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The Welding Metallurgy of Nickel Alloys in Gas Turbine Components

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The Welding Metallurgy of Nickel Alloys in Gas Turbine Components

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Abstract

Materials for gas turbine engines are required to meet a wide range of temperature and stress application requirements. These alloys exhibit a combination of creep resistance, creep rupture strength, yield and tensile strength over a wide temperature range, resistance to environmental attack (including oxidation, nitridation, sulphidation and carburization), fatique and thermal fatique resistance, metallurgical stability and useful thermal expansion characteristics. These properties are exhibited by a series of solid-solution-strengthened and precipitation-hardened nickel, iron and cobalt alloys. The properties needed to meet the turbine engine requirements have been achieved by specific alloy additions, by heat treatment and by thermal mechanical processing. A thorough understanding of the metallurgy and metallurgical processing of these materials is imperative in order to sucessfully fusion weld them. This same basic understanding is required for repair of a component with the added dimension of the potential effects of thermal cycling and environmental exposure the component will have endured in service. This article will explore the potential problems in joining and repair welding these materials.

Introduction

The gas turbine aircraft engine has evolved to its present form over the past 45 years. Because of the critical nature of the gas turbine engine, the materials used in its manufacture represent some of the most thoroughly tested and evaluated materials used in any application. New materials are exhaustively tested and evaluated before being introduced into an engine design. To meet the demanding stress, temperature and environmental requirements of the engine application, requires the science of the alloy developer and process metallurgist be pushed to the limit. Strengthening of these materials is achieved by the addition of solid solution strengthening elements to a nickel matrix (Ref 1). Nickel does not have a particularily high modulus of elasticity. It appears the ability of nickel to form solid solutions with a wide variety of elements without undue phase stability problems as well as its its tendency with the addition of chromium to form a chrome rich protective oxide leads to alloys which can be used up to 0.8 Tm (melting temperature). Solid solution strengthening is achieved by the addition cobalt, Iron, chromium, molybdenum, tungsten, aluminum and titanium. Alloying elements such as carbon, boron, magnesium and zirconium tend to segregate to the grain boundaries and significantly improve the hot workability, creep and creep rupture properties of these materials. The addition of aluminum, titanium, niobium and tantalum leads to the precipitation of a finely dispersed gamma prime phase in the gamma matrix. The precipitation of this phase leads to age hardening of the material with significant increases in strength.

Table 1 shows a representative list of the alloys which currently find application or have been used in gas turbine engines.

Table 1 (Ref 2)

Solid solution nickel base alloys
Hastelly N
Hastelloy S
Hastelloy X
Haynes 230
Inconel 600
Inconel 601
Inconel 617
Inconel 625

Precipitation hardenable nickel base alloys
GMR 235
Inconel 702
Inconel 706
IN 713C
In 738
In 739
Inconel 718
Inconel 722
Inconel X-750
Incoloy 901
M252
Rene 41
Udimet 700
Waspalloy
Haynes 214

Solid solution iron base alloys
16-25-6
17-14 CuMo
19-9 DL
Incoloy 800H
Incoloy 802

Precipitation hardenable iron base alloys
A286
Discolloy
Haynes 556
Incoloy 903
Incoloy 909

Solid solution cobalt base alloys
Haynes 25

Haynes 188
S-816

Effects of Metallurgy and Metallurgical Processing on Fusion Welding

We will limit comments to fusion welding, although it is understood that other processes such as resistance welding, brazing and solid state bonding are used to join materials for this application. Several weldability problems can develop when joining this group of alloys: fusion zone cracking, heat affected zone cracking and post weld heat treatment cracking.

Fusion zone and heat affected zone cracking

Solid solution strengthening elements, cobalt, iron, chromium, molybdenum, tungsten, aluminum and titanium have not been shown to adversely effect the weldability of these alloys. The addition of elements which segregate to the grain boundaries; boron, carbon, magnesium and zirconium, can have a significant effect on the resistance of materials to heat affected zone cracking and fusion zone cracking. These elements are essential to the hot working and creep and creep rupture ductility and therefore the high temperature strength of the materials. At least one or a combination of these elements are present in most of these alloys. Present individually, additions of boron at 0.005 wt. %; zirconium at 0.020 wt%; magnesium at 0.025 wt%, will generally not adversely effect heat affected zone or fusion zone cracking resistance. Alloy content much above these levels will result in fusion zone and heat affected zone microfissuring. The effects of these additions tend to be additive, therefore the individual addition element limits will be less when two or more elements are present in combination. Increased carbon content in combination with any of the other three addition elements will increase the sensitivity to heat affected zone and and to a lesser degree fusion zone cracking.

Heat affected zone cracking has been clearly linked to grain size in most of these alloys (Ref.4). Fine grain material, grain size less than ASTM #5, is less sensitive to heat affected zone micro fissures than coaser grain material, grain size larger than ASTM#5. Coarse grain size is desired for high temperature creep and creep rupture strength. It may result from the hot working finishing temperatures of the material being in the grain coarsening temperature range or final annealing temperatures in the grain coarsening solution annealing temperature range. Fine grain sizes are produced by lowering of the hot working finishing temperatures to a temperature at or slightly below the recrystallization temperature and/or careful selection of the subsequent final annealing temperatures. In addition to providing fine grain material the thermo mechanical processing can be used to significantly increase the strength of some alloys by retaining strain energy in the material. The welding thermal cycle will result in recovery and recrystallization in the weld heat affected zone and thus reduce the strength of the material in the weld heat affected zone.

Fusion zone cracking sensitivity can be adversely effected by trace elements such as sulphur and phosphorous: sulphur at the 0.010 wt% level and phosphorous at the 0.025 wt% level. These elements tend to be additive in their effect.

Post weld heat treatment cracking

Post weld heat treatment cracking (strain age cracking) is a problem associated with the age hardenable alloys. Increasing levels of aluminum and titanium and therefore volume percent gamma prime, increase the sensitivity to post weld heat treatment cracking (Ref. 4). While the fusion zone and weld heat affected zone cracking noted in the earlier discussion are of a micro nature, post weld heat treatment cracking can be much more extensive and destroy the usefulness of the fabricated components. There are at least two factors which lead to the cracking. Yield strength level residual stresses resulting from the welding thermal cycle are not relaxed sufficiently rapidly in highly creep resistant materials during the heat up portion of the heat treatment cycle, to avoid a short time stress rupture failure. Adding to the residual stresses, the stress developed by the rapid precipitation of gamma prime in the gamma matrix increases the problem.

Various methods have been used to heat treat materials prior to welding to avoid the strain age cracking problem. These heat treatments involve over aging the material thereby reducing its creep resistance and allowing stress relaxation to take place more readily. The welding operation is followed by a solution treatment and age hardening cycle which recovers the desired tensile, creep and creep rupture strength.

For materials with very high gamma prime volume fraction, such as cast IN 713C, fabricators have used a weld preheat temperature in or slightly above the gamma prime precipitation/coarsening temperature. The preheat temperature is maintained thoughout the welding operation and is increased to the solution annealing temperature without allowing the component to cool to room temperature. The solution annealing is followed by the aging heat treatment.

Alloys such as Inconel alloy 718 derive their aging response from additions of niobium. The aging response of this type alloy is sluggish in comparison the aluminum/titanium hardened alloys and tends to be far less susceptible to post weld heat treatment cracking problems. The ability to weld and direct age harden fabrications of Inconel alloy 718 has made this alloy very useful for gas turbine engine applications.

Effect of contamination on weld soundness

Fusion zone cracking can be a problem from contamination in the weld joint or in the vacinity of the weld joint. Heat affected zone cracking has been noted by in a number of instances when copper was inadvertently introduced on the surface of the alloy in the weld heat affected zone . If it is located in the weld heat affected zone, the copper will become liquid and result intergranular liquid metal stress cracking. Copper tooling provides an excellent heat sink and is commonly used for tooling and fixturing in mechanized welds.

While it would not seem reasonable to introduce lead into the weld joint, a number of instances can be sited where a lead hammer was used to "adjust" the fit up of a joint leaving lead residue to cause either or both weld fusion zone or weld heat affected zone cracking. Similar problems can be introduced by using either brass or copper hammers. Sulphur containing cutting fluids and other contamination regardless of the source must be removed prior to welding in order to avoid fusion zone cracking problems. Most of these materials are not prone to porosity if properly welded. Carboneous surface contamination can however, introduce damaging levels of porosity.

Repar Welding

The need for repair welding is frequently the result of thermal fatique cracking due to the thermal cycling the engine sees in service. This type of problem is most often encountered in the sheet metal ducting surrounding the engine. The damage is frequently associated with the high temperature areas of the sheet metal ducting although not necessarily limited to these areas. Repairs are accomplished by cutting the damaged section out of the assembly and welding a new replacement section into its place.

Wear from erosion and oxidation is a problem in the turbine section of the engine. The efficiency of the engine is decreased as the gaps between surfaces increase. These components are repaired by a number of different techniques including fusion welding. The damaged section of the component is not replaced with new material but rather metal is overlayed onto the component surface to allow re-machining to again establish the desired tight tolerances.

In these examples and in all cases where repair is being considered a detailed metallurgical understanding of the material is needed to determine whether repair will provide a component fit for service in the application.

The first issue of whether we should repair or replace hinges on the damage the particular component has suffered during operation. In the case of the thermal fatique damaged sheet metal it would be desirable to remove **all** of the damaged material. In addition to thermal fatique the service conditions may have resulted in nitridization, carburization, oxidation and/or sulphidation or can lead to the precipitation of low ductility phases such as sigma, laves phase, and intergranular carbide films. It is necessary to cleanly remove the damaged material and fit up the replacement section so that a quality repair weld can be made. Computer Numerical Controlled laser cutting has been used to facilitate removal and fit up of replacement sections. Good practice requires that root gas protection be provided for fusion welds. As noted, a clean surface free from contamination is imperative to assure quality welds.

In all repair welds it is important to understand the "mill" condition of the material as it was supplied and fabricated but in addition we need to know what thermo mechanical treatment(s) were applied during fabrication. As an example, a material might have been supplied and welded into a subassembly in a fine grain crack resistant condition. The subassembly was subsequently subjected to a high temperature brazing operation to join it to other components. The temperature of the brazing cycle caused caused grain growth and resulted in heat affected zone repair weld cracking sensitivity.

Summary

Understanding the metallurgical problems associated with joining the alloys used in gas turbine engines requires a detailed understanding of the metallurgical characteristics of each of these alloys. Most of the alloys are readily weldable, some however, require special procedures to achieve the desired results. Repair welding requires the same level of basic metallurgical understanding with the addition complications introduced by the service and service environment of the component.

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