Welding Metallurgy, Part 1: Understanding Mechanical Properties

A knowledge of basic welding metallurgy can help inspectors better understand why certain conditions occur during welding

BY SCOTT C. HELZER

A basic understanding of metallurgy can provide inspectors with fundamental reasons for why conditions occur in welding and why there are procedures that must be followed. Having worked in inspection for almost 20 years and having taught numerous CWIs, I began to contemplate two questions as I wrote this article, the first of a series that will discuss welding metallurgy and its importance for inspectors. First, what is a good definition of welding metallurgy as related to inspection? Second, which part of welding metallurgy is most beneficial to inspectors?

Let's start with a definition of metallurgy. Simply stated, metallurgy is the science and technology of metals, and it has two main parts:

1. Process metallurgy, which is the reduction of orders, refining of metals, alloying, casting, shaping, and forming of them into their semifinished and finished products;

2. Physical metallurgy, which focuses on heat treatment, mechanical testing, metallography, and numerous other subjects dealing with the application, design, testing, and inspection of semifinished and finished products.

Upon first review, we might consider that welding would seem to be merely a part of process metallurgy, as it is considered to be an operation for shaping metal into a finished product. But upon closer inspection, welding is more than just a part of process metallurgy and more than just a part of physical metallurgy: welding encompasses the entire scope of metallurgy. So then welding metallurgy may be defined as *the changes that occur in metals as a result of being joined by the welding process.* These changes are manifested by changes in mechanical properties. Physical properties generally result in distortion and the heat transfer rates of the base material. When discussing welding metallurgy, there are two main factors that will always affect the metallurgical changes discussed here: they are time and temperature. In welding metallurgy, we are concerned with the time the material is at an elevated temperature and the rate at which the heat energy is applied to the base during welding as well as the rate at which the heat energy is removed during cooling after welding.

Whenever we begin a discussion about metallurgy, we typically look at properties by dividing them into three distinct groups: mechanical properties, physical properties, and chemical properties. Then we assess the changes in these properties as a result of welding. These properties are generally further divided into two subcategories of structure sensitive and structure insensitive. Structure sensitive properties are those that will be affected by welding, and structure insensitive properties are those that do not vary from one metal sample to another of the same kind. Typically, structure insensitive properties are calculated based on the metal's chemical composition. Let's start with a brief review of mechanical and physical properties and their structure sensitivity.

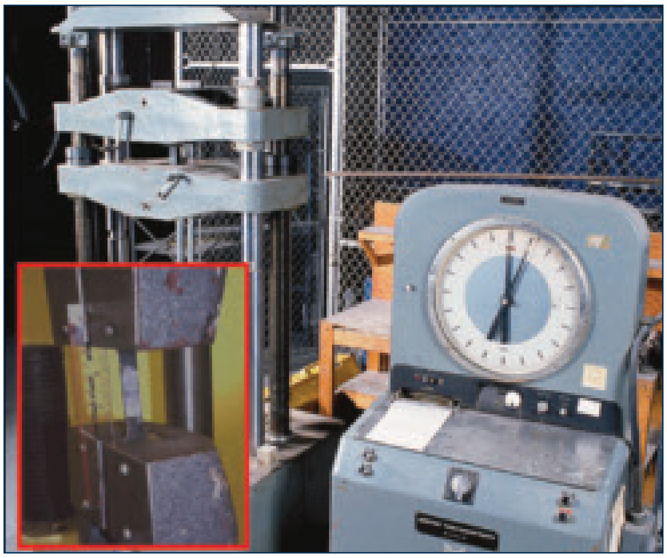

Fig. 1 — Tensile testing machine.

Table 1 shows the mechanical and physical properties with the further categorization of structure sensitive and insensitive properties in each category, respectively. As shown in Table 1, the mechanical properties are mostly structure sensitive and the physical properties are mostly structure insensitive. For the first part of this article, we will be examining the mechanical and physical properties with most of the emphasis being spent on mechanical.

Ultimate Tensile Strength

One of the most commonly used mechanical properties of metals is the ultimate tensile strength. The ultimate tensile strength is calculated by dividing the applied load by the area of the specimen. Ultimate tensile strength is commonly tested using a tensile testing machine with a tensile testing specimen. Figure 1 shows a universal machine that can do both compression and tensile testing. A common tensile specimen is the 505.

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Table 1 — The Properties of Metals (Linnert, 1994)

	Structure-Insensitive Properties	Structure-Sensitive Properties
Mechanical Properties	Elastic Moduli	Tensile Strength True Breaking Strength Yield Strength Elastic Limit Proportional Limit Creep-Rupture Strength Strain Hardening Rate Tensile Reduction of Area Fracture Strength Fatigue Strength Impact Strength Hardness Damping Capacity Tensile Elongation Creep Strength
Physical Properties	Thermal Expansion Thermal Conductivity Melting Point Specific Heat Emissivity Vapor Pressure Density Thermal Evaporation Rate Thermoelectric Properties Thermionic Emission	Magnetic Properties Electrical Conductivity
Chemical Properties	Electrochemical Potential Oxidation Resistance Catalytic Effects	

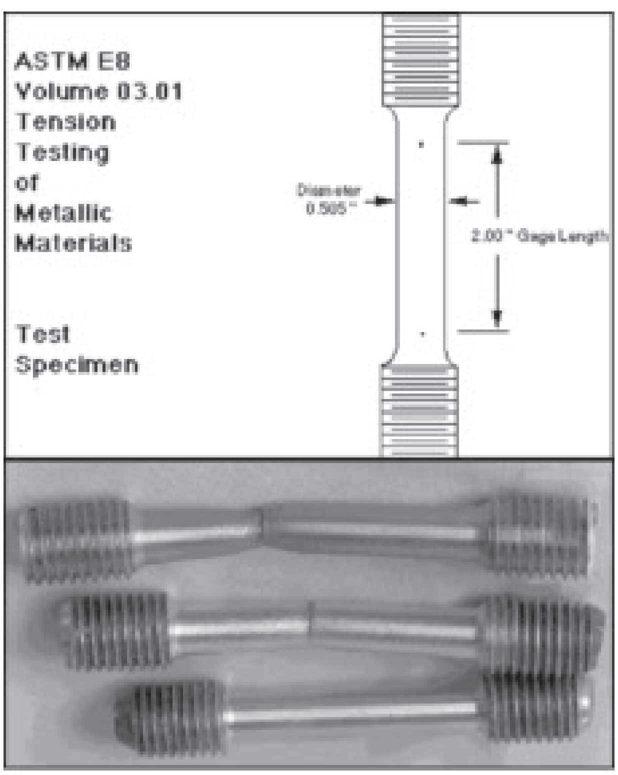

Fig. 2 — 505 tensile specimens.

The dimensions for the 505 are shown in the top-half of Fig. 2. The diameter of the 505 is 0.505 in., which gives the specimen a cross-sectional area of 0.2 sq-in.

The insert in Fig. 1 shows a slightly different machine pulling a flat bar specimen.

In tensile testing, as the material is strained the slippage planes are being locked up through the mechanisms of slip and twinning. The material is getting stronger, but as it is being stretched (elongated), it is also getting smaller in diameter. When the cross-sectional area can no longer bear the applied load, the specimen breaks in a tensile failure as shown in the lower half of Fig. 2. The plotting of the tensile test produces a stress-strain diagram. The stress-strain diagram plots stress in pounds on the vertical axis vs. strain in in./in. on the horizontal axis. The plot of stress vs. strain reveals the material's proportional limit, the elastic limit, yield point, ultimate tensile strength, and breaking point. An example of the stress-strain diagram is shown in Fig. 3.

Yield Strength

Another property determined from the tensile test is yield strength. Yield strength is determined from the stress-strain diagram. The 0.2% offset yield is the common way to calculate yield strength for steels. A practical method utilized to determine the yield strength of a metal is illustrated in Fig. 4. The red line is drawn parallel to the Modulus Line A from a point on the abscissa, representing 0.2% (0.0020 in./in.) elongation. The point where the red line intersects the curve the green line is drawn parallel to the X axis to intersect the stress level of

Table 2 — Hardness Conversion Chart Example

Brinell Hardness	Rockwell Hardness			Tensile Strength
Tungsten Carbide Ball 3000 kg	A Scale 60 kg	B Scale 100 kg	C Scale 150 kg	(Approximate)
638	80.8	—	59.2	329,000
630	80.6	—	58.8	324,000
627	80.5	—	58.7	323,000
601	79.8	—	57.3	309,000

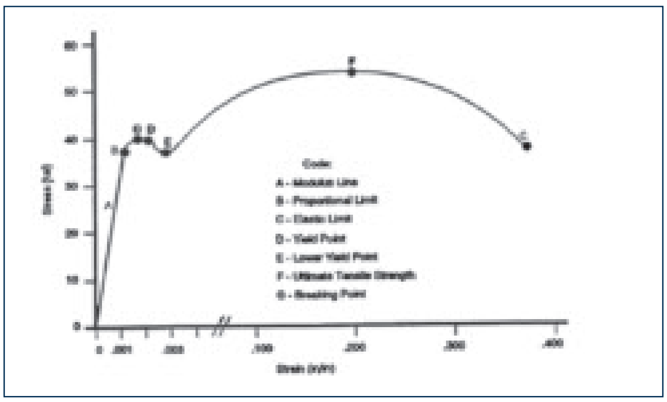

Fig. 3 — Stress-strain diagram.

approximately 38 ksi (260 MPa). This stress is the yield strength of the tested metal.

Hardness

Hardness is defined as resistance to penetration or indentation. Two common tests for hardness are the Brinell and the Rockwell. Both of them force an indenter into the base material to measure the material's resistance to indenter penetration. As a metal's hardness increases, the strength increases while the toughness and ductility go down. This relationship allows us to use hardness values to correlate the metal's hardness with strength as shown in Table 2. Rockwell scales change based on the indenter used and the major load. Common indenters used for the Rockwell are the diamond brale and the $\frac{1}{16}$-in. ball — Fig. 5.

Another useful tool for tensile strength is to use the Brinell hardness number and multiply it by 500 for an estimate of a material's tensile strength. In Table 2, the BHN of 630 × 500 = 315,000 lb/in.^{2} and the table value is 324,000 lb/in.^{2}, better to err on the low side than to overestimate.

Ductility

Ductility is the amount of plastic deformation that a specimen or a structure goes through as external forces act upon it. Many times the percentage elongation from the tensile test is used as a measure of a material's ductility. Unfortunately, values for ductility are meaningful only for the size and shape of the test specimen. While most inspectors understand what ductility is and can even list several ductile materials, there is no fundamental test for ductility.

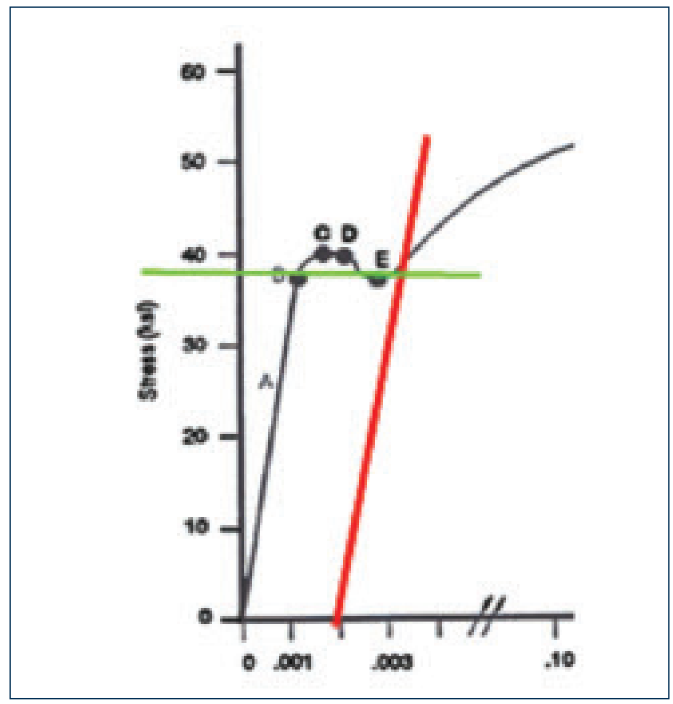

Fig. 4 — 0.2% offset yield.

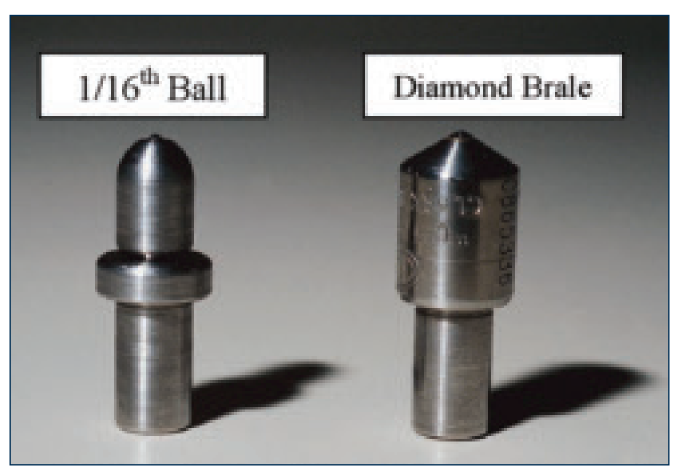

Fig. 5 — Rockwell indenters.

Toughness

The ability of the metal to deform plastically and to absorb energy in the process before fracturing is defined as toughness. Toughness is an important property that must be understood and carefully considered when inspecting structures, especially those joined by welding. Many times tension and bend tests are used for metals to try and estimate toughness. But in the early 1900s, it became clear that the test could not fully predict the mechanical behavior of metals, particularly under the conditions encountered in service. The frequency of brittle fracture indicated a serious problem in predicting a metal's ability to perform in a tough, dependable manner under varying conditions.

There is only one assessment of toughness that can be made with reasonable certainty from ordinary tension bend test results; a metal that displays very low ductility is not likely to behave in a ductile matter in any other tests carried to fracture. However, a metal that displays good ductility and tension or bend tests will not necessarily behave in a ductile manner in other kinds of mechanical tests. As a result, we still lack reliable methods of evaluating toughness in metals and tests to determine required toughness ranges for various applications.

What's Next

In the next issue of *Inspection Trends*, we will examine physical properties and the changes that happen to metals upon heating and upon cooling as well as critical and subcritical heat treatments. The last segment will deal with using metallurgy fundamentals to spot welding problems in the inspection process.❖