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A Review Paper on Inconel alloys

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Abstract: Inconel alloys genrally known for corrosion resistantance to oxidation and their ability to maintain their structural integrity in high temperature atmospheres. There are several Inconel alloys that are used in applications that requires a material that requires a material that does not easily succumb to caustic corrosion, corrosion caused by high purity of water, and corrosion cracking. While each variation of Inconel has a unique traits that makes it effective in different circumstances, the majority of alloys are used frequently in chemical, aerospace industries. Welding Inconel alloys is difficult due to cracking and microstructural segregation of alloying elements in the heat affected zone. However, several alloys are have been designed to overcome these problems. The most common welding methods are gas tungsten arc welding and electron beam welding.

Introduction

Inconel alloys are oxidation-*corrosion*-resistant materials well suited for the extreme environments subjected to pressure and heat. When heated, Inconel forms a thick, stable, passivating oxide layer protecting the surface from further attack. Inconel retains strength over a wide temperature range, attractive for high temperature applications where aluminium and steel would succumb to creep as a result of thermally induced crystal vacancies. Inconel's high temperature strength is developed by solid solution strengthening or precipitation hardening, depending on the alloy.

Properties

- Corrosion performance is particularly suited to the sour environments of down – hole crude oil and natural gas wells.
- Very high strength, applicable to tooling applications and reducing suspended load of critical temperatures.
- Excellent resistance to stress corrosion cracking.
- Excellent resistance to pitting and crevice corrosion.

Applications

- Down hole equipment for corrosive/sour service such as valves, hangers, tool joints and packers.
- Marine and pump shafts.
- High strength fasteners.
- Chemical process industry components.

Inconel alloy types:

- Inconel 188: It is readily fabricated for commercial gas turbines and aerospace applications.
- Inconel 230: This plate is mainly used by the power, aerospace, chemical processing and heating industries, aerospace materials.
- Inconel 600: It is a solid solution strengthened.
- Inconel 617: It is a solid solution strengthened, high temperature strength, corrosion and oxidation resistant and high weld ability.
- Inconel 625: Acid resistant and good weld ability.
- Inconel690: It is a Low cobalt content for nuclear applications, and low resistivity
- Inconel 713C: It is a precipitation hard enable nickel – chromium base cast alloy.
- Inconel 718: Gamma double prime strengthened with good weld ability.
- Inconel X-750: It is used in gas turbine components, including blades, seals and rotors.
- Inconel 751: Increased aluminum content for improved rupture strength of 1600^0 F.
- Inconel 792: Increased aluminum content improved high temperature properties and used in gas turbines.
- Inconel 939: It is gamma prime strengthened to increase weld ability.
- Inconel 925: It is non stabilized austenitic stainless steel with low carbon content.

LITERATURE REVIEW

1. Friction stir welding of Inconel alloy 600

Author: Fuxing Ye.

The diameter of the probe was 6 mm and its length was 1.8 mm. The base material was a 2-mm-thick nickel-based super alloy (commercially called Inconel 600) with a melting point of 1630 K, and its nominal composition (wt.%) was 76.0 Ni, 15.5 Cr, 8.0 Fe, 0.25 Si, 0.50 Mn, 0.08 C and 0.008 S. welding speed of 1.67 mm/s and a tool rotation speed 400 rpm. The tool was tilted at 3^0.

Microstructure: Macro- and microstructures of the stir zone of the transverse cross section of the joint and the microstructure of the Inconel 600 base metal (BM) (Etched by HNO3 + HCl + H2O). No volumetric defect and kissing bond were observed within the joint. The stir zone was recrystallized and intergranular boundaries were not deeply etched. The measurement position was 1 mm from the surface of the test piece with an applied load of 200 gf at 0.25 mm intervals.

Conclusion:

The transverse failure of the joint occurred through necking outside the weld region, which also means that the tensile strength of the stir zone was greater than that of the BM. The fractured joint surface exhibited intergranular dimples and the fracture initiated mainly from the grain boundaries and the precipitation sites. The fractured FSW stir zone showed smaller dimples, which resulted partly from the smaller grain size in the stir zone. The yield strength of the high melting point materials is an indicator as friction stir weldability.

2. A Review on Super alloys and IN718 Nickel-Based INCONEL Super alloy

Author: Enes Akca, Ali Gursel

Inconel Alloy 600: (76Ni-15Cr-8Fe) is a standard material of construction for nuclear reactors, also used in the chemical industry in heaters, stills, evaporator tubes and condensers.

Nimonic alloy 75: (80/20 nickel-chromium alloy with additions of titanium and carbon) used in gas turbine engineering, furnace components and heat-treatment equipment.

Alloy 601: Lower nickel (61%) content with aluminium and silicon additions for improved oxidation and nitriding resistance chemical processing, pollution control, aerospace, and power generation.

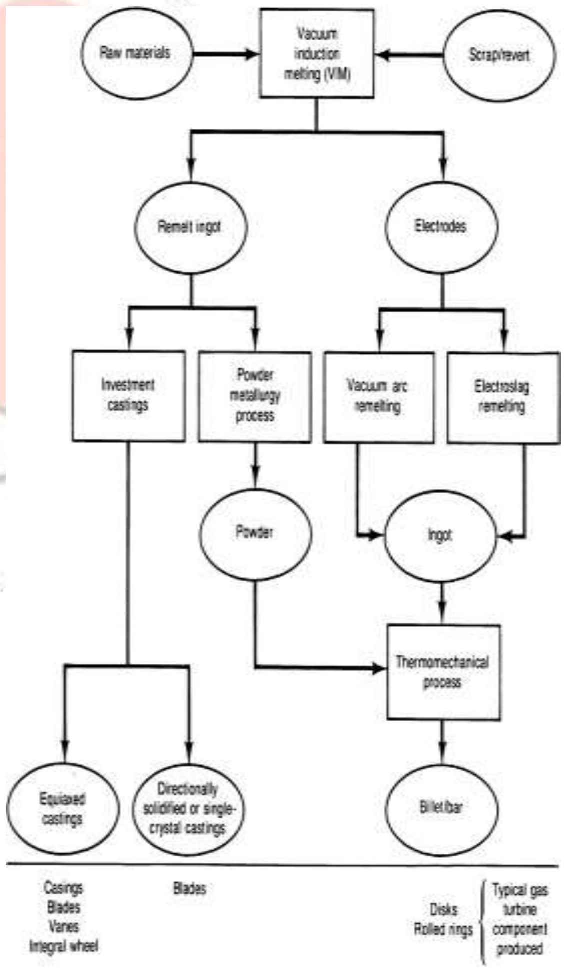
Alloy X750: Aluminium and titanium additions for age hardening. Used in gas turbines, rocket engines, nuclear reactors, pressure vessels, tooling, and aircraft structures,

Alloy 718: (55Ni-21Cr-5Nb-3Mo). Niobium addition to overcome cracking problems during welding. Used in aircraft and land-based gas turbine engines and cryogenic tankage.

- Alloy X (48Ni-22Cr-18Fe-9Mo + W):High- temperature flat-rolled product for aerospace applications.
- Waspaloy (60Ni-19Cr-4Mo-3Ti-1.3Al). Proprietary alloy for jet engine applications.
- ATI 718Plus:A lower cost alloy which exceeds the operating temperature capability of standard 718 alloy by 100 Fº (55 Cº) allowing engine manufacturers to improve fuel efficiency.
- Nimonic 90. (Ni 54% min Cr 18-21% Co 15-21% Ti 2-3% Al 1-2%) : used for turbine blades, discs, forgings, ring sections and hot-working tools.

o Rene' N6. (4Cr-12Co-1Mo-W6 -Ta7- Al5.8 - Hf 0.2 - Re5- Bal Ni): 3rd generation single crystal alloy used in jet engines,

- TMS 162 (3Cr- 6Co-4Mo-6W-6Ta-6Al-5Re-6Ru-Balance Ni) : 5th generation single crystal alloy for turbine blades.



Super alloy process flow chart

Conclusion:

A super alloy is a metallic alloy which is developed to resist most of all high temperatures, usually in cases until 70 % of the absolute melting temperature. All of these alloys have an excellent creep, corrosion and oxidation resistance as well a good surface stability and fatigue life.IN718 nickel-based super alloy which is the last version of Inconel 718 has been proceeding in the way to become a material that aerospace and defense industries are never replace of any other material with combining its good mechanical properties, easy machinability and of low cost.

3. Mechanical Properties of Friction-Stir-Welded Inconel 625 Alloy:

Author: Kuk Hyun Song, Kazuhiro Nakata

The material used in this study was an Inconel 625 sheet with size of 65mm*150mm*2mm and its chemical Composition in mass% was follows: Cr: 21.99%, Fe: 3.24%, Mo: 9.00%, Nb: 3.53%, C: 0.01%, MN: 0.10%, Si: 0.09%, S: 0.001%, Al: 0.18%, Ti: 0.32% and Ni-balance. FSW was carried out at a tool rotation speed of 200rpm and a traveling speed of 100mm/min and using a tungsten carbide cobalt (WC-Co) tool with a shoulder diameter of 15mm and a probe with diameter and length of 6mm and 1.8mm, respectively. In order to achieve good weld quality, the tool was tilted forward by 3^0.

Microstructures: To observe the macrostructures and microstructures of the welded materials, a solution consisting of 15ml HCl, 10ml CH3COOH3, and 5ml HNO3 was prepared. The surfaces of the samples were etched with solution after polishing them with abrasive paper. Furthermore, microhardness and tensile tests were carried out in order to investigate the mechanical properties of the alloy. The Vickers hardness test was carried out along the cross section of the weld zone using a load of 9.8N and a dwell time of 15s.

Conclusion:

Inconel 625, which is solid solution strengthened material because of the presence of Mo and Nb, was successfully welded using the FSW technique without the formation of any weld defects. In addition, the FSW resulted in the grain refinement of the alloy accompanied by an enhancement in its mechanical properties. In particular, the ultimate tensile strength of the FSW stir zone specimen was improved by more than 20% as compared to that of the base material. Therefore, Inconel 625 manufactured from Ni-based super alloys, which was extensively used in chemical power plants, and it can be used in commercial applications after being friction stir welded, because FSW causes an enhancement of its mechanical properties.

4.Microstructure IN718 and micro-texture evolution during large strain deformation of Inconel alloy

Author: Niraj Nayan a, N.P. Guraob, S.V.S. Narayan Murty

samples with dimensions of 15 mm (length) × 13 mm (width) × 12 mm (thickness) were fabricated from the hot rolled plate of IN718 super alloy. Using a thermo-mechanical simulator (Gleeble 3500) capable of controlling the specimen temperature, strain and strain rate, plane strain compression tests were performed. In order to conduct the test, specimens were heated to the desired temperature in the range of 950 °C to 1100 °C. Heating of the specimen was done at 5Ks−1 from ambient temperature to the specified temperature by direct resistance (Joule heating) and then compressed in a single stroke after soaking at the desired temperature for 60 s. The compressive deformation was carried out in the time periods of 1.38 s and 138sso as to impose nominal strain ratesof1s−1 and0.01s−1,respectively. Immediately after the deformation, the specimens were insitu water quenched. Post compression, specimens were cut from the sample by a slow speed diamond saw for optical microscopy and for EBSD analysis.

Conclusion:

IsothermalhotPSCtestsonInconel718toatruestrain dominantrole of dynamic recrystallization over at temperature range of 950–1100 °C and at strain rates of 0.01 and 1 s−1. Only the sample deformed at 950 °C and strain rate of 1 s−1 shows dynamic recovery. Thus at higher strains dominant in PSC, dynamic recrystallization regime is expanded in the temperature-strain rate space at the expense dynamic recovery regime. However, the complex state of stress and the role of twinning in dynamic recrystallization needs further investigation.

5. Mechanical properties of hot deformed Inconel 718 and X750

Author: A. Nowotnik

The cuboidal samples (20x10x20mm) were conductive heated to 1150°C at heating rate of 3°C/s, held for 300 s and finally cooled to the compression temperature. The temperature was controlled by a type K thermocouple inserted and welded in an opening hollowed out in the central part of the sample by spark erosion technique. Three additional thermocouples were used to acquire the distribution of the temperature from one of the faces to the centre of the specimen. A combination of graphite and molybdenum foils was used to reduce the friction between the anvils and the specimen as well as the gradient of temperature along the specimen. The deformation for all the tests was controlled by the stroke and measured by means of a load cells attached to the jaws. The tests were carried out in an argon atmosphere.

Tests: Compression tests were carried out on precipitations hard enable nickel based super alloys of Inconel 718 and X750 at constant true strain rates of 10-4, 4x10-4s-1 within temperature through which precipitation hardening phases process occurred (720-1150°C) using thermo mechanical simulator Gleeble and dilatometer Baehr 850D/L equipped with compression unit.

Conclusion:

High-temperature deformation of the examined Inconel alloys may possibly find some practical use in the workshop practice to predict a flow stress values, but only within a particular temperature and strain rate ranges. Dissimilar energy activation values obtained under various conditions (depending on a research centre) or for a variety of materials make impossible to do a direct comparison of measurements.

6. Microstructure and Mechanical Properties of Borided Inconel 625 Super alloy

Author: Ali Gunen

Prior to a boriding treatment, 40x40x5 mm rectangular samples were cut from 5-mm thick alloy sheet. All samples were ground using 1200 grit Sic paper and then washed in distilled water and ultrasonically cleaned in acetone for a 10 minutes. The samples were then packed with commercially Ekabor II powders in a stainless steel container. Boriding was performed at 800, 900 and 1200 ºC for 2, 4, and 6 h. Commercial Ekrit powders (finely ground Si C) were added a thin layer to minimize oxidation. After boriding, the steel container was removed from the furnace and allowed to cool in the open air.

The borided samples were cut to dimensions of 10×10×5 mm, cold mounted and then ground with up to 1500 grit Si C papers and polished with 0.25 μm alumina paste followed by 1μm diamond paste to obtain a good surface finish. The polished samples were then etched with a solution of 5 ml HNO3 ml, 10 CH3COOH ml and 15 HCI ml to reveal fine microstructural.

Microstructure: Metallographic studies were carried out using a Nikon MA-200 inverted metallurgical microscope equipped with Clemex Vision software. Scanning Electron Microscopy (SEM) studies were conducted using a JEOL JSM-5600 SEM equipped with Energy Dispersive Spectroscopy (EDS) capability, at 25 kV accelerating voltage. Microhardness values of boride layers were obtained by utilizing a Highwood HWMMT-X3 hardness tester using 100 g load and 15 s dwell time. Hardness measurements on silicide layers were made using 25 g load after cracking was observed at 100 and 50 g load.

Conclusion:

Inconel 625 Ni-based super alloy was pack borided efficiently at temperatures of 800 °C, 900 °C and 1000 °C for 2, 4 and 6 h durations. The coating layers produced the surface had a smooth morphology. The layer produced consisted of three zones:

- These zones, moving from the outer surface to the core were marked as the silicide layer, the multi-phase boride layer, the diffusion zone and substrate respectively.
- The application of the boriding treatment under Ar atmosphere has a positive effect on reducing silicide formation especially at high duration time (6h).
- Increase in boriding temperature and duration time did not only contribute to increase in microhardness v Both surface hardness and applied load were effective in changing the wear mechanism and wear resistance of the Ni-based Inconel 625 super alloy.

7. Microstructure and Phase of INCONEL Alloy 617

Author: W. L. MANKINS

Creep specimens were selected for the study because they would provide a close approximation of material exposed to temperature under load in actual service. The specimens were 0.252 in. diameter with a 2.25 in. gauge length. The maximum amount of plastic strain recorded for any specimen was 9.39 pct, and the creep curves indicated that none of the specimens had begun tertiary creep.

Microstructure: Samples for optical microscopy were prepared from the gage length of each creep specimen. The samples, about 0.250 in. (6.35 mm) diameter, were mounted, polished, and electro lytically etched at 10 V and 0.5 A in 80 pet phosphoric acid/20 pct of distilled water.

Conclusion:

INCONEL alloy 617 is used for its exceptional creep and rupture properties at temperatures in excess of 1800 of compares rupture properties of this alloy with those of INCONEL alloy 625. Unlike INCONEL alloy 625, which depends on a sluggish precipitation of Ni- and Cb-rich gamma prime for its strengthening, INCONEL alloy 617 achieves its strengthening through the precipitation of stable, discrete M~3C 6 carbides. It therefore maintains its strength in the temperature range (1400 to 1800) and (760 to 982) where gamma prime is in solution. From (1400 to 1600) and (760 to 871)~ the impact strength is improved, and this is to be expected in view of the microstructures that has been presented.

8. Processing and characterization of Inconel 625 Nickel base Super alloy

Author: R. K. Gupta

The progress of aerospace industry witnessed all over the world in the last few decades would not have been possible but for the major advancement in the high temperature materials area. Nickel based alloys assume prime role among the super alloys are used in aerospace systems. The principal characteristics of Nickel as an alloy base are

i) high phase stability of the face centred cubic (FCC) matrix, ii) high modulus of elasticity, iii) low diffusivity of secondary alloying elements at service temperatures and iv) greater solubility of alloying elements. The FCC structure being a close packed lattice, and offers more resistance to the time dependent deformation processes like creep and hence imparts high strength along with corrosion resistance at room temperature as well as elevated temperatures to the super alloys.

The alloy was processed through primary vacuum induction melting (VIM) followed by secondary electro slag refining (ESR) process. Nickel, chromium, carbon are charged in to the crucible, in atmospheric condition. A leak rate of 10 micron/ metre square was maintained. Once the melting starts at 20 Torr pressure & 17.0A melting current with 700 kW power, nickel and chromium are added twice to build the Ingot. To make the ingot chemically uniform, stirring was carried out for 1 to 2 minutes after addition of the alloying elements. This stirring was done automatically by induction method. De oxidation was done by maintaining argon flushing. Primary VIM ingot of diameter of 350 mm was melted to obtain a secondary ingot of 450mm Dia. Melting rate of 420 Kg+/- 20 Kg /hr was maintained in steady state. Generally during melting it varies anywhere from 520Kg/hr to 300 Kg/hr. Hot topping was carried out to avoid the pipe defects and bring homogeneity to the ingot. This was done by bringing down the current from 15.0 A to 11.0 A.

Conclusion:

Processing of Ni based super alloy Inconel 625 was carried out through vacuum induction melting followed by electro slag refining route. Forging/ rolling was carried out in the temperature range of 1070-1100°C. The material has resulted in grain size of the ASTM 4-7 confirming good amount of mechanical working in blocks of 50mm thick sections. The forgings were also meeting the AMS 5599 specification and NDT requirements specified and found suitable for the intended for end use.

9. A Review on Laser Powder Bed Fusion of Inconel 625 Nickel-Based Alloy

Author: Zhihua Tian

Inconel 625 (IN625) is a nickel-based super alloy. It mainly draws support from solution strengthening of some elements in the Ni–Cr matrix, such as Mo and Nb, to obtain high-temperature strength, high creep resistance. It also exhibits excellent corrosion resistance in various environment conditions and good weldability . However, due to its high hardness, low thermal conductivity, and high workhardeningrate,IN625 is considered as an alloy difficult to machining or subtractive processing. Machining tools are worn too fast and it is difficult to control the properties of IN625 in casting or forging. Therefore, new technologies are ingreatneed for manufacturing complex-shapedIN625parts, which are often demanded in aerospace industries.

Macroscopic:

The surface morphology of LPBF parts is related to the laser scanning process. In the work conducted by Li et al. the surface of the as-built IN625 sample presented a typical "V" shape morphology, which is similar to the situation in the welding process. The width of the melt track is about 100 μm, and the adjacent tracks overlap closely, resulting in nearly 100% density and almost no gaps. The "V" angle increases as the laser scanning speed decreases.

Conclusion:

Characterize the macroscopic defects and microstructure of as-built and post-treated IN625 alloy to deeply explore the formation mechanism of macroscopic defects (pores, micro cracks, balling, un-melted zone) and the microstructure evolution mechanism (grain boundary, second-phase, dislocation, sub grain boundary, stacking fault, etc.).Study the anisotropy and site-specific features of high and low-temperature performance(strength, fatigue,creep,corrosion,etc.).LPBFIN625alloy and clarify the reasons, especially the influence of macro anisotropy and microstructure anisotropy at the as-built and post-treated states on the above-mentioned properties. Establish models to predict the microstructure evolution and residual stress distribution of LPBF IN625 alloy, i.e., building the relationship between the LPBF parameters, microstructure, residual stress, and mechanical properties.

10. High Speed Machining of Inconel 718 Focusing on Tool Surface Topography of CBN Tool

Author: Tatsuya SUGIHARA

The experiments conducted using a CNC lathe (Mori Seiki Corp., Duraturn 2050) with high CBN content tool (CBN content: 93%, Grain size: 2 μm). The experimental setup is illustrated in Fig. 1. Inconel 718 pipe with thickness of 2 mm was used as a work piece. The orthogonal cutting experiments were carried out with three different cutting speeds (20, 100, 300 m/min) until cutting length reached 25 m. Soluble type cutting fluid (NEOS Co., Ltd., Fine cut 2500) was supplied in all those work pieces.

Work piece	Inconel 718	
Tool geometries	Rake angle Flank angle	5° 6°
Cutting speed	20 m/min 100 m/min 300 m/min	
Feed rate	0.1 mm/rev	
Cutting fluid Supply late	Soluble type (JIS A2) 6.1 L/min	

Conclusion:

At low cutting speed, the crater wear progresses by the cycle of adhesions of work piece material and their removals, and severe as wear occurs by flaking tool substrate when the adhesion is removed. At cutting speed of over 100 m/min, diffusion due to high cutting temperature is dominant factor for promoting crater wear, and the crater wear progresses proportionally to the cutting length. In high speed machining of Inconel 718, micro surface topography of CBN tool, such as grinding marks, has a strong correlation with the crater wear resistance. Experimental results clearly showed that a smoothing of tool surface is especially effective for extending the life of CBN tools in high speed machining of Inconel 718.

11. DETAIL INVESTIGATION OF MICROSTRUCTURES AND MECHANICAL PROPERTIES OF INCONEL 617 SHEET OF FIBER LASER WELDING

Author: Prabhat Kumar

A 400 W Fiber laser was used to weld the Inconel alloy 617. The spot diameter of the laser beam was 0.25 mm with focal length 30 mm. The Nitrogen (N2) gas was used as a shielding gas. The pressure of the Nitrogen (N2) gas was 3.0barthe parent material Inconel 617 of 1.5 mm sheet is used. Sheet was further cut into the section of 80 mm × 25 mm × 1.5 mm. Welding is performed by the single pass full penetration by fiber laser welding with nitrogen gas as a shielding gas. The welding parameters like welding power, welding speed are varied.

Microstructure:

The microstructure of the specimen were taken using field emission scanning electron microscopy (FESEM) at various zone i.e., weld zone, heat affected zone (HAZ) and base metal (BM). The uniform tree like structure was observed in Figure-3(a) and this tree like structure is known as dendrite structure in metallurgical term. The crystal of the material starts to minimize its areas where it has highest surface energy, therefore the structure become sharper as dendrite growth takes place more and more.

Hardness test:

The hardness distributions of the welded cross sections have been analysed using a Vickers micro-hardness tester with a load of 100 g. The micro-hardness test has been carried out at 200 micron on the surface beginning on the base metal to fusion zone to base metal. As a result, the hardness is found maximum at the centre of the weld zone and the melted and cooled material is remarkable as compared to the base metal due to its high cooling rate.

Conclusion: After EDAX analysis it is observed that the carbon and Sulphur content has been increased significantly in the weld zone.

i. Due to rapid cooling rate in this welding process the microhardness in the FZ is found to be higher than the microhardness in the HAZ and the BM.

ii. There is no solidification cracks were found in the fusion zone but some overheated point in HAZ was found.

iii. Whereas the decrease in average power decreases the heat input to the target increasing the hardness value.

12.Welding processes for Inconel 718- A brief review

Author: Jose Tom Tharappel

Inconel 718 is a super alloy with higher amount of nickel initially developed by Elseistein of International Nickel Company for use in wrought condition. Now this alloy has been extensively using in investment cast form in the manufacturing of hot-section components of aero engines, gas turbines, and other high-temperature applications mostly involving high temperature environment such as chemical and process industries, and nuclear reactors. This is due of its oxidation and corrosion resistance and relatively good strength at elevated temperatures [1-4]. Investment cast structures welded during their fabrication stage or for some weld repairs. Table.1 shows a typical chemical composition of this alloy. Inconel 718 alloy has outstanding weldability in both age hardened or annealed condition. However, this alloy has high resistant to strain-age cracking yet this alloy has still weldability problems such as micro fissuring and solidification cracking. Formation of Nb rich Laves phase which is a brittle intermetallic phase of Ni, Cr, Fe2, or Nb, Mo, Ti, in the inter dendritic region at the time of solidification is another main problem.

Conclusion:

Use of Inconel 718 is stretching due to its ability to maintain high strength at temperatures ranging from 450 to 700°C complimented by excellent oxidation and corrosion resistance and outstanding weldability in either the age hardened or annealed condition. However, alloy 718 is reputed to possess good weldability liquation cracking and weld metal cracking problems persist. Fusion zone cracking, liquation cracking (micro fissuring) are serious defects in Inconel 718 weldments. Researchers presented different wedging processes, heat treatment methods, selection of process parameters and alloying elements to minimize these defects. Laves phase are main culprits for liquation cracking and formation of this phases depends on initial grain size and composition of the base metal. Proper pre/post weld heat treatment minimises the Liquation cracking. Use of elliptical oscillation techniques can minimize the Nb segregation and Laves formation to minimize these defects.

Overall conclusion:

By studying all those papers we concluded that these Inconel alloys are mainly used in aerospace applications .And these alloys are corrosion resistant, Inconel retains high strength over a wide range of temperature applications. And these Inconel alloys temperature strength is developed by solid solution strengthening. And for finding hardness using Vickers hardness testing machine and for microstructure scanning electron microscope are used.

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