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INTRODUCTION

This textbook addresses the topics of welding metallurgy and weldability. The two topics are inextricably intertwined since the weldability of a material is closely related to its microstructure. While the term *welding metallurgy* is universally accepted as a subset of physical metallurgy principles, the term *weldability* has been subject to a wide range of definitions and interpretations. In its broadest context, weldability considers aspects of design, fabrication, fitness for service, and, in some cases, repair. This broad treatment is reflected in the definitions for weldability that are provided by both the American Welding Society and the ISO Standard 581:1980. Thus, weldability can be used to describe both the ability to successfully fabricate a component using welding and the capacity for that component to perform adequately in its intended service environment.

AWS Definition of Weldability

The capacity of a material to be welded under fabrication conditions imposed into a specific, suitably designed structure and to perform satisfactorily in the intended service.

In a *Welding Journal* article published in 1946 entitled "This Elusive Character Called Weldability," W.L. Warren from the Watertown Arsenal in the United States stated, "That word (weldability)…has grown to mansize in stature and importance in respect to its significance in modern welding application. This term has been and is used with such a variety of shades of meaning that one may rightly conclude weldability to possess a value as changeable as a chameleon" [1].

Welding Metallurgy and Weldability, First Edition. John C. Lippold.

FIGURE 1.1 Henri Granjon, Institut de Soudure.

> **ISO 581:1980 Definition of Weldability**
>
> Metallic material is considered to be susceptible to welding to an established extent with given processes and for given purposes when welding provides metal integrity by a corresponding technological process for welded parts to meet technical requirements as to their own qualities as well as to their influence on a structure they form.

Henri Granjon (Fig. 1.1) in his text *Fundamentals of Welding Metallurgy* defined weldability as "…the behavior of (those) joints and the constructions containing them, during welding and in service…" [2] R.D. Stout in *Weldability of Steels* states that "the term weldability has no universally accepted meaning and the interpretation placed upon the term varies widely according to individual viewpoint" [3]. At a conference held at The Welding Institute (TWI) in 1988 entitled *Quantifying Weldability* [4], Trevor Gooch from TWI (Fig. 1.2) stated that "…the concept of weldability of a material is complex." At the same conference, A.D. Batte of British Gas Corporation is quoted as saying that "…it is incongruous to find that the definition of weldability is still an active area of debate," and W.G. Welland from BP International stated that "the concept of weldability is of little interest to the builders and users of most welded fabrications." Despite the many papers published by Warren F. Savage (Fig. 1.3) and

FIGURE 1.2 Trevor Gooch, The Welding Institute, 1992.

FIGURE 1.3 Warren F. "Doc" Savage, Rensselaer Polytechnic Institute, 1986.

FIGURE 1.4 Fukuhisa Matsuda, Osaka University, 1988 (W.A. “Bud” Baeslack III in the background).

his students at Rensselaer Polytechnic Institute and Fukuhisa Matsuda (Fig. 1.4) and his students at Osaka University, there are no definitions of weldability attributed to them (perhaps for good reason).

In this text, weldability will be considered from the standpoint of materials’ resistance or susceptibility to failure. From a fabrication standpoint, this relates to the ability to produce welds that are defect-free. There are multiple weld defects that can occur during fabrication, as described in Section 1.1, and these can be separated into those that are related to the welding process and procedures and those associated with the material. For example, defects such as lack of fusion, undercut, and slag inclusions are related primarily to the welding process and can usually be avoided by changes in process conditions. Defects such as solidification cracks and hydrogen-induced cracks are primarily related to the metallurgical characteristics of the material and are usually difficult to eliminate by changes in process conditions alone.

The term weldability also describes the behavior of welded structures after they are put into service. There are many examples of welded structures that are free of fabrication defects that later fail in service. These include failure modes involving corrosion, fatigue, stress rupture (creep), or complex combinations of these and other failure mechanisms. The service-related failure modes are perhaps the most serious

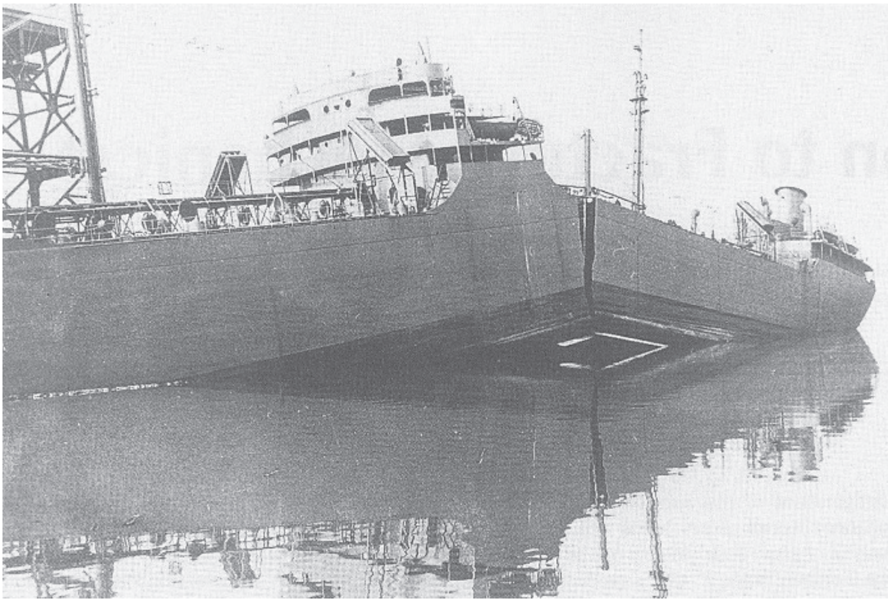

FIGURE 1.5 Liberty ship failure.

of the weldability issues discussed here, since failure by these mechanisms can often be unexpected and catastrophic. As an example of this, consider the catastrophic Liberty ship failures (see Fig. 1.5) during World War II that led to the sinking of many transport ships and the loss of many lives.

This text will focus primarily on the aspects of weldability that are influenced by the metallurgical properties of a welded structure. As such, chapters addressing various fabrication cracking mechanisms are included. These chapters are designed to not only describe the underlying mechanisms for cracking but to provide insight into how such forms of cracking can be avoided. Similarly, the various forms of service cracking are described, particularly those associated with corrosion, brittle fracture, and fatigue. In order to provide the reader with sufficient metallurgical background to interpret the contents of these chapters, a chapter on welding metallurgy principles has been included.

1.1 FABRICATION-RELATED DEFECTS

Fabrication-related defects include cracking phenomena that are associated with the metallurgical nature of the weldment and process- and/or procedure-related defects. A list of common fabrication defects is provided in Table 1.1. The defects associated with the metallurgical behavior of the material can be broadly grouped by the temperature range in which they occur.

Hot cracking includes those cracking phenomena associated with the presence of liquid in the microstructure and occurs in the fusion zone and PMZ region of

TABLE 1.1 Fabrication-related defects

"Hot" cracking
Weld solidification
HAZ liquation
Weld metal liquation
"Warm" cracking
Ductility dip
Reheat/PWHT
Strain age
Liquid metal embrittlement (LME)
"Cold" cracking
Hydrogen-induced (or hydrogen-assisted) cracking
Delayed cracking
Process control
Lack of fusion
Weld undercut
Excessive overbead
Incomplete penetration
Slag inclusions
Others
Geometric defects (design or fit-up)
Metallurgical anomalies (e.g., local softening or embrittlement)
Porosity

the HAZ. Liquid films along grain boundaries are usually associated with this form of cracking.

Warm cracking occurs at elevated temperature in the solid state, that is, no liquid is present in the microstructure. These defects may occur in both the fusion zone and HAZ. All of the warm cracking phenomena are associated with grain boundaries.

Cold cracking occurs at or near room temperature and is usually synonymous with hydrogen-induced cracking. This form of cracking can be either intergranular or transgranular.

A number of nonmetallurgical defects that can occur during fabrication are also listed in Table 1.1. These are generally associated with poor process/procedure control and include lack of fusion, undercut, incomplete joint penetration, and geometric defects. Such defects can usually be remedied by careful attention to process conditions, joint design, material preparation (cleaning), etc. This text will not address the nature or remediation of these types of defects.

1.2 SERVICE-RELATED DEFECTS

Welds are subject to a wide range of service-related defects. Since welds are metallurgically distinct from the surrounding base metal and may contain residual stresses, they are often susceptible to failure well in advance of the base metal.

TABLE 1.2 Service-related defects

Hydrogen induced
Environmentally induced (i.e., corrosion)
Relaxation cracking
Fatigue
Stress rupture
Creep and creep fatigue
Corrosion fatigue
Mechanical overload

These defects are usually manifested as cracks that form under specific environmental and/or mechanical conditions. A list of service-related defects is provided in Table 1.2.

Corrosion of welds is often a problem due to both the microstructural and local mechanical conditions of welded structures. The presence of fabrication-related defects can often accelerate service failures, particularly by fatigue. Welds in many engineering materials may contain softened regions that can promote mechanical overload failures. Conversely, local hard zones can result in reduced ductility and possible brittle failure.

1.3 DEFECT PREVENTION AND CONTROL

Although the understanding of the mechanisms leading to various forms of cracking is important, developing a methodology to prevent cracking is the ultimate goal of the welding engineer. Preventative measures can usually not be developed until the nature of the failure is understood. In some cases, changes in welding technique, or procedure, may be effective. For example, simple changes in heat input and bead shape can sometimes prevent weld solidification cracking. Another example is the use of preheat and interpass temperature control to prevent hydrogen-induced cracking.

Before such preventative measures can be implemented, the nature of failure must be determined in order that the "cure" does not lead to other weldability problems. Many Ni-base weld metals are susceptible to both solidification cracking and ductility-dip cracking, but the remedy for each defect type is different.

This textbook provides the necessary background to understand and interpret weld failures and recommends possible remedies for such failures. It should be noted, however, that the solution for many weldability problems will require a change in material rather than a "tweaking" of composition or process parameters. For example, reheat and strain-age cracking are significant problems when welding thick-section or highly restrained Cr–Mo steels and Ni-base superalloys, respectively. Again, knowledge of the precise mechanism of failure is required before remedial measures can be implemented.

REFERENCES

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