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Introduction

Welding as a process for joining materials, in general, and metals and alloys, in particular, is a double-edged sword.[1] On the one hand, welding offers one of the best methods for obtaining joints with strength comparable to (or even superior to) the physical elements being joined, with a lesser weight penalty than mechanical fastening (e.g. bolting or riveting) and a greater environmental durability than adhesive bonding (whether using organic adhesives, such as epoxies, or inorganic adhesives, such as cement). It also offers one of the assured ways of achieving leak tightness against fluids (i.e. gases and liquids), can be performed indoors or outdoors, manually or automatically (using mechanization or robots) using a wide variety of process embodiments, and, for better or worse, produces joints that are permanent.[2] On the other hand, the use of welding always demands thoughtful structures and joint designs, proper equipment and consumables (e.g. shielding gases or fluxes and fillers), skilled operators, appropriate quality assurance for joint performance demands, and, most importantly, an understanding of what it takes to produce a sound weld. The latter requirement typically leads to most problems encountered with welding.

Problems with welding normally relate to unacceptable welds, i.e. welds that fail to pass nondestructive evaluation immediately following their production *or* welds that fail to provide intended functions in service. Some examples of the former include welded assemblies that fail to meet the geometric and dimensional criteria (i.e. do not provide needed fit and/or function), welds that contain surface or internal flaws or defects that fail to meet the required quality specifications (e.g. freedom from cracks and freedom from porosity), or welds that degraded the base material components (e.g. because of cracking, severe oxidation, hardness loss,

1 From the notion that if two sides of the same blade are sharp, it cuts both ways. The metaphor may have originated in Arabic, in the expression سيف ذو حدين (sayf zou hadayn, "**double-edged sword**"), but it is first attested in English in the fifteenth century.

2 The permanency of a joint is desirable only if a structure is never intended to be disassembled, particularly without destroying the components of the assembly or having the process employed be simple. The inability to disassemble the welded components of the #4 light water graphite-moderated nuclear reactor at the Chernobyl Nuclear Power Plant near Pripyat in Ukraine, which suffered catastrophic failure on 26 April 1986 (Figure 1.1), is a prime example, as highly radioactive remains had to be entombed in a massive concrete "Object Shelter" (Figure 1.2), or sarcophagus, for the next 1000 years, as the massive welded containment vessel could not be disassembled!

A Practical Guide to Welding Solutions: Overcoming Technical and Material-Specific Issues,
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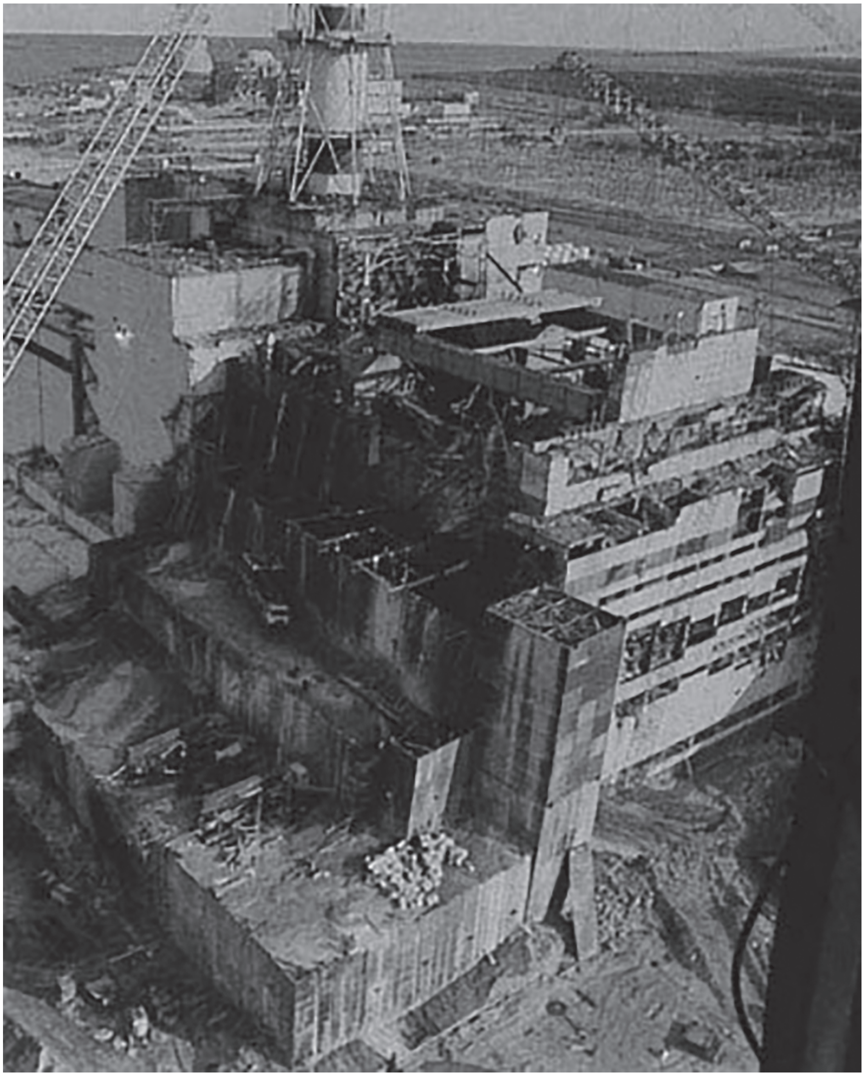

Figure 1.1 Remains of the #4 light water graphite-moderated reactor unit at the Chernobyl Nuclear Power Plant near Pripyat in Ukraine shortly after it catastrophically failed on 26 April 1986, because of a series of errors by Soviet operators during safety check tests. Source: Photograph by an unknown source posted by Garvey STS on en.wikibooks.org. Freely used under Creative Commons ShareAlike CC BY-SA 4.0.

or, contrarily, embrittlement). Also not to be ignored are welds that do not look good, as, in welding, internal "beauty" (i.e. quality) is often related to external "beauty" (i.e. appearance) the reason being a lack of care in welding, in particular, suggest a lack of care in manufacturing, in general, and, ultimately, a lack of care in design, marketing, senior management, etc. Very typically, the quality of an organization, starts at the top, with leadership by example meaning more than rules and regulations.

Figure 1.2 After several iterations to safely contain the highly radioactive remnants of the #4 reactor unit at the Chernobyl Nuclear Power Plant, the current New Safe Confinement or NSC was in position as of October 2017. Entombment was necessary because much of the steel structure used in the reactor containment vessel could not be disassembled as it was welded to be permanent and because it is highly radioactive. Besides safe containment of radiation, the €1.5B structure prevents damage by weather and runoff of lingering radioactive contamination. Source: Wikipedia.com "Chernobyl new safe confinement". Freely used under CC BY-SA 4.0; posted by Tim Porter on 13 October 2017.

Figure 1.3a,b shows a couple of examples of extremely well-executed welds made in stainless steel and an Al alloy using the gas tungsten arc process with a filler wire, whereas Figure 1.3c shows a very badly executed repair weld on a steel automobile part, and Figure 1.3d shows a badly factory-made gas–metal arc repair weld on an Al alloy boat.

To date, books that deal with the welding of metals and alloys, at least, have been found to deal with one or the other of (i) the processes employed to make welds *or* (ii) the metallurgy that underlies welding (i.e. welding metallurgy).[3] The former seldom, if ever, mention problems with welding or welds, as welding, not welds, is their purpose. The latter typically spend the first 80–90% of the book presenting the underlying physical metallurgy that allow welds to be made in metals and alloys in the first place and that can produce sound structure in the weld (i.e. fusion zone and surrounding heat-affected zone using fusion-welding processes), if everything is done properly. The remaining 10–20% on what can go wrong, how to detect such short-comings, and, finally, how to resolve any short-coming(s). It is almost as if the author is telling a story and carefully avoiding the outcome, as in a mystery. Not surprisingly, producing high-quality welds through welding *is* a mystery for many users.

3 A notable exception is *Principles of Welding: Processes, Physics, Chemistry and Metallurgy* by R.W. Messler, Jr., 1st ed., 24 March 1999, Wiley VCH, ISBN-13: 978-0471253761 or ISBN-10: 0471253766.

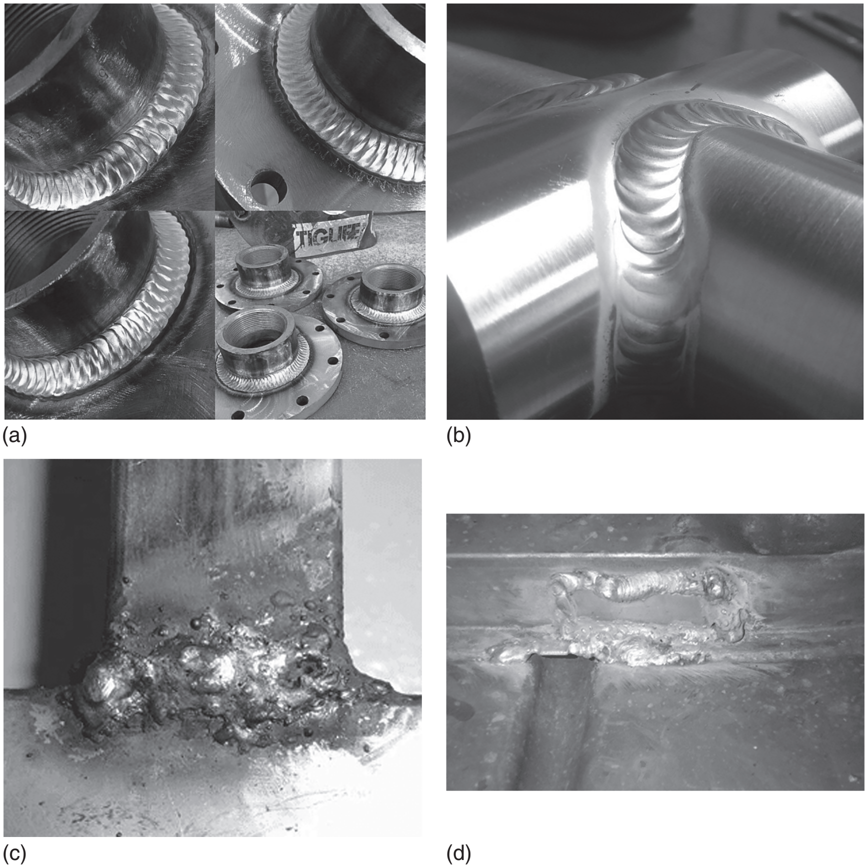

Figure 1.3 Two examples of superbly made fusion arc welds using manual gas tungsten arc (TIG) welding in (a) steel fittings and (b) Al alloy bicycle frames. In addition, two badly made welds: using a gas–metal arc to repair (c) a steel automobile part and (d) an Al alloy boat structure at a factory repair shop, with neither source being identified – fortunately for them – as images are in the public domain! Source: The former by Scott Raabe at his Clean Cut Metal Works, Houston, TX, USA and used with his kind permission; and the latter on the website www.cycling.zanconato.com by Mike Zanconato at Zanconato Custom Cycles, Sutton, MA, USA and used with his kind permission.

This book will approach the problems with welding and the welds produced in a reverse order: starting with the problem(s) and working backward to the cause(s) and resolution(s).[4] As such, not to underestimate the ultimate importance of understanding the process (i.e. physics and chemistry) that is used to make a weld and, even more importantly, the physical metallurgy that underlies and enables the production of welds of sound quality and properties, but to simply deal with the nature of real-world engineering in which pragmatism often prevails over detailed understanding of principles, the reason for the rising

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4 See Part IV, chapter 34, pp. 237–244 of *Engineering Problem-Solving 101: Time-Tested and Timeless Techniques* by R.W. Messler, Jr., 1st ed., 5 October 2012, McGraw-Hill Education, ISBN-13: 007199966 or ISBN-10: 007199966.

of various problems encountered will be covered briefly. Details will be left to the reader to seek information on welding metallurgy from other references. The rationale behind the approach of this book is as follows: engineers seek answers to problems and often achieve their goal(s) without having to delve into every detail. Every young engineer soon learns upon entering practice from college: the solution to a problem often only needs to be good enough, not perfect. A minimalist approach to engineering is often just as good as the minimalist approach used by a jockey to get a thoroughbred to win a race. Encourage the horse by clicks and chortles, tugs on the mane, and the light snap of a riding crop to increase the length of its stride at full gallop, without needing to know and understand all the details of equine physiology, like a veterinarian. After all, few veterinarians could ever ride a horse to victory in any race, no less in the Kentucky Derby!

This approach will work because those electing to use welding to create a structural assembly employ a backward problem-solving technique anyway. Knowing the end goal of a challenge (e.g. to get a man onto the Moon and back to the Earth safely), they work backward from the desired goal to identify the steps, methods, and procedures needed at each step to incrementally reach that goal from some given starting point. Regrettably, this enlightenment only dawns on young engineers once they leave engineering school, where most of what they are taught is the step-by-step process for reaching a goal by starting from first principles and seeing where the steps lead.

The reason a backward problem-solving approach often works, and often suffices, is that the first step will be to recognize the shortcoming (e.g. a severely distorted structure following cooling after welding; cracks in the fusion zone of a weld made in an austenitic stainless steel, such as type 304, using a recommended filler metal; cracks in the heat-affected zone of an arc weld made in a low-alloy steel that has been successfully welded before using the same process, same operators, and same parameters and procedures; and cracking in the base metal in some component after service). With this as a start, one could – and often does – begin to “troubleshoot” by checking each and every step for some potential cause–effect relationship. However, in this book, an organized collection of problems, categorized by the way in which they manifest themselves (i.e. distortion, cracking, porosity, and inclusions) and/or, in addition or alternatively, by where they are located (e.g. in the fusion zone with or without the use of a filler metal, in the high-temperature portion of the heat-affected zone or in the low-temperature portion of the heat-affected zone, and in the unaffected base metal), and/or a few problems predominantly, if not uniquely, associated with certain types of alloys (e.g. as-quenched martensite in hardenable steels; reheat cracking in some age-hardenable alloys) or, occasionally, pure metals (e.g. abnormal grain-growth or germination in cold-worked pure copper, as well as in some brasses), will guide the user toward the means of either avoiding such a problem in the future or, in some cases, attempting to resolve the already-present problem. Some of these latter-type problems may, in fact, be covered by manifestation or location but are covered here as well for easier searching by readers.

To facilitate problem solving, each chapter ends with a “Troubleshooting Guide.” Each guide tabulates the problems covered therein, the most likely cause, and a suggested approach to correct the problem. As described in Chapter 2, the chapters are divided into groups (i.e. parts) in the following manner: (i) how the most commonly encountered problems manifest themselves (Part I), (ii) where the problems with welds arise in or around a weld by location (Part II), and (iii) what problems tend to arise only in (or most often in) specific materials (Part III). This arrangement is also intended to guide users during troubleshooting.

Once again, so as not to underestimate the importance of – and, hopefully, natural technical curiosity of – an engineer from seeking to understand *why* something happens, each problem addressed will include a brief explanation of the cause, with readers desiring more details being encouraged to refer to other references (such as those listed at the end of this chapter).

The goal of this book is simple: help practicing engineers practice their profession and achieve their desired and needed outcomes.

In conclusion, it should not go unnoticed that all professionals – medical doctors, surgeons, attorneys at law, dentists, veterinarians, etc. – refer to what they do as a "practice." Rather than any intent to downplay the rigor with which each obtains their formal education or to suggest any sense that what one does is take a stab in the dark to achieve the goal, what is meant is simply that only gets better and better at what they do as they do it – repeating and building upon successes and learning from and voiding any repeat of failures.

Further Reading

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