PRINCIPLES OF WELDING

Processes, Physics, Chemistry, and Metallurgy

ROBERT W. MESSLER, Jr.
Materials Science and Engineering Department
Rensselaer Polytechnic Institute
Troy, NY

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PREFACE

Perhaps no secondary process has been and continues to be more important to the survival, comfort, and advancement of humankind than welding. It has let us build our world. It enables the planting and harvesting of our crops through the manufacture of tillers, tractors, and combines. It enables processing of our food through the manufacture of crushers, cookers, and conveyors. It enables the mining of minerals and metals, the building blocks of all structures, through the manufacture of drills, excavators, and trams. It enables the transport of grown, mined, and manufactured goods across town, across states, across nations, and across oceans through the manufacture of trucks, trains, and ships. It enables transportation through the manufacture of cars, buses, and planes. It enables the maintenance of our security, and the general security of the world, through the manufacture of tanks, missiles, and submarines. It enables the generation and transmission of power, the communication of information, and on and on and on! Yet, learning about this essential but complex process has never been easy, and this has led to less-than-optimal understanding and implementation and advancement.

Despite the essential nature of the process, there has never been a comprehensive treatise on welding that could be used as a primer for students of welding as well as a refresher and lifelong reference for both neophytes and seasoned practitioners. There have been good, comprehensive basic and advanced treatments dealing with the specific processes of welding, but these unanimously fail to deal with the physics and chemistry no less the metallurgy of weld formation. Contrarily, there have been good, comprehensive treatments of the physics, chemistry, and metallurgy of weld formation, but these either fail to deal with the general and specific processes for making welds or gloss over the subject in a chapter or less.

The time has come for the critically important process of welding to be treated comprehensively, in one source, in precise, unambiguous language, in readable format, and in sufficient depth to satisfy the experienced engineer but sufficiently clear and concise so as not to overwhelm the new student of welding or the interested layperson.

The book is divided into four parts and seventeen chapters. Part One addresses the process and processes of welding. Chapter 1 introduces the reader to what welding is, how it evolved as a process, what it means to make a weld, ideally and in the real world, and the advantages and shortcomings of welding. Chapter 2 considers why welding processes should be classified, and presents alternative ways of accomplishing that classification. Based on whether the process requires melting and solidification to produce a weld, or whether a weld is made in the solid state without melting, Chapters 3 and 4 describe fusion and nonfusion welding processes, respectively, by principal source of energy. These two chapters are about as comprehensive in scope, yet of reasonable depth, as presented in any single reference of this sort.

Part Two addresses the physics of welding. Chapter 5 looks at the sources, characterization, roles, and favorable and unfavorable effects of energy for making welds. Chapter 6 describes how heat flows in a weld and in weldments and what the effects of that heat are. Chapter 7 discusses thermally induced distortion and residual stresses during welding. Chapter 8 explains the physics underlying each major category of welding by energy source in the only treatment of its kind. Chapters 9 and 10 deal with the physics of molten metal transfer from consumable electrodes to the weld pool and of molten metal movement within the weld pool, respectively.

Part Three addresses the chemistry of welding in two chapters. Chapter 11 describes molten metal and weld pool reactions with the environment, the means of providing protection from such adverse reactions, and the means of providing additional metallurgical refinement. Chapter 12 looks at the origins and consequences of chemical heterogeneity in the weld pool and final weld.

Part Four considers the all-important metallurgy of welding. Chapter 13 addresses the phenomena of melting and solidification in pure metals and alloys, under nonequilibrium as well as equilibrium conditions, looking at the development of structure, substructure, and defects, and does so to a level and with clarity unparalleled in welding texts. Chapter 14 presents an almost unique treatment of eutectic and peritectic reactions in two-phase alloys, as well as major postsolidification transformations that can occur in the fusion zone. Chapter 15 addresses the unheralded and poorly understood partially melted zone and looks at some particular problems that can arise there. Chapter 16 addresses the heat-affected zone, considering what can happen as a consequence of the heat of welding based on how the base material obtains its strength and other properties in the first place. Finally, Chapter 17 addresses the testing of a material's weldability and a weld's properties.

I have attempted to create a unique welding reference. It's not encyclopedic in scope, depth, or drudgery; but neither is it an overly simplistic pseudo-text that fails to present and expound upon the principles underlying this critical group of production processes. It clearly explains theory, but never fails to mention where and how reality deviates from theory. It's what I looked for more than twelve years of teaching welding to engineering undergraduates and graduates, practicing engineers involved with welding directly or peripherally, and welders desirous of knowing more about their chosen trade. I hope it succeeds by being informative, interesting, and, perhaps, enlightening and entertaining. If so, I've created the book I wished I had 35 years ago.

To accompany this book, or simply to aid study of the principles of welding, *Work, Practice, and Thinking Problems* is available on floppy disk directly from the author at email address messlr@rpi.edu or at Rensselaer Polytechnic Institute, Materials Science and Engineering Department, Troy, NY 12180-3590.

A book like this cannot be written without help. The information that found its way into this book is the sum of the knowledge obtained from others by whom the author has been touched. Sometimes that touch was through another's writings, as is the case from unseen "friends" and colleagues like George Linnert, James Lancaster, Kenneth Easterling, Sindo Kou, and Henri Granjon. Other times that touch was quite personal, as was the case of mentors at RPI like Carl D. Lundin, John J. McCarthy, Ernest F. Nippes, and, most of all, Warren F. "Doc" Savage.

Making a book read well and look good is also a tedious task. In this case, the selfless assistance of some reviewers unknown to me and the professionalism of the editorial staff at John Wiley & Sons, Inc. is gratefully acknowledged. Artwork for the new figures was made possible by a talented former student, Suat Genc, to whom I am very grateful. Countless hours of research in libraries were shared with my student Leijun Li, a truly scholar and wonderful protegé, of whom I am extremely proud. The cover design was the brainchild of my daughter Victoria and the illustration was by her (and my) dear friend Avrau Kaufman.

To my wife, Joan, and daughters, Kerri and Vicki, I thank you for your endless patience with a compulsive personality, and for your understanding and love.

Writing a book like this can be a lonely process—hours and hours at the library and at the word-processor. But it really wasn't lonely for me. Just as I, and many others, sometimes feel Doc Savage's presence while I'm lecturing in a classroom, I frequently felt Doc's presence while writing this book. Sometimes that presence was felt when I tried to take a short cut or gloss over a point. Sometimes it was when I was tackling a particularly tough topic, like peritectic reactions. But, it was always a great support to feel the presence of a truly gifted mentor. I'm grateful for the chance to have known Doc, and for his eternal presence. Thanks, Doc!

ROBERT W. MESSLER, JR.

January 5, 1999

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PART 1

THE PROCESS AND PROCESSES OF WELDING

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CHAPTER 1

INTRODUCTION TO THE PROCESS OF WELDING

1.1. WHAT IS WELDING?

In its broadest context, welding is *a process in which materials of the same fundamental type or class are brought together and caused to join (and become one) through the formation of primary (and, occasionally, secondary) chemical bonds under the combined action of heat and pressure* (Messler, 1993). Common dictionaries tend to narrow the definition somewhat, as typified by the definition given in *The American Heritage Dictionary*[1]: "To join (metals) by applying heat, sometimes with pressure and sometimes with an intermediate or filler metal having a high melting point." The definition found in ISO standard R 857 (1958) states, "Welding is an operation in which continuity is obtained between parts for assembly, by various means," while the motto on the coat of arms of The Welding Institute (commonly known as TWI) simply states "e duobus unum," which means "from two they become one." All slightly different, but all similar in essential ways. Let's pause for a moment to consider those essential ways.

First and foremost is the central point that *multiple entities are made one by establishing continuity*. Here, continuity implies the absence of any physical disruption on an atomic scale, that is, no gaps, unlike the situation with mechanical attachment or mechanical fastening where a physical gap, no

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[1] Second College Edition by Houghton Mifflin, Boston, MA, 1985.

matter how tight the joint, always remains.[2] Continuity as used here does not imply homogeneity of chemical composition through or across the joint, but it does imply the continuation of like atomic structure. A weld can be made homogeneous, as when two parts made from the same austenitic stainless steel are joined with a filler of the same alloy, or they can be made to be intentionally dissimilar (heterogeneous), as when two parts made from gray cast iron are joined with a bronze filler metal. Similarly, two polymers or plastics[3] can be joined and made to be homogeneous if they are of identical (or essentially identical) type or composition, as when two pieces of thermoplastic polyvinyl chloride are thermally bonded or welded, or heterogeneous when two unlike but compatible thermoplastics are joined by thermal bonding. Alternatively, a compatible thermoplastic filler could be used as what is called an adhesive, and, when this is the situation, the result can also correctly be called a weld.

The key in each case is that even when the material across the joint is not identical in composition (i.e., homogeneous), it is essentially the same in atomic structure, thereby allowing the formation of chemical bonds: primary metallic bonds between similar or dissimilar metals, primary ionic or covalent or mixed ionic–covalent bonds between similar or dissimilar ceramics, and secondary hydrogen, van der Waals, or other dipolar bonds between similar or dissimilar polymers. The problem comes about when the materials to be joined are fundamentally different in structure at the atomic or (for polymers) molecular level. When this is the case, welding by the strictest definition (e.g., that of Messler, 1993, above) cannot be made to occur. An example is the joining of metals to ceramics or even thermoplastic to thermosetting polymers. In both cases, the fundamental nature of the bonding that must take place differs from that in at least one of the joint elements. For metals to ceramics, the metallic joint element is held together by metallic bonds, while the ceramic joint element is held together by either ionic or covalent or mixed ionic–covalent bonds. Clearly, there must be a disruption of bonding type across the interface of these fundamentally different materials. And for the case of a thermoplastic being joined to a thermoset, a degree of ionic bonding can occur in the thermoset to cause cross-linking, but not so in the thermoplastic. Thus, a dissimilar adhesive alloy is required to bridge this fundamental incompatibility (Messler, 1993). In short, the key is achieving continuity of structure by forming chemical bonds, and this limits possibilities to like types or classes even if not identical compositions of materials. More is said about how to achieve this essential continuity in Section 1.3.

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[2] Not incidentally, the persistence of a physical gap, no matter how tight it might be made, is what gives mechanical attachment or fastening its essentially unique and often desirable capability for allowing intentional disassembly without damaging the elements comprising the joint, or, under the right circumstances, for relative motion to take place between parts held in proximity and alignment, and, under the wrong circumstances, for fluids to leak through the joint.

[3] The preferred term in materials science for plastics is polymers, and so that term will be used throughout this work.