Welding: Metallurgy and Methodology

An Online Continuing Education Course for Engineers

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Welding: Metallurgy and Methodology

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Introduction

This course delves into the intricate relationship between metallurgy, welding, and the welding variables that are pertinent to specific metals. This course aims to equip engineers with a comprehensive understanding of how metallurgical characteristics directly impact the welding process, enabling them to make informed decisions and achieve the needed results in their welding projects.

In the realm of engineering, welding serves as a vital method for joining metals, playing a pivotal role in industries spanning construction, manufacturing, aerospace, and the automotive industries. The effectiveness and longevity of welded joints heavily rely on a profound grasp of metallurgy—the science and study of metals.

Many courses are already available that cover the basic, but important, aspects of welding such as the physics of welding, detailed weld process descriptions, weld stress analysis, joint design, weld troubleshooting, etc. However, fewer resources are available to discuss the specific metallurgical requirements of metals regarding welding and the impact welding has on metallurgy.

This course will emphasize the significance of welding variables specific to individual metals. Each metal possesses unique characteristics and responses when subjected to welding between welding parameters such as heat input, filler material selection, welding techniques, and the properties of the base metal. By understanding this relationship, engineers will be better prepared to make informed decisions, strategically manipulating welding variables to optimize the strength, ductility, toughness, and other crucial mechanical properties of the welded joint.

It is hoped that the information in this work will continue to be valuable to the point it is kept as a reference document. It was structured and written with that goal in mind.

A Brief History of Welding Metallurgy

Undoubtedly, the discovery and use of metals have revolutionized human civilization. Without the discovery of metals, human activities would be limited by the capabilities of wood and stone. This means that nearly all modern conveniences would not exist. It is not hard to imagine how the quality, and likely length, of life would be worse for all of mankind.

The discovery of metals was most likely an accident resulting from ancient man building their campfires in areas containing copper, tin, and/or aluminum. The heat from the fire melts the metal and it solidifies as the fire cools. Once man realized that the metal could be remelted and cast into small molds, it became usable and valuable.

The Bronze Age began when man used prolific copper alloys. These alloys were predominantly bronze (copper and tin), but also copper alloyed with aluminum and or tin. These alloys have the advantage of melting at relatively low temperatures. Eventually, residents in regions of North Africa and around the Mediterranean were able to begin making iron tools and starting the Iron Age.

It was difficult for ancient man to cast iron into the shapes desired due to the difficulty of generating the temperatures required to melt iron. This required the craftsman to heat and hammer the rough casting into the desired shape and the birth of forging. It wasn’t until the 19th century that modern machinery made it possible to make repeatable casting and forging possible.

Joining metal together was limited to mechanical means until forge welding was developed. Forge welding is accomplished by heating the two workpieces to a relatively high temperature and hammering them together. However, forge welding does not result in the complete fusion of the two workpieces as it is more akin to mechanically “zipping” the contact surfaces together. Since this effect is limited to the thin region of the surfaces, it can be difficult to consistently achieve a strong reliable bond.

Modern welding techniques have been around for over 100 years. Welding is a superior technique to forge welding since when welding the material of the two parts in the vicinity of the joint is melted and blended to form a permanent connection. Welding increases the fabrication flexibility by allowing various shapes, castings, forgings, etc., and even metals of different alloys to be fused. It is no longer necessary to overlap the workpieces to be joined and the thickness of the weld can be held to the thickness of the parts to be joined. Also, welding allows for the permanent repair of cracked parts. Today, arc welding is widely accepted as the best, most economical, and most practical method of welding. Nearly all metals are weldable provided the proper process and techniques are used. The proper process and technique require an understanding of the composition, structure, and properties of the metal. This knowledge requirement creates a close relationship between metallurgy and weldability.

Welding Metallurgy - An Overview

Metallurgy is the field of science and engineering involving the study of the physical and chemical properties of metallic elements and their mixtures known as alloys. The field encompasses the extraction, and refining processing of ores, and the processing of metals their composition, structure, various properties, and response to various service conditions. There are two branches of metallurgy: process and physical. Process metallurgy refers to the extraction and process of ore into finished mill products. Physical metallurgy refers to the composition of metals, their structures, and changes in properties as a response to various processes (forging, stamping, welding, etc.). Personnel who specialize in the field of metallurgy are referred to as metallurgists.

Ancient man, and to some extent man of the not-too-distant past, did not understand why some materials could be worked without cracking, why other materials cracked merely upon exposure to cold temperatures, or why some materials were stronger than others. Metallurgical research was able to uncover these mysteries and advance the knowledge and usefulness of metals, increasing the quality and breadth of materials available for use. The importance of metallurgical welding cannot be understated. An understanding of how metals react when melted, cooled, solidified, reheated, etc. is mandatory to generate successful welds.

Welding involves the application of intense heat and/or pressure to the weld area to melt the metal and fuse the two workpieces. In arc welding, the heat source is an arc that forms because of the electrical current jumping the air gap between the workpiece and electrode. The heat not only melts the workpiece but also the electrode (or filler rod), and the resulting molten metal drops from the electrode and adds to the weld volume. The weld puddle is similar to the molten contents in a crucible during steelmaking. In the ladle and most arc welding processes, a layer of non-metallic slag forms over the top of the molten metal helping to control the temperature, cooling rate, and reducing impurities in the weld. Similarly, since the molten puddle is constrained to a small area it can be compared to the pouring of molten metal into an ingot mold. Additionally, both the base metal around the mold and the mold are preheated to slow the cooling rate of the metal. The products can be further refined by rolling, forging, machining, etc. These comparisons provide a basic understanding of how both process and physical metallurgy have an important place in various welding operations.

To understand the impact welding has on the metal microstructure, it would be advantageous to review the common microstructures and transformations that exist. Since most welding is performed using ferrous metals, that will be the focus of the review. The reader is encouraged to review the various types of non-ferrous metals independently. The ability and tendency to produce the microstructures below depends on the chemical composition, particularly carbon, and the rate of cooling.

Ferrite – This microstructure has a Body Centered Cubic (BCC) crystal structure, is fairly soft, and is thermodynamically stable up to approximately 1650°F (899°C). It has a maximum carbon solubility of 0.02%. It is also referred to as α-iron.

Cementite – Also referred to as iron carbide. It is composed of 93.3% iron and 6.67% carbon by weight. It is hard and brittle. Cementite is not thermodynamically stable and if heated for long periods will transform into iron and graphite. Above temperatures of about 1350°F (732°C) (referred to as the critical temperature, cementite will decompose into austenite and other constituents depending on bulk carbon content.

Pearlite – This microstructure is composed of alternating layers of ferrite and cementite, 87.5% and 12.5% by weight, respectively. This microstructure forms as austenite cools to temperatures below 1350°F (732°C). This is the likely most common ferrous microstructure that will be encountered. It is composed of layers, or laminations, of ferrite and cementite, Figure 1.

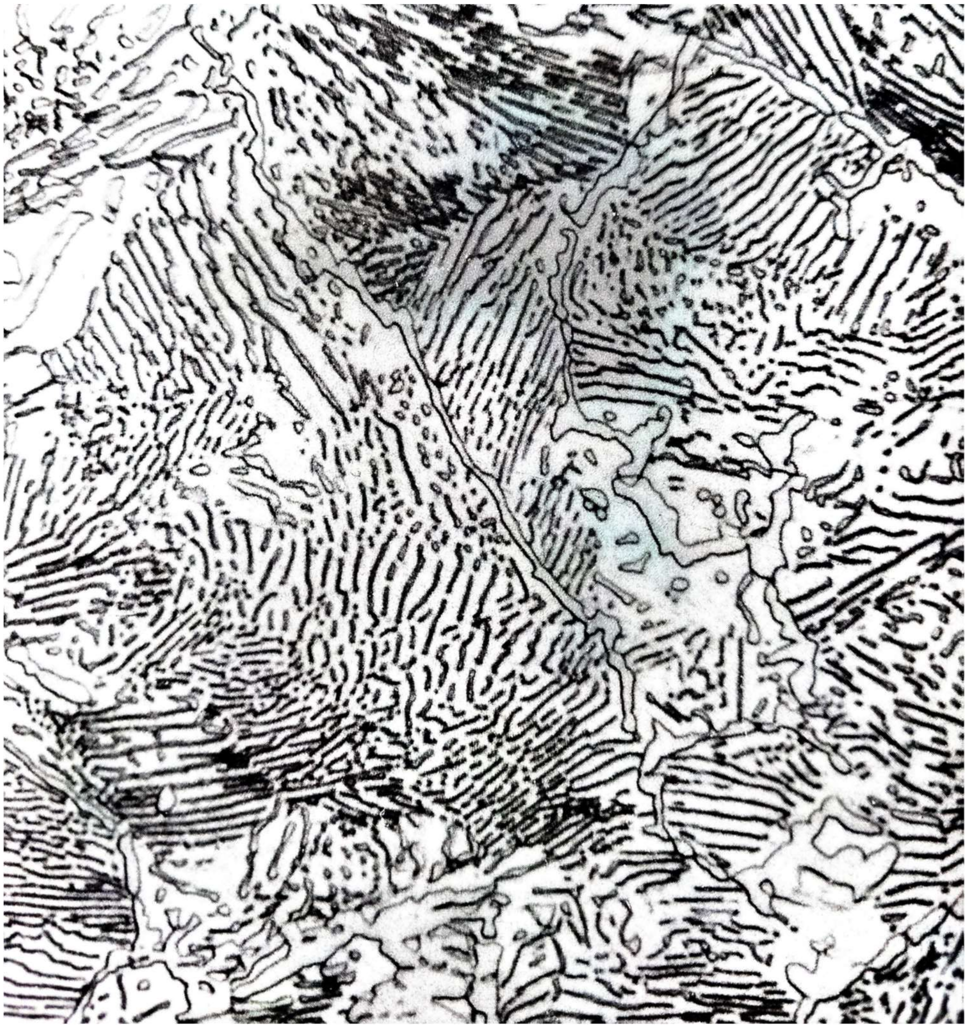
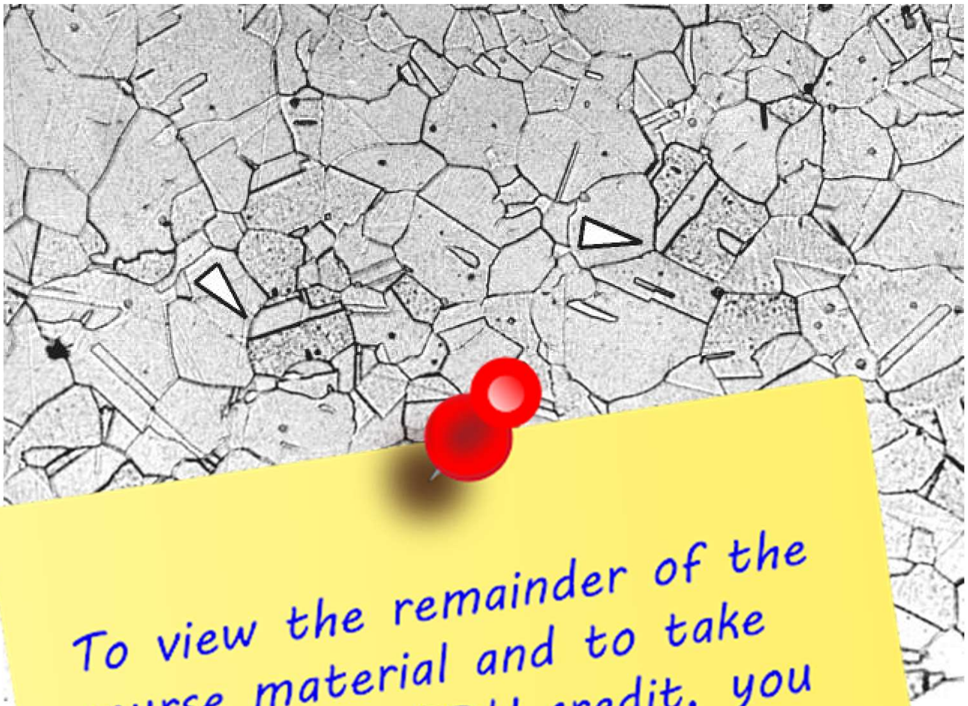


Figure 1: Pearlite microstructure showing the layers of ferrite (light-colored) and cementite (dark-colored) constituents (3000x magnification).

Martensite – This microstructure is formed by the rapid cooling of austenite to below about 350°F (177°C). The carbon does not have time to diffuse and precipitate which results in a supersaturated solution of carbon in a highly strained Hexagonal Closed Pack (HCP) microstructure, Figure 2. It is very hard and brittle. When heated, martensite is unstable and the carbon precipitates resulting in cementite in a ferrite matrix, softening the metal.

Figure 2: Martensitic microstructure (1220x magnification)

Austenite – This microstructure has an FCC crystal structure. It is all referred to as γ-iron. It is non-magnetic and exists at temperatures above approximately 1650°F (899°C). The austenitic stainless steels have this microstructure at room temperature due to alloy content, Figure 3.



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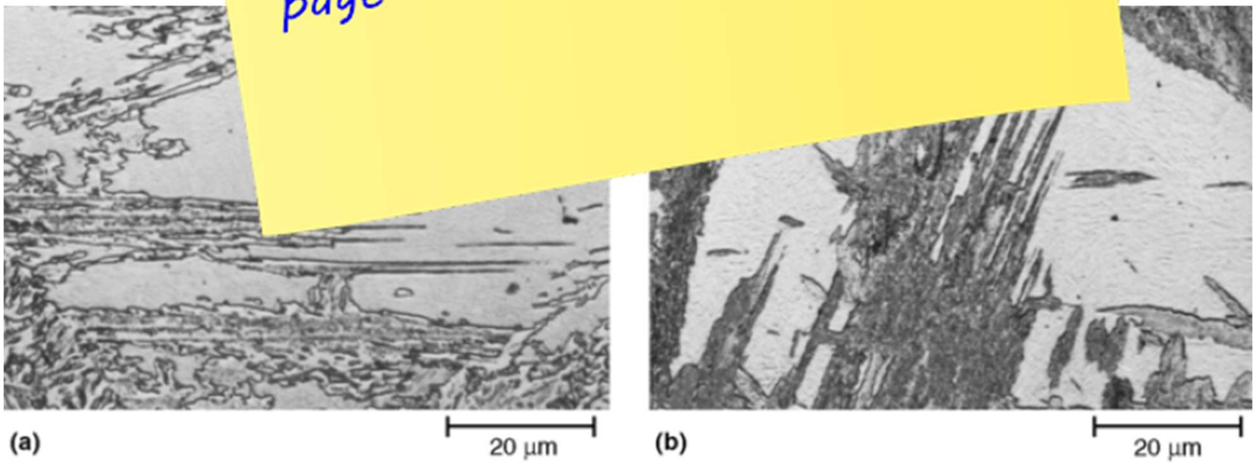

Figure 4: The two bainite morphologies (a) upper bainite and (b) lower bainite.