WELDING OF INCONEL ALLOY 718: A HISTORICAL OVERVIEW

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Abstract

The introduction of Inconel alloy 718 represented a major advancement in the nickel-base-superalloy class of materials. One of the most significant reasons was its lack of sensitivity to strain-age cracking during heat treatment of weldments. In addition, the general weldability of the alloy proved to be quite good. It has reasonably good resistance to fusion-zone cracking, and its sensitivity to heat-affected-zone microfissures in the base metal is comparable to other nickel-chromium/nickel-chromium-iron alloys. The metallurgy of alloy 718 as it applies to welding issues, strain-age cracking behavior, and fusion-zone and heat-affected-zone fissuring resistance are reviewed in this paper.

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Introduction

The alloy development effort that would lead to Inconel Alloy 718 was a search for a solid-solution-strengthened non-age-hardenable alloy for use in mainstream lines (1). The application required high strength and long-term metallurgical stability at 1200 to 1400 °F (650 to 760 °C). Since stability was a key requirement, screening tests to explore age-hardening response and metallurgical stability were a standard part of the battery of tests used in the development study. These tests showed an unexpectedly large aging response when columbium was added to base composition. The search for a non-age-hardenable alloy was put aside for the moment, and exploration began on the development of a new age-hardenable alloy.

The resulting alloy developed strength comparable to the best available materials at the time—alloys such as Rene 41, Udimet 700, Inconel alloy X-750, and Waspalloy. From a weldability standpoint, these alloys were all considered weldable in sheet-metal thicknesses without major difficulty; however, all suffered from strain-age cracking during the post-weld aging treatment. The metallurgists at General Electric–Evandale were the first to recognize the potential advantage of the sluggish aging response exhibited by alloy 718 in avoiding the strain-age cracking problem (1). This lack of sensitivity to strain-age cracking was to provide a significant advancement in weldability for this class of high-strength age-hardenable nickel-based superalloys.

In this overview, we will briefly review the metallurgy of alloy 718 as it applies to weldability issues and review the weldability of alloy 718 with regard to strain-age, fusion-zone, and heat-affected-zone cracking sensitivity.

Metallurgy of Alloy 718

The chemical composition range of alloy 718 is shown in Table I.

Table I. Composition Range of Alloy 718 (wt%)

Nickel	50.00–55.00
Chromium	17.00–21.00
Iron	Balance
Columbium	4.75–5.50
Molybdenum	2.80–3.30
Aluminum	0.20–0.80
Titanium	0.65–1.15
Manganese	0.35 max.
Silicon	0.35 max.
Boron	0.006 max.
Carbon	0.08 max.
Sulphur	0.15 max.
Magnesium	Residual

Several elements have been identified as specifically affecting weldability. Addition of columbium has historically been used to improve fusion-zone-cracking resistance in the nickel and high-nickel alloys (2,3). The columbium and molybdenum are also involved in the formation of carbides, carbo-nitrides, and laves phase. These phases can affect ductility and can be involved in heat-affected-zone liquation in the base-metal grain boundaries. The tendency to form laves phase is reduced by increased nickel or reduced iron content.

Sulphur, phosphorous, and boron exert the same effect in this alloy that they do in other systems; all cause fusion-zone cracking problems if present in sufficient amounts (i.e., sulphur greater than 0.008 wt%, phosphorous >0.025 wt%., and boron >0.010 wt%). Boron causes increased heat-affected-zone cracking sensitivity if present much above 0.003 wt% .

Magnesium is used by some producers as a deoxidizer and malleabilizer. A residual amount will be present and can lead to fusion-zone cracking problems if the amount exceeds 0.030 wt%.

Silicon, in all of the nickel/chromium and nickel/chromium/iron alloys, has been identified with increased sensitivity to fusion-zone cracking (2,3). Silicon also appears to control the kinetics of laves phase formation in this alloy; increasing the silicon results in a greater volume fraction and apparent increased stability of laves phase present in the microstructure.

A time-temperature-transformation diagram (T-T-T) for alloy 718 is shown in Figure 1. The T-T-T diagram shows a number of phases that precipitate in alloy 718 base metal: gamma prime, CbC, M_6C, delta phase (Ni_3Cb), and laves phase. All of these phases go into solution around 1950 °F (1065 °C). Because the grain-boundary phases are going into solution and are therefore no longer pinning the boundaries, grain growth occurs at temperatures above about 1900 °F (1040 °C).

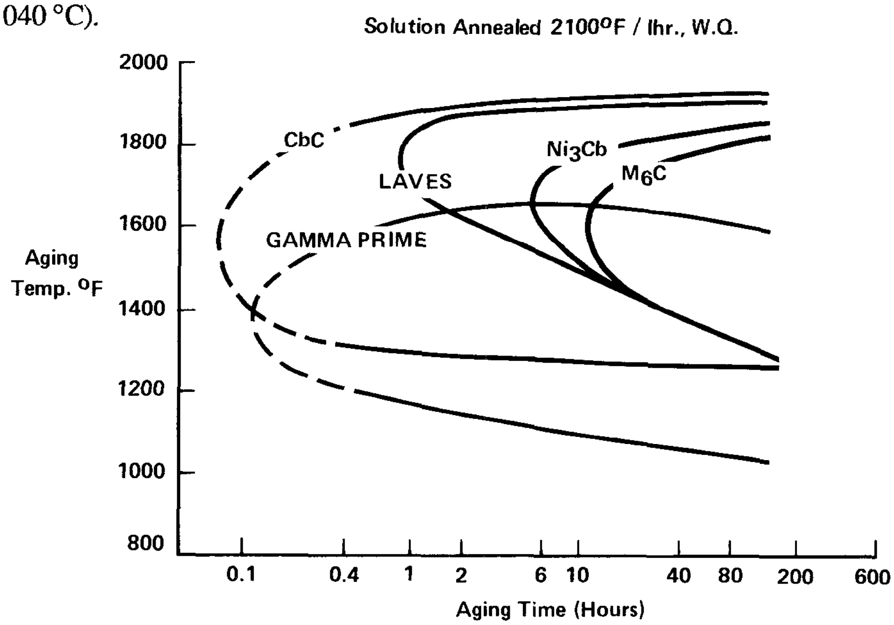

Figure 1 – Time-temperature-transformation diagram for alloy 718. Note that the material was solution-annealed at 2100 °F (1149 °C) for 1 hour and water-quenched.

These same phases would be expected to be present in the fusion-zone structure. Figure 2 shows a fusion-zone structure that has been heat-treated at 1750 °F (955 °C). Both laves phase and delta phase are present; both lead to reduced ductility, particularly in the age-hardened condition.

Strain-Age Cracking

As noted in the introduction, the most significant advancement alloy 718 offered from a welding standpoint was its reduced sensitivity to strain-age cracking. The age-hardenable alloys in this strength class were all hardened by the precipitation of gamma prime, Ni_3Al or Ni_3Ti. Their age-hardening response was very rapid whereas that of alloy 718, with its columbium-based gamma-prime aging constituent, Ni_3Cb, is much more sluggish. Figure 3 shows hardness-*vs.*-time data for Rene 41, M-252, Astroloy, and alloy 718 to illustrate the point (4).

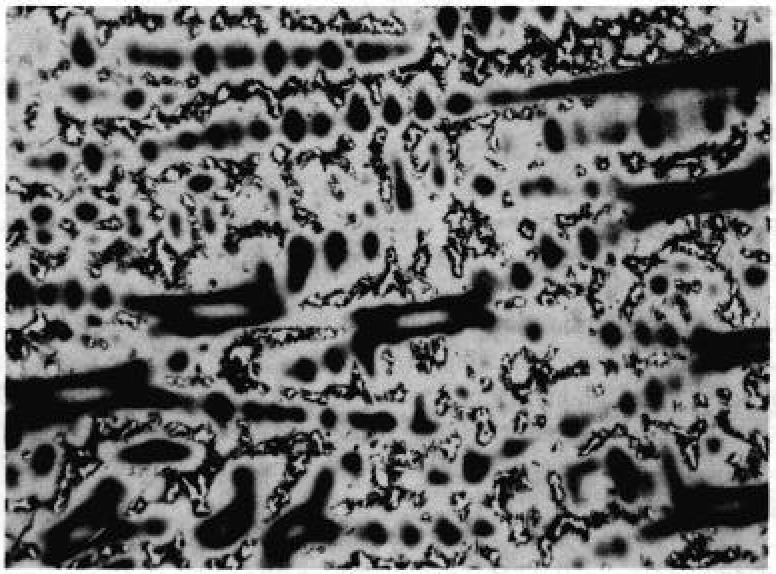

Figure 2 – 500×. Gas-tungsten-arc weld in alloy 718 base metal. The weld was heat-treated at 1750 °F (955 °C), followed by an age-hardening treatment. Note the white-appearing laves phase present in the interdendritic areas and the needle-like delta phase precipitated during the heat treatment. Etchant: 5% chromic acid in water-electrolytic.

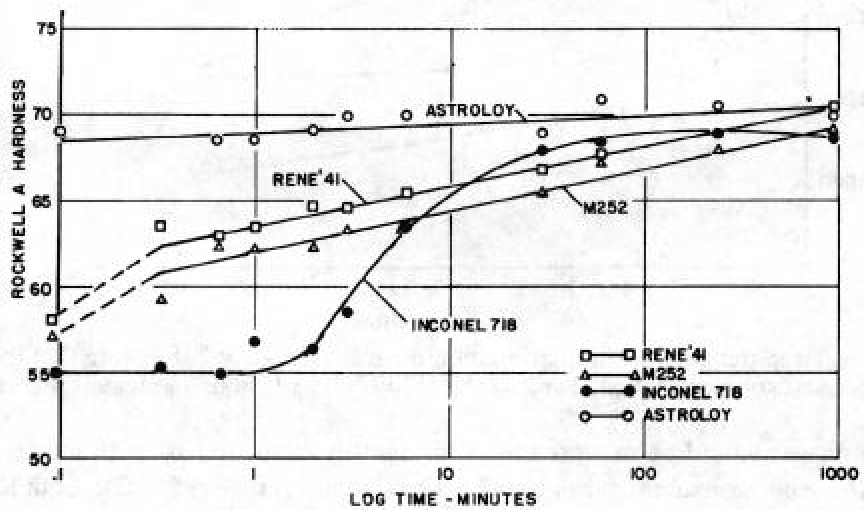

Figure 3 – Age-hardening-response curves for several alloys. Note alloy 718's sluggish response (4).

Eiselstein (5) suggested that the reason for the improved resistance to strain-age cracking involved the capability of sluggish-aging alloy 718 to relax the yield-strength-level, weld-induced residual stresses. The more rapid aging Al/Ti-hardened alloys suffered a short time-stress-rupture failure.

The weldability test used to assess strain-age cracking sensitivity was the Pierce-Miller Patch Test. Figure 4 shows a schematic illustration of the test configuration. The weld that joins the sheet-metal sample to the heavy-section restraining block of the same alloy and the sheet-metal-to-sheet-metal circle-patch weld produced a yield-strength-level tensile-residual stress. After welding is completed, the entire assembly is heat-treated. Aluminum- and titanium-hardened alloys such as alloy X-750 and Rene 41 crack extensively during heat treatment. These alloys can be made to survive the Pierce-Miller Patch Test crack-free; however, the procedure requires a pre-weld overaging heat treatment, follow welding with a solution anneal, and finally an age-hardening heat treatment of the weldment.

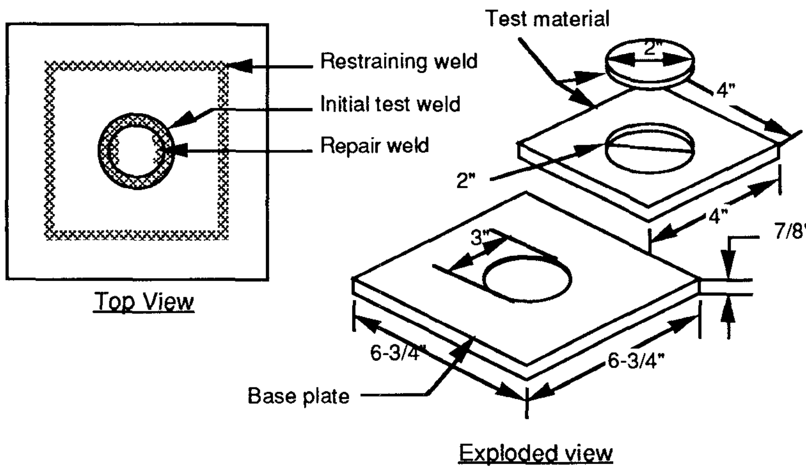

Figure 4 – Schematic diagram of the Pierce-Miller Patch Test. The square blank is GTA-welded to the restraining block, and the patch is welded in place. The repair welds are done after the heat-treatment cycle.

Alloy 718's capability to withstand a direct age cycle significantly reduced the number of heat-treatment operations and the related distortion problems frequently encountered in heat treatment. The Pierce-Miller Patch Test was used further to demonstrated that alloy 718 could be repair-welded in the aged condition followed by a re-aging treatment. Welding in the fully aged condition is not a recommended procedure if it can be avoided.

Sensitivity to Fusion-Zone Cracking

As with most of the various Inconel compositions, alloy 718 has sufficient fusion-zone cracking resistance to be autogenously welded with the gas-tungsten-arc (GTA) welding process in sheet-metal thicknesses. Heavy-section electron-beam welds have been consistently produced free of fusion-zone cracking problems. The alloy-base composition has been successfully used as a filler metal in heavy-section, multiple-pass GTA weldments. It has never been recommended for use as a gas-metal-arc (GMA) welding filler metal, although GMA weldments have been successfully made using very closely controlled conditions.

This overview of the fusion-zone cracking resistance is generally borne out by Varestraint test results such as shown in Figure 5 (5). The cracking-threshold strain for alloy 718 is difficult to define since the fusion-zone crack tends to backfill from the molten weld pool. The tendency to backfill is due to the wide liquidus-solidus temperature spread exhibited by the alloy. This same characteristic can also explain the steep slope of alloy 718's curve of Average Total Crack Length *vs*. Per Cent Augmented Strain. The Varestraint test measures the characteristic temperature range over which a crack can easily propagate (6). Several other alloys are shown for the sake of comparison. Inconel alloy 600 has sufficient cracking resistance to be autogenously GTA welded in sheet-metal thicknesses but does not have sufficient resistance to fusion-zone cracking to be useful as a GMA filler metal. Inconel Filler Metal 82 exhibits the most crack-resistant behavior of the Inconel alloys evaluated.

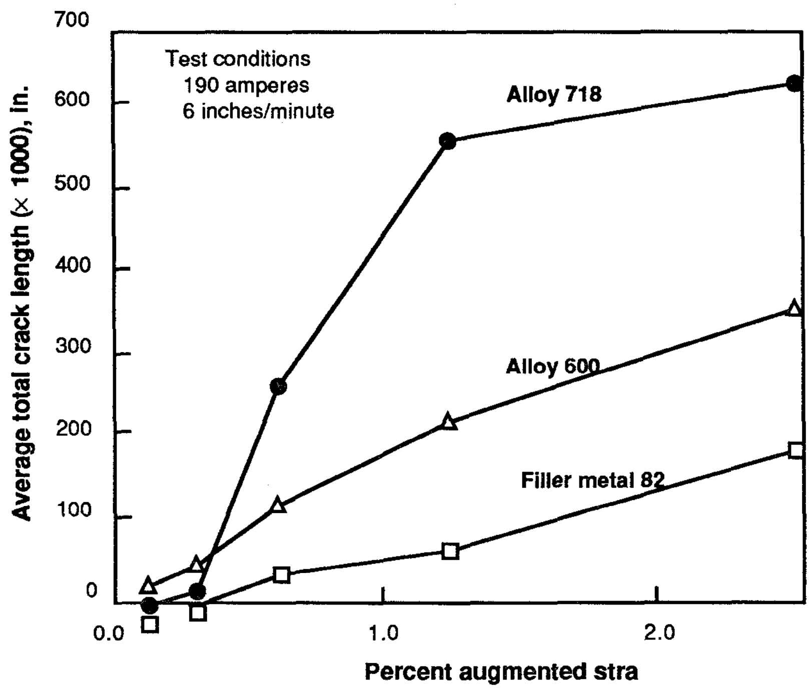

Figure 5 – Varestraint weldability test data for Inconel alloys 600, 606, and 718. These data represent an average of a number of heats for each alloy.

Sensitivity to Heat-Affected-Zone Microfissuring

The thermal cycle resulting from any of the fusion-welding processes can be easily shown to result in plastic strain in the heat-affected zone of the weld (7). Intergranular microfissuring occurs in the heat-affected zone if the base metal is unable to accommodate the strain. The reason most often cited for microfissures is liquation of the grain boundary due to segregation of elements to the boundary, which depress the melting temperature. Figure 6 shows an example of grain-boundary melting in a GTA weld. In alloy 718, both carbides and laves phase have been identified as possible culprits. Owczarski suggested that the problem occurred on cooling and was due to a lack of grain-boundary ductility recovery (8,9). In some very recent work, Kelly suggested that the presence of boron in cast alloy 718 caused the molten carbides to wet the grain boundary, thus explaining the deleterious role of boron in regard to microfissuring sensitivity (10). A complete understanding of the mechanism for heat-affected-zone microfissuring has yet to be completely defined.

What is understood is that alloy 718 shows the same tendencies seen in most of the nickel/chromium and nickel/chromium/iron alloys; sensitivity to heat-affected-zone

Figure 6 – Melting and microfissuring of the grain boundaries in alloy 718 gas-tungsten-arc weld. Etchant: Chromic acid–electrolytic.

microfissuring in the base metal is dependent on thermomechanical processing (grain size), the severity of the welding process used, and the chemical composition of the material (7). A coarse grain size (whether arrived at by high-temperature annealing treatment or by hot-rolling practice) increases sensitivity to microfissuring. Figure 7 shows microfissuring in a base material with an average grain size of ASTM #0. Generally, grain sizes coarser than ASTM #5 show an

Figure 7 – 100×. Base-metal microfissuring in solution-annealed alloy 718. Grain size: ASTM #0 (0.014 inch).

increased sensitivity to base-metal microfissuring. Achieving a fine grain size requires that finishing temperatures for hot-working be kept below about 1950 °F (1065 °C). Alloy 718 recrystallizes in the 1750–1800 °F (955–982 °C) temperature range; at temperatures above about 1900–1950 °F (1040–1065 °C) the grain-boundary phases go into solution and grain growth occurs.

The electron-beam welding process and the spray-transfer gas-metal-arc welding process have been demonstrated to be the most demanding, from a cracking standpoint, on the base metal (7). Cracking has been particularly noted in electron-beam welds near the nail head. Setting of machine parameters to avoid nail head formation is recommended to avoid the problem. The GTAW process and other less demanding processes (e.g., shielded-metal-arc, pulsed-arc, and short-arc welding processes) can be used to produce welds free of heat-affected-zone microfissures in fine-grained base metal. We were unsuccessful in consistently producing weldments free of heat-affected-zone microfissures in coarse-grained material with any of the fusion-welding processes (7).

As noted in the section on metallurgy, the presence of boron increases the sensitivity to base-metal microfissuring. Boron is an essential addition to the alloy for hot malleability and for stress-rupture ductility. The addition of 0.001 to 0.003 wt% enables the achievement of acceptable weldability characteristics while still meeting the physical property and processing requirements.

The problem of base-metal sensitivity to microfissuring in coarse-grain-size materials can limit the physical properties by restricting the useful heat-treatment temperatures. Annealing in the 1750–1800 °F (955–982 °C) range produces a fine-grained microstructure desired to minimize microfissuring sensitivity. This treatment also results in the best room-temperature tensile strength, the best fatigue strength, and notch ductility in stress rupture. On the negative side, the treatment results in low stress-rupture strength, reduced transverse ductility, notch brittleness in the room-temperature tensile test, and a microstructure that has a large number of precipitates.

Annealing in the 1900–1950 °F (1040–1065 °C) or higher temperature range produces the best smooth-bar stress-rupture strength, better room-temperature tensile ductility, some degree of grain growth, and a relatively clean microstructure. The heat treatment also produces a notch brittle condition in stress rupture. This can be overcome to some degree by a slow cool from 1950 to 1750 °F (1065 to 955 °C) to reprecipitate carbides and/or delta phase (Ni_3Cb) in the grain boundaries. The presence of these grain-boundary phases improves the notch-bar stress-rupture strength but not to the point of being notch ductile.

The tensile elongation of as-welded direct-aged alloy 718 weld metal is approximately 10%, which is adequate for many applications. ASME Boiler Code applications contain a side-bend-test requirement that can't be met with that level of ductility. Heat treatment at 1950 °F (1065 °C) will solution the laves phase and improve the elongation to 20% or greater. This is illustrated in Figure 8; compare this microstructure with that shown in Figure 2. This level of ductility will meet a 5T bend-test requirement. A number of heat-treatment combinations are illustrated in Figure 9. Applying the 1950 °F (1065 °C) solution anneal while correcting the weld-metal ductility problem also increases the sensitivity of the weldment to base-metal microfissuring. This can be a significant problem if repair welding becomes necessary.

Figure 8 – 500×. Alloy 718 gas-tungsten-arc weld, annealed at 1950 °F (1065 °C), furnace-cooled to 1750 °F (955 °C), and age-hardened. Most of the laves and delta phase seen in Figure 3 has been put in solution. Weld-metal ductility is significantly increased by the 1950 °F (1065 °C) solution-anneal treatment. Etchant: 5% chromic acid in water–electrolytic.

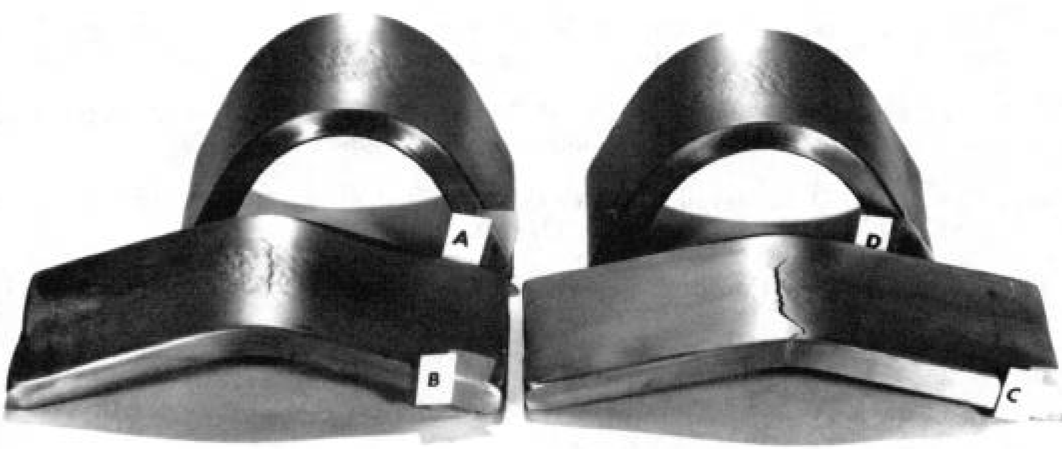

Figure 9 – 5T longitudinal face bend tests in 1/2-inch-thick alloy 718 base metal, gas-tungsten-arc welded with alloy 718 filler metal. **Bend A**—as-welded; **Bend B**—1325 °F (720 °C) aging treatment; **Bend C**—1750 °F (955 °C) anneal plus aging treatment; **Bend D**—1950 °F (1065 °C) anneal, furnace cool to 1750 °F (955 °C), plus aging treatment.

Summary

There have been more welding and weldability studies reported in the literature for alloy 718 than for any other currently used nickel-base alloy. The very high strength achievable with this alloy, the potential for welding the alloy into complex structures without the problem of strain-age cracking, and the complexity of the alloy all have led to this high level of interest by the various investigators. Heat-affected-zone microfissuring has been the topic of these studies most frequently dealt with. This is reasonable since dealing with sensitivity to heat-affected-zone microfissuring remains a key element in defining the welding process and heat-treatment cycle that can be applied. Even with the problem of sensitivity to heat-affected-zone microfissuring, alloy 718 represents the most weldable of the nickel-base superalloys. The development of the alloy represented a major advancement in metals technology.

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