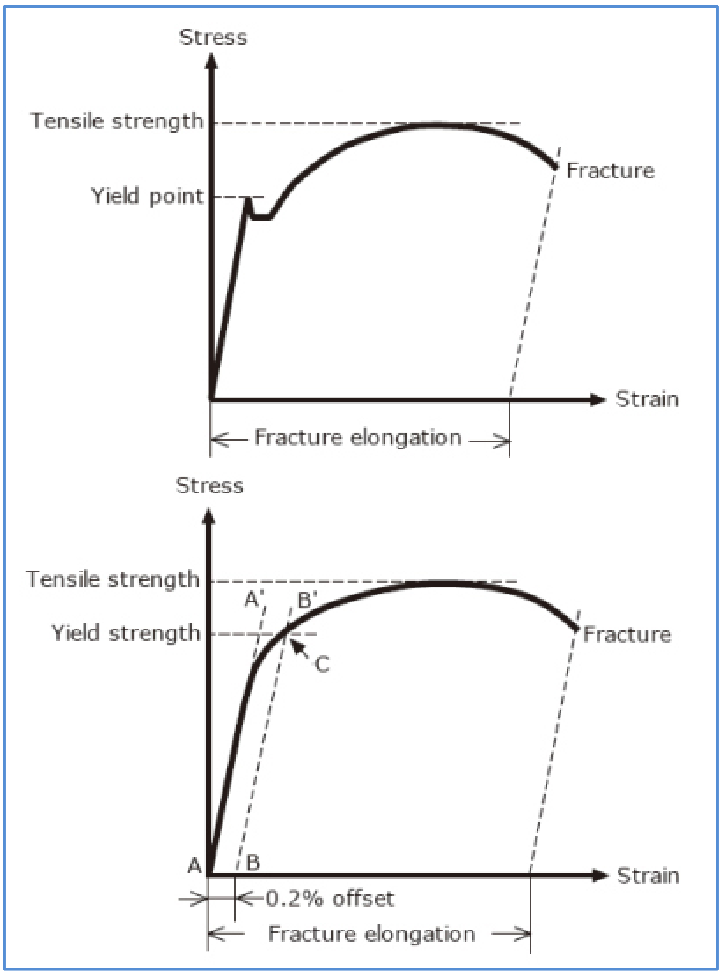
Various procedures and approaches are utilized to determine if a given material is suitable for a certain application or if a certain product has been manufactured per the required specifications. The material may be tested for its ability to deform satisfactorily during a forming operation, or perhaps for its ability to operate under a certain stress level at high temperatures. For technological purposes, economy and ease of testing are important factors. This article will cover the most common testing methods utilized in testing laboratories throughout the world.

MECHANICAL TESTING

Tensile Testing:

Tensile test is widely used to provide basic design information on the strength of materials and as an acceptance test for the specification of materials. It is conducted to determine yield strength, ultimate tensile strength, percent elongation, and modulus of elasticity. During the test a specimen is subjected to a continually increasing uniaxial tensile force while simultaneous observations are made of the elongation of the specimen. Below figures show typical stress-strain curves for two different alloys. Satisfactory stress-strain curves can only be obtained through the use of an extensometer that is attached to the test specimen as the load is applied.



During the tension test many materials reach a point at which the strain begins to increase rapidly without a corresponding increase in stress. This point corresponding to the sharp knee in the curve is called the yield point. Not all materials have an obvious yield point. For this reason, yield strength is often defined by an offset method as shown below, where line BB' is drawn parallel to AA' (the slope of this line represents E, modulus of elasticity). Point B corresponds to definite or stated amount of permanent set, usually 0.2 percent of the original gage length. Some materials essentially have no linear portion to their stress-strain curve, for example soft copper alloys or gray cast iron.

For these types of materials the usual practice is to define the yield strength as the stress to produce some total strain, for example 0.005.

The size, shape, orientation and location of the test specimen along with the strain/loading rate can all influence the test results. Therefore standard procedures established in ASTM A370 or equivalent should be followed.

Hardness Testing:

In many cases it is possible to substitute for the relatively time consuming and costly tensile test with a more convenient test of the plastic deformation behavior of metals, a hardness test. Hardness is defined as resistance of a material to penetration of its surface, and the majority of commercial hardness testers force a small penetrator (indenter) into the metal by means of an applied load. A definite value is obtained as the hardness of the metal, and this number can be related to the tensile strength of the metal.

In the Rockwell test, hardness is measured by the depth to which the penetrator moves under a fixed load. The elastic component of the deformation is subtracted from the total movement. In the Brinell and Vickers/Knoop scales, on the other hand, the hardness is measured by dividing the load by the area of an indentation formed by pressing the corresponding indenters into the metal. Therefore while the Rockwell number is read directly from a gage, which is part of the tester, the Brinell and Vickers/Knoop require optical measurements of the diameters or diagonals, respectively.

While all indentation hardness tests may be thought to serve the same purpose, each one has definite advantages with some being more applicable to certain types of materials and size and shape parts than the others. Brinell is used primarily for forgings and cast irons. Its large test area allows an average representative value to be obtained in a material that contains features/phases with vastly different properties (i.e. graphite, matrix, carbides, etc.). Vickers and Knoop are used on very small and thin parts as well as for case depth determinations, and Rockwell on almost all other applications. The table below provides basic information regarding the most commonly used hardness tests.

Type	**Penetrator**	**Usual load range, kg**	**Typical range of hardness**	**Surface preparation needed for testing**
Rockwell-C Scale	Diamond cone	150	Medium to very hard	Fine sanding
Rockwell-B Scale	1/16" carbide ball	100	Soft to medium	Fine sanding
Brinell	10 mm carbide ball	500-3,000	Soft to hard	Coarse sanding
Vickers	Diamond pyramid	0.5-100	Very soft to very hard	Polishing
Knoop (microhardness)	Diamond pyramid	0.01-1	Very soft to very hard	Fine polishing

Although the Rockwell test procedure is relatively straight forward, a number of items can contribute to inconsistent and incorrect readings and should not be overlooked. These items include the following:

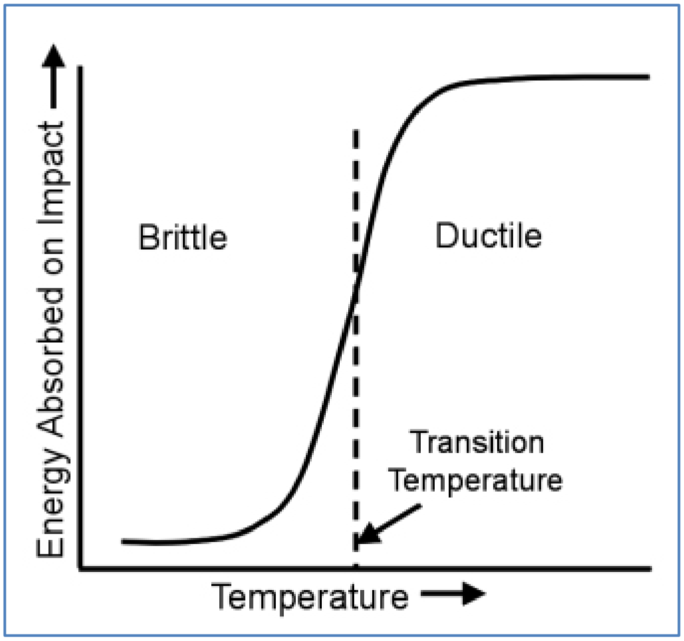
- Cleanliness of the tested surface and the support anvil
- Curvature of the surface (correction factors must be used)
- Test surface not being perpendicular to the indenter
- Readings taken too close to the sample edge
- Readings taken too close together
- Test sample too thin for the hardness scale being used
- Part not supported properly
- Damaged indenter

Standard method for testing metallic materials using the Rockwell scales can be found in ASTM E18, whereas Brinell test methods are described in ASTM E10.

Toughness Testing:

Charpy impact testing is one the most common method of determining the tendency of a material to behave in a brittle manner. This type of test detects differences between materials that are not observable in a tension test. The principal measurement from the impact test is the energy absorbed in fracturing the specimen, usually expressed in foot-pounds. Steels behave in a unique manner compared to other materials and can fail in a brittle manner when exposed to low temperatures. This ductile to brittle transition occurs abruptly when certain temperatures are reached. For some heats of steel this transition may even take place at around ambient temperature.

The standard Charpy specimen has a square cross-section (10x10 mm) and contains a 45° V-notch, 2 mm deep with a 0.25mm root radius. It is supported as a beam in a horizontal position and loaded behind the notch by the impact of a heavy swinging pendulum. Standard method of testing is covered in ASTM E23.



Typical toughness behavior of steels with change in temperature

Charpy test is frequently used for quality control and material acceptance purposes. The chief engineering use of the Charpy test is in selecting materials, which are resistant to brittle fracture by means of transition-temperature curves. The design philosophy is to select a material that has sufficient notch toughness when subjected to severe service conditions. Therefore, if the product is going to be used at cold temperatures then the impact properties of the material at the expected service temperature should be determined.

Chemical Analysis:

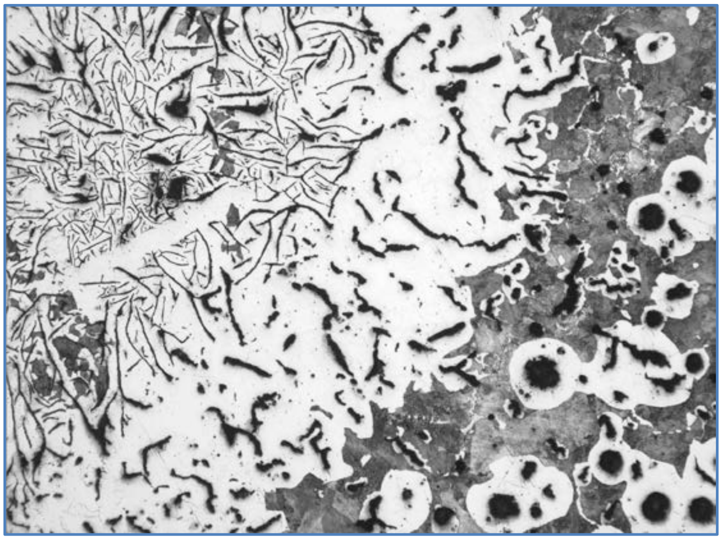
Optical Emission Spectroscopy, also known as OES analysis, is one of the most widely used analytical chemistry techniques for analyzing solid metal and alloy samples. It is an analytical tool that offers fast, accurate elemental analysis for metal composition. OES data is useful for material certification, quality checking, or to identify an unknown material. It is typically faster and less expensive than other techniques such as inductively coupled plasma (ICP), X-ray Fluorescence (XRF), and atomic absorption (AA). Typically a sample is prepared by sectioning off a piece, which is then sanded smooth and placed against an electrode. A plasma burn is generated that excites the atoms, which give off different wavelengths based on the individual elements present in the sample. The instrument reads the wavelengths given off from the plasma burn and determines the materials chemistry. Typically multiple burns are conducted and the average is calculated and corrected by the OES software.

Most chemical analysis on metal samples will damage the samples either from burning the sample or having to section the sample to fit into the instrument for analysis. For finished parts that cannot be damaged but material grade needs to be identified, XRF analysis will have to be conducted. Positive material identification (PMI) testing on such parts may be performed by utilizing a hand held XRF analyzer. However, PMI testing typically works best on materials that have alloying elements; it cannot determine carbon content so it is not effective on low alloyed steels where carbon is the determining element.

Another analytical technique, Energy Dispersive Spectrometry (EDS) used in conjunction with the Scanning Electron Microscope (SEM) can focus a very narrow electron beam to a very small area to determine the chemical makeup of minute particles, such as an inclusion or a second phase. Chemical results generated by SEM-EDS are considered semi-quantitative.

Microscopic Examinations:

Metallographic examinations are conducted to determine the actual processing/heat treat conditions of materials or if the scheduled processing steps were inadvertently omitted or incorrectly performed. Sample preparation for this type of analysis is critical. Abrasive cutting using coolants should be utilized to avoid overheating the area to be examined since the original heat treat condition (microstructure) may be altered by the heat generated during the cutting process. Sample preparation steps such as mounting, grinding, sanding and final polishing should be carried out following standard metallographic techniques described in ASTM E3. Usually samples in as-polished condition contain very little information but they should still be examined because etching may obliterate fine details such as microcracks, inclusions, other features or plating layers. Etching with a suitable chemical will reveal grain boundaries and phases and will allow viewing of the microstructure. The part's processing history (cast, forged or wrought material), heat treat condition, presence of inclusions, secondary phases, chemical variations (segregation), grain deformations, weld joints can all be revealed as shown in below examples.



Microstructure showing graphite flakes near the surface of a ductile cast iron component

Macrograph showing the grain flow lines in a forged component

NONDESTRUCTIVE TESTING

Nondestructive testing methods are techniques used both in production and in-service environments without damage or destruction of the item under inspection. The field of nondestructive inspection is too broad to be covered in this article. Therefore, a brief description of the most common inspection techniques will be provided.

The effectiveness of any particular method of NDI depends upon the skill, experience, and training of the person performing the inspection process. The person(s) responsible for detecting and interpreting indications, using techniques such as penetrant, ultrasonics, magnetic particle or X-ray, must be qualified and certified to specific government or industry standards. Each process is limited in its usefulness by its adaptability to the particular component to be inspected. Making the correct NDI method selection requires an understanding of the basic principles, limitations, and advantages and disadvantages of the available methods and an understanding of their comparative effectiveness and cost. The main factors affecting the selection are:

- The critical nature of the component (i.e. degree of inspection sensitivity required)
- The material, size, shape and weight of the part
- The type of defect sought
- Maximum acceptable defect limits in size and distribution
- Possible location and orientation of defects
- Part accessibility

The below table provides a list of the advantages and disadvantages of the four methods.

METHOD	ADVANTAGES	DISADVANTAGES
Penetrant	Portable Inexpensive Sensitive to very small discontinuities 30 min. or less to accomplish Minimum skill required	Locates surface defects only Rough or porous surfaces interfere with test Part preparation required (removal of finishes) High degree of cleanliness required Direct visual detection of results required
Magnetic Particle	Can be portable Inexpensive Sensitive to small discontinuities Immediate results Moderate skill required Detects surface and subsurface discontinuities Relatively fast	Surface must be accessible Rough surfaces interfere with test Part preparation required (removal of finishes) Semi-directional requiring general orientation of field to discontinuity Ferro-magnetic materials only Part must be demagnetized after test
Ultrasonic	Portable Sensitive to very small discontinuities Immediate results Little part preparation Wide range of materials and thicknesses can be inspected	Surface must be accessible to probe Rough surfaces interfere with test Highly sensitive to sound beam-discontinuity orientation High degree of skill and experience required to set-up test and interpret results Couplant required
X-Ray	Detects surface and internal flaws Can inspect hidden areas Permanent test record obtained Minimum part preparation	Safety hazard Expensive Highly directional, sensitive to flaw orientation High degree of skill and experience required for exposure and interpretation Depth of discontinuity not indicated

Penetrant Inspection (PT)

The basic purpose of penetrant inspection is to increase the visible contrast between a discontinuity and its background. This is accomplished by applying a liquid of high penetrating power that enters the surface opening of a discontinuity. Excess penetrant is removed and a developer material is then applied that draws the liquid from the suspected defect to reveal the discontinuity. The visual evidence of the suspected defect can then be seen either by a color contrast in normal visible white light or by fluorescence under black ultraviolet light.

Magnetic Particle Inspection (MT)

Magnetic particle inspection is a method for detecting cracks, laps, seams, voids, pits, subsurface holes, and other surface, or slightly subsurface, discontinuities in ferro-magnetic materials. Magnetic particle inspection uses the tendency of magnetic lines of force, or flux, of an applied field to pass through the metal rather than through the air. A defect at or near the metal's surface distorts the distribution of the magnetic flux and some of the flux is forced to pass out through the surface. The field strength is increased in the area of the defect and opposite magnetic poles form on either side of the defect. Fine magnetic particles applied to the part are attracted to these regions and form a pattern around the defect. The pattern of particles provides a visual indication of a defect. To locate a defect, it is necessary to control the direction of magnetization, and flux lines must be perpendicular to the longitudinal axes of expected defects.

Ultrasonic Inspection (UT)

Ultrasonic inspection is an NDI technique that uses sound energy moving through the test specimen to detect flaws. The sound energy passing through the specimen is displayed on a screen where indications of the front and back surface and internal/external conditions will appear as vertical signals on the CRT screen or nodes of data in the computer test program. Two basic ultrasonic inspection techniques are employed: pulse-echo and through-transmission.

Pulse-Echo process uses a transducer to both transmit and receive the ultrasonic pulse. The received ultrasonic pulses are separated by the time it takes the sound to reach the different surfaces from which it is reflected. The size (amplitude) of a reflection is related to the size of the reflecting surface. The pulse-echo ultrasonic response pattern is analyzed on the basis of signal amplitude and separation.

The ultrasonic instrument has to be calibrated using reference standards before any inspections. Reference standards serve two purposes, to provide an ultrasonic response pattern that is related to the part being inspected, and to establish the required inspection sensitivity. To obtain a representative response pattern, the reference standard configuration must be the same as that of the test structure, or a configuration that provides an ultrasonic response pattern representative of the test structure. The reference standard should contain a simulated defect (notch) that is positioned to provide a calibration signal representative of the expected defect. The notch size is chosen to establish inspection sensitivity (response to the expected defect size).

Radiographic Inspection (RT)

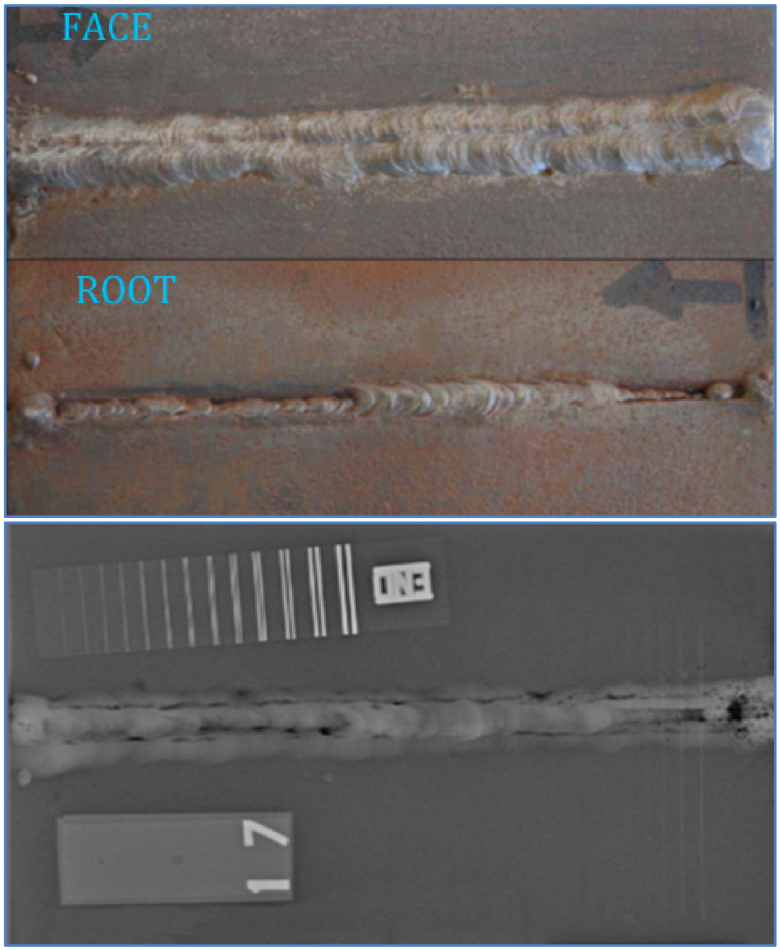
Radiography (x-ray) is an NDI method used to inspect material and components, using the concept of differential adsorption of penetrating radiation. Each specimen under evaluation will have differences in density, thickness, shapes, sizes, or absorption characteristics, thus absorbing different amounts of radiation. The unabsorbed radiation that passes through the part is recorded on film, fluorescent screens, or other radiation monitors. Indications of internal and external conditions will appear as variants of black/white/gray contrasts on exposed film, or variants of color on fluorescent screens.

The principal advantage of real-time radiography over film radiography is the opportunity to manipulate the test piece during radiographic inspection. This capability allows the inspection of internal mechanisms and enhances the detection of cracks and planar defects by allowing manipulation of the part to achieve the best orientation for flaw detection. Since the ability of radiography to detect planar discontinuities, such as cracks, depends on proper orientation of the test piece during inspection, part manipulation during inspection simplifies three-dimensional dynamic imaging for the determination of flaw location and size. In film radiography, depth parallel to the radiation beam is not recorded. Consequently, the position of a flaw within the volume of a test piece cannot be determined exactly with a single radiograph.

Computed Tomography (CT) is another important radiological technique with enhanced flaw detection and location capabilities. Unlike film and real-time radiography, CT involves the generation of cross-sectional views instead of a planar projection. The CT image is comparable to that obtained by making a radiograph of a physically sectioned thin planar slab from an object. This cross-sectional image is not obscured by overlying and underlying structures and is highly sensitive to small differences in relative density.

Controlling the quality of a radiograph through the use of image quality indicators (IQIs) is essential in radiography. IQIs, which are also referred to as penetrameters, provide a means of visually informing the film interpreter of the contrast sensitivity and definition of the radiograph. The IQI indicates that a specified amount of change in material thickness will be detectable in the radiograph, and that the radiograph has a certain level of definition so that the density changes are not lost due to lack of sharpness. Without such a reference point, consistency and quality could not be maintained and defects could go undetected.

Image quality indicators take many shapes and forms due to the various codes or standards that invoke their use. In the United States, two IQI styles are prevalent: the placard, or hole-type and the wire IQI. IQIs come in a variety of material types so that one with radiation absorption characteristics similar to the material being radiographed should be used.



A radiograph showing the types of weld defects (lack of penetration, undercut) that can be detected with this inspection technique

Radiography and ultrasonic are the two generally-used, nondestructive inspection methods that can satisfactorily detect flaws that are completely internal and located well below the surface of the test part. Neither method is limited to the detection of specific types of internal flaws. However, radiography is more effective when the flaws are not planar, while ultrasonic is more effective when flaws are planar.