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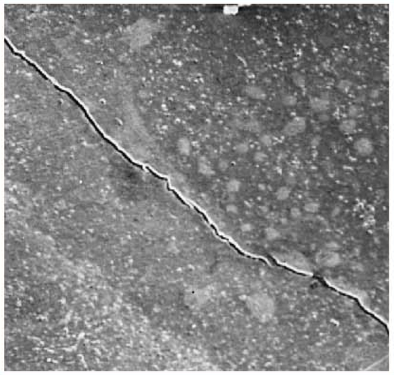

Weld cracking in ferrous alloys

Edited by Raman Singh

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Weld cracking in ferrous alloys

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Raman Singh

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Introduction

R K S I N G H, Monash University, Australia

Welding emerged as a result of engineering necessity for joining two metal pieces. However, to me, what makes fabrication and performance of steel welds most fascinating is that it is possibly the only single topic that necessitates education in almost the entire spectrum of metallurgical engineering. For example, ensuring sound performance of a cracking-resistant welded steel vessel for handling a corrosive fluid would need an understanding of:

- metallurgy of solidification and solid state phase changes associated with fabrication (and sound microscopic evaluation of the phase changes);
- non-destructive evaluation (NDE) of defects and stresses in welded structure;
- corrosion and synergistic influence of stress and corrosion causing cracking;
- fracture mechanical evaluation of the design and remaining life of the welded structure;
- NDE of the extent of damages in the aged welded structure;
- fractography and failure analyses of cracked structure; and
- metallurgy and NDE evaluation of the repair of cracked structure.

Adequate modelling coupled with key experimentation and validation approaches are essential inputs for quality and cost-effective welding management. Welding technology concerns traditional metallurgical engineering, which is underpinned by the fundamentals of physics, chemistry, materials and mechanical engineering. Unfortunately, metallurgical engineering in most modern materials engineering curricular contents has been dwindling worldwide. However, welding will continue to be an indispensable fabrication process for industrial structures, and the problems associated with welding will continue to perplex designers, manufacturers and plant operators. Because of the lack of adequately trained engineers in the field of traditional welding/metallurgical engineering, more and more professionals from other disciplines (such as mechanical and chemical engineers, who will be required to design, manufacture the components and run the plants) will have to shoulder the responsibilities of weld design, fabrication and robust operation over the lifetime of the plant.

In the planning and development of this book, particular care has been taken to make the chapters suitable for professionals from other disciplines who will need to learn and apply the information provided to the welds and their cracking/failures. Therefore, wherever possible, each chapter provides short descriptions (either within the main text or in an appendix) of the traditional metallurgical terminology and/or phenomena.

This book benefits tremendously from the participation of international experts in complementary topics of welding technology and research. The chapters deal invariably with the most recent technological advances in the respective topics while keeping an eye on the other primary purpose of the book, i.e. to make the chapters suitable for those without formal training in welding/metallurgical engineering (for the reasons described above).

The book has three parts. Part I aims at providing fundamentals as well as most recent advances in the areas of welding technology, design and material selection for preventing weld cracking. This part consists of chapters on such topics as robust welding technologies, component design against cracking and selection of crack-resistant stainless steels.

Part II discusses weld crack behaviour, evaluation and repair of cracking/cracked welds. NDE is the most critical tool for monitoring the health of welded components as well as their life prediction. The book benefits from an extensive and robust chapter on the topic of NDE and quality control that is contributed by one of the strongest non-destructing evaluation and development groups in the world. There is another chapter on the specialised use of neutron diffraction in evaluation of residual stresses of weldments. Chapters on fracture toughness and other common mechanical properties of welds deal with the role of fundamental metallurgical aspects on these properties and their evaluation. Some of the sets of data included in these chapters have been generated over extended testing and are extremely relevant to the performance of actual welds and their cracking. The chapter on the application of cellulosic girth welding provides an elaborate fundamental treatment of the major issue of weld cracking in the millions of kilometres of pipelines of welded steel structure. Similarly, the chapter on weld repair provides modern metallurgical approaches for restoration of the cracked welded structure. To develop an appreciation for the direct industrial relevance of these topics, Part II includes a chapter on a few typical case histories of weld cracking in different industrial situations and the systematic engineering and metallurgical approaches that were adopted to mitigate the problem of weld cracking in each case.

Part III covers environment-assisted weld cracking. Corrosion in conjunction with stresses (called stress corrosion cracking, SCC) can lead to catastrophic cracking. Such failures are particularly severe in the case of welded structures that are invariably under considerable residual stresses, which can lead to

SCC failures if the welds are not suitably stress relieved. Therefore, environment-assisted weld cracking has received tremendous research and development attention over the several decades. This part includes an elaborate chapter on corrosion and corrosion-assisted cracking of steel weldments. It also has chapters on a modern technique on evaluation of SCC susceptibility, and on relatively less explored types of corrosion-assisted failures of welds and the existing research and development potentials.

The editor finds it extremely fulfilling to have been able to receive participation of a galaxy of experts in the complementary areas of welding technology, design, evaluation and maintenance. However, special thanks must go to Indira Gandhi Centre for Atomic Research (IGCAR), a reputable research centre of Indian Atomic Energy and its distinguished director, Dr Baldev Raj. IGCAR is possibly the most self-sufficient centre for welding technology, design and evaluation, having extensive programmes on each of the areas listed earlier. Dr Raj has been the key factor in encouraging his colleagues for the participation in this book, and in ensuring that a sound mechanism was in place for the delivery of the committed chapters.

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Part I

Welding technology and design to prevent weld cracking

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1
Selection of weld-crack resistant stainless steels

J N DUPONT, Lehigh University, USA

Abstract: Stainless steel alloys are used in a wide variety of applications that often involve welding. Depending on the specific alloy type and composition, these alloys can be susceptible to various forms of cracking during welding. This chapter provides an overview of the various types of stainless steels, descriptions of potential cracking mechanisms, and techniques for avoiding cracking.

Key words: stainless steels, solidification cracking, HAZ cracking, liqud cracking, hydrogen cracking, primary solidification mode.

1.1 Introduction

Stainless steels are used in a wide range of applications that require good resistance to corrosion along with various combinations of strength, ductility, and toughness. Most applications will require fabrication by fusion welding. Although stainless steels are generally readily weldable, there are some forms of cracking that can occur during welding that need to be avoided. The objective of this chapter is to provide an overview of cracking mechanisms that can occur during welding of stainless steels. A brief description of the physical metallurgy applicable to various classes of stainless steels is provided first. The types of cracking mechanisms that are operable in stainless steels are then reviewed. In this section, particular attention is given to solidification cracking and heat-affected zone (HAZ) liquation cracking, since these are the most common problems that need to be avoided. The chapter concludes with general recommendations for avoiding the various types of cracking that can occur in stainless steels during welding.

1.2 Types of stainless steels

1.2.1 Martensitic stainless steels

Table 1.1 summarizes compositions of some common martensitic stainless steels. These alloys generally contain 11.5 to 18 wt% Cr for corrosion resistance. The strength of these alloys is primarily obtained by an austenitize-cool-temper heat treatment procedure that is designed to form a tempered martensitic microstructure with carbides. Additional strength can be imparted due to solid solution hardening by the presence of dissolved solute elements (such

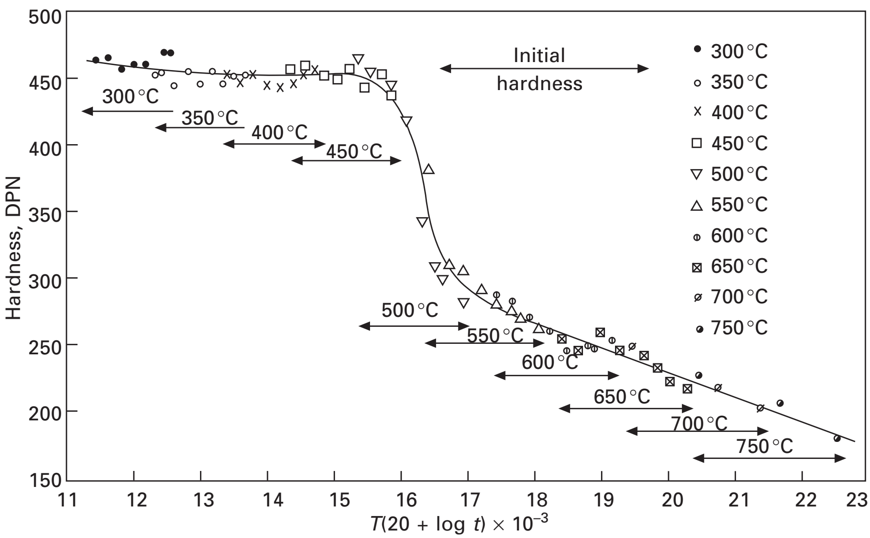
Table 1.1 Compositions of some common martensitic stainless steels. All values in weight percent. Unless noted, single value is a maximum

Alloy	UNS no.	C	Cr	Mn	Si	Ni	Other
403	S40300	0.15	11.5–13.0	1.00	0.50	–	–
410	S41000	0.15	11.5–13.5	1.00	1.00	–	–
420	S42000	0.15 min.	12.0–14.0	1.00	1.00	–	–
431	S43100	0.20	15.0–17.0	1.00	1.00	1.25–2.50	–
440A	S44002	0.60–0.75	16.0–18.0	1.00	1.00	–	0.75 Mo
CA-6NM	–	0.06	11.5–14.0	1.00	1.00	3.5–4.5	0.4–1.0 Mo

as Ni and Cr), the precipitation of carbides during tempering, and by control of the prior austenite grain size. Since martensite is the primary strengthening mechanism, the hardness and strength of these alloys increase significantly with increasing carbon content. Cold working also provides a significant increase in strength, but the ductility and toughness are adversely affected, so this strengthening mechanism is typically not exploited in practice.

The austenitizing treatment is required as the initial step so that martensite can form from the austenite during cooling. Formation of fully martensitic structures in simple Fe–Cr alloys is limited to ~ 10–12 wt%. Above this Cr level, austenite is replaced by ferrite at higher temperatures, thus restricting the ability to form martensite during cooling. Additions of elements such as C, N, and Ni are useful in this regard because they widen the austenite phase field. This permits the addition of higher Cr contents while allowing formation of a fully austenitic structure at higher temperatures. Unlike low alloy steels, the relatively high Cr content of these alloys leads to high hardenability, so that quenching is generally not required to form a uniform martensitic microstructure during cooling. The as-quenched martensite exhibits very high hardness and strength, but is usually of insufficient toughness for most engineering applications. Thus, tempering is required to impart adequate toughness and ductility (with a concomitant reduction in strength and hardness).

Master tempering curves are often available to correlate changes in mechanical properties to heat treatment time and temperature. An example of this for a 12Cr–0.14C martensitic stainless steel is shown in Fig. 1.1 [1]. In this plot, the change in hardness is plotted against a Larson–Miller type



1.1 Master tempering curve for a 12Cr–0.14C martensitic stainless steel.

tempering parameter (where T is temperature and t is time). This type of information permits one to determine various combinations of time and temperature that produce equivalent results in terms of tempering and resultant properties. The reduction in hardness occurs due to release of carbon from the super saturated martensite, which is also accompanied by precipitation of various carbides. It is worth noting, however, that the tempering temperatures between 475 and 550 °C are generally avoided in martensitic stainless steels in order to avoid temper embrittlement. This form of embrittlement produces a significant reduction in toughness that is associated with segregation of tramp elements to the prior austenite grain boundaries during tempering.

1.2.2 Ferritic stainless steels

Table 1.2 lists typical compositions of some common ferritic stainless steels. The presence of austenite stabilizing elements in these alloys is lower than the martensitic stainless steels and, as a result, these alloys generally remain ferritic from room temperature up to melting. Thus, they cannot be strengthened by heat treating. Some alloys can contain minor amounts of martensite, but most alloys are fully ferritic. Ferritic stainless steels exhibit inferior mechanical properties compared with martensitic and austenitic stainless steels, and are susceptible to various forms of embrittlement at service temperatures above ~ 400 °C. However, they have good resistance to general and localized corrosion (e.g. stress corrosion cracking). Thus, these alloys are typically used where low temperature corrosion resistance, rather then mechanical properties, is of primary concern.

Ferritic stainless steels are susceptible to several types of embrittlement phenomena that induce severe losses in toughness and ductility and warrant brief discussion. These include 475 °C embrittlement, sigma phase embrittlement, high temperature embrittlement, and notch sensitivity. Alloys with Cr levels from 15 to 70 wt% can undergo 475 °C embrittlement. This process is generally believed to be associated with the formation of a coherent α' precipitate at temperatures below 550 °C, which is expected from the miscibility gap that exists in the Fe–Cr system. Alloys aged below this temperature can form a two phase microstructure that consists of Fe-rich (α) and Cr-rich (α') phases. The rate of precipitation increases with increasing Cr content and increasing cold work. This form of embrittlement can also reduce corrosion resistance due to selective attack of the low Cr α phase. The brittle σ phase can form in alloys with 20–70 wt% Cr when exposed to temperatures from 500 to 800 °C. As with 475 °C embrittlement, the rate of σ phase formation increases with plastic deformation and increasing Cr content. Sigma phase embrittlement can be reversed if the alloy is heated above 800 °C, which results in dissolution of the σ phase.

High temperature embrittlement occurs when alloys are heated above ~

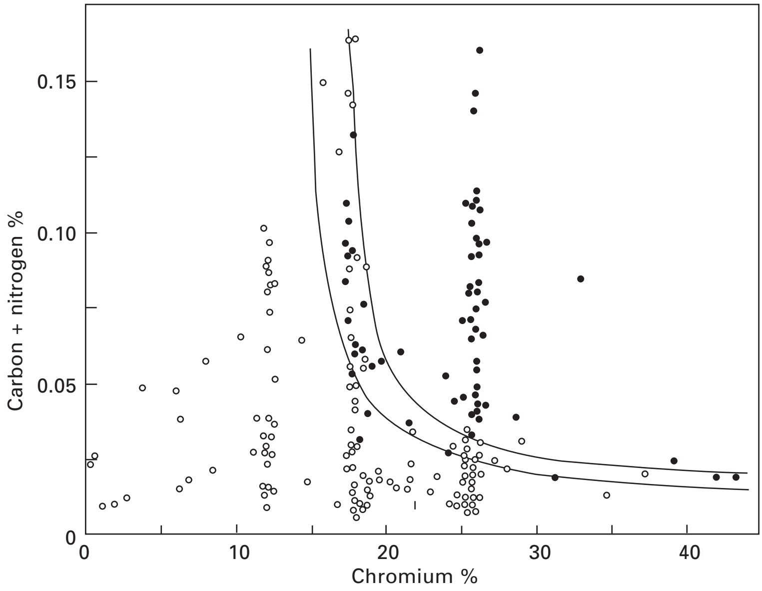
Table 1.2 Compositions of some common ferritic stainless steels. All values in weight percent. Unless noted, single value is a maximum. P levels are typically < 0.04, and S levels are typically < 0.03

Alloy	UNS no.	C	Cr	Mn	Si	Ni	Other
405	S40500	0.08	11.5–14.5	1.00	0.50	0.60	0.10–0.30 Al
409	S40900	0.08	10.5–11.75	1.00	1.00	0.50	Ti = 6 × C – 0.75
434	S43400	0.12	16.0–18.0	1.00	1.00	–	0.75–1.25 Mo
446	S44600	0.20	23.0–27.0	1.50	1.00	0.75	0.25 N
468	S46900	0.03	18.0–20.0	1.00	1.00	0.50	0.03 N, 0.07–0.30 Ti, 0.10–0.60 Nb

950 °C. Since this is well above the service temperature of ferritic stainless steels, this process can occur during processing operations such as casting, welding, and/or thermo-mechanical processing. The level of interstitial elements such as carbon, nitrogen, and oxygen, have a strong influence on high temperature embrittlement. At high temperatures, these elements can be dissolved. During cooling, their presence can lead to precipitation of Cr-rich carbides, nitrides, or carbo-nitrides that induce a severe reduction of impact toughness and increase in the ductile to brittle transition temperature. Even when ferritic stainless steels can be processed without the three forms of embrittlement described thus far, they still exhibit notch sensitivity. As shown in Fig. 1.2, notch sensitivity is a strong function of Cr content and the combined interstitial level (carbon + nitrogen) [2].

1.2.3 Austenitic stainless steels

Austenitic stainless steels represent the most widely used alloys of all the stainless steels. This can be attributed to their combination of good corrosion resistance, ease of fabricability by a variety of techniques (e.g., casting, welding, and various forming processes), and good mechanical properties. Table 1.3 lists the composition of some common grades of austenitic stainless

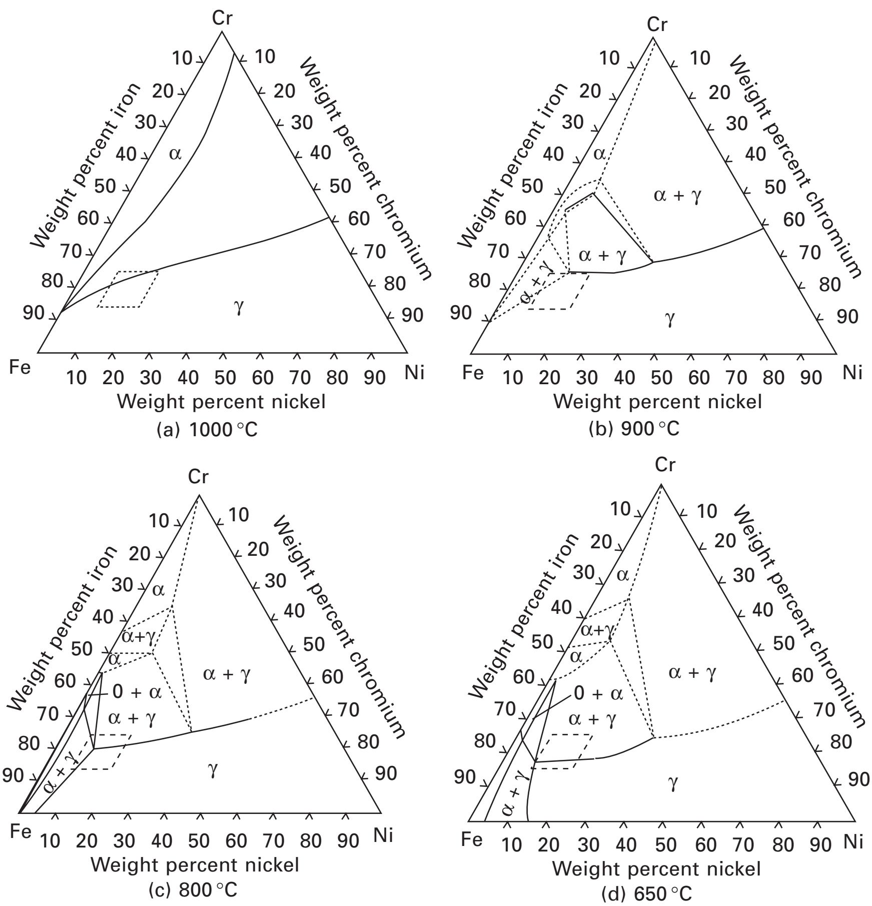


1.2 Notch sensitivity of ferritic stainless steels as function of Cr content and combined C + N content. Open circles represent high impact strength alloys; closed circles represent low impact strength alloys.

Table 1.3 Compositions of some common austenitic stainless steels. All values in weight percent. Unless noted, single value is a maximum. P is < 0.045 and S is < 0.03

Alloy	UNS no.	C	Mn	Si	Cr	Ni	Other
304	S30400	0.08	2.0	1.0	18.0–20.0	8.0–10.5	–
308	S30800	0.08	2.0	1.0	19.0–21.0	10.0–12.0	–
309	S30900	0.20	2.0	1.0	22.0–24.0	12.0–15.0	–
316	S31600	0.08	2.0	1.0	16.0–18.0	10.0–14.0	2.0–3.0 Mo
321	S32100	0.08	2.0	1.0	17.0–19.0	9.0–12.0	Ti = 5 × C – 0.70
347	S34700	0.08	2.0	1.0	17.0–19.0	9.0–13.0	Nb = 10 × C – 1.00

steels. It should be noted that this is only a small list from a very wide range of commercially available alloys. These alloys are based on the Fe–Ni–Cr system and generally contain a minimum of ~ 8 wt% Ni that is added to stabilize the γ-austenite matrix to low temperatures. The influence of Ni is readily observed from isothermal sections of the Fe–Ni–Cr ternary system shown in Fig. 1.3 [3]. Austenite (γ) and ferrite (referred to as either α or δ) are the primary phases that cover most of the temperature–composition space associated with the Fe–Ni–Cr system. The brittle σ phase can also form at lower temperatures and higher Cr concentrations. Although the kinetics associated with formation of the σ phase are typically sluggish, it has been

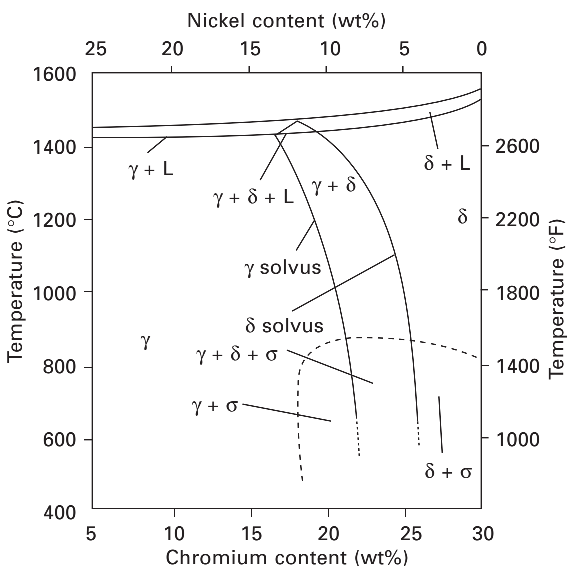


1.3 Isothermal sections of the Fe–Ni–Cr ternary system shown at various temperatures. The small boxes (dotted lines) represent the typical range of Ni (~ 8–20 wt%) and Cr (~ 15–25 wt%) concentrations found in many commercially austenitic stainless steels.

observed in several higher Cr alloys and can compromise both mechanical properties and corrosion resistance [4]. The small boxes (dotted lines) shown in Fig. 1.3 represent the typical range of Ni (~ 8–20 wt%) and Cr (~ 15–25 wt%) concentrations found in many commercially austenitic stainless steels. Note that most alloys will be fully or nearly fully austenitic.

Austenitic stainless steels can exhibit either primary ferrite or primary austenite solidification modes [5,6]. This can be understood by reference to the 70 wt% Fe isopleth section extracted from the Fe–Ni–Cr system that is shown in Fig. 1.4 [7]. The ternary liquidus projection for this system exhibits a line of twofold saturation that separates primary δ-ferrite solidification from primary γ-austenite solidification. This line has a slope of ~ 3Cr : 2Ni on the ternary liquidus projection, and the line is reduced to a 'eutectic point' on the isopleth section of Fig. 1.4. Alloys rich in Ni located to the left of the eutectic will exhibit primary γ solidification, and γ will generally remain stable after solidification (as previously mentioned, the σ phase can potentially form in some higher Cr alloys). Alloys higher in Cr located to the right of the eutectic will solidify as primary δ. However, in most commercial austenitic stainless steels, this ferrite is not stable with decreasing temperature and can transform to austenite with continued cooling. Depending on alloy composition and cooling rate, the alloy may contain some remnant ferrite (either stable or unstable), or may be fully austenitic.

Although the phase diagrams shown in Figs 1.3 and 1.4 are useful for understanding phase transformation sequences and potential microstructures,



1.4 The 70 wt% Fe isopleth section extracted from the Fe–Ni–Cr system.