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Welding processes for Inconel 718- A brief review

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Abstract. Inconel 718 is being extensively used for high-temperature applications, rocket engines, gas turbines, etc. due to its ability to maintain high strength at temperatures range 450-700°C complimented by excellent oxidation and corrosion resistance and its outstanding weldability in either the age hardened or annealed condition. Though alloy 718 is reputed to possess good weldability in the context of their resistance to post weld heat treatment cracking, heat affected zone (HAZ) and weld metal cracking problems persist. This paper presents a brief review on welding processes for Inconel 718 and the weld defects, such as strain cracking during post weld heat treatment, solidification cracking, and liquation cracking. The effect of alloy chemistry, primary and secondary processing on the HAZ cracking susceptibility, influence of post/pre weld heat treatments on precipitation, segregation reactions, and effect of grain size etc. discussed and concluded with future scope for research.

1. Introduction

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 microfissuring and solidification cracking. Formation of Nb rich Laves phase which is a brittle intermetallic phase of Ni, Cr, Fe_2, or Nb, Mo, Ti, in the inter dendritic region at the time of solidification is another main problem. As Laves phases diminish the matrix of vital alloying elements and aid for favourable sites for crack initiation and its growth [5]. Detailed discussion on the weldability of this alloy was presented by Muralidharan et al. [6]. The main aim of this review is to present various welding process used by researchers for welding of Inconel 718 alloy and issues related to weldability of Inconel 718 strain age cracking, solidification cracking and the importance of post-weld treatments and alloying elements in fusion zone and HAZ intergranular cracking. Remaining part of this paper divided into a brief review on welding defects, processes used for welding of Inconel 718, finally conclusions and scope for future research in this area.

Table.1. Composition (Wt-%) of Inconel 718 [5]

Ni	Cr	Nb + Ta	Mo	Ti	Al	Si	C	Mn	S	P	Fe	B	Cu	Co
53	18.2	5.19	3.15	1.02	0.48	0.07	0.027	0.07	0.006	0.005	Bal	0.005	0.02	0.02

2. Welding Defects

2.1. Fusion zone cracking
Inconel 718 has sufficient fusion zone cracking resistance autogenously welded with gas-tungsten arc (GTA) process. However, it does not have sufficient resistance to fusion zone cracking to be useful as gas metal arc (GMA) filler metal. Heavy sections usually welded with multiple passes GMA welding filler metal. The cracking threshold strain for this alloy is difficult to define because fusion zone crack tends to backfill from molten weld pool.

2.2. Sensitive to Heat-Affected Zone (HAZ): Microfissuring/ Liquation cracking
Thermal cycle in fusion welding processes results in plastic strain in the HAZ of the weld [7]. Inter-granular microfissuring occurs in the HAZ, if the base metal does not accommodate this strain. The reason for this is liquation of grain boundary due to the segregation of elements to the boundary. In Inconel 718 alloy, carbides and Laves phase are main causes for this defect. Until now, the mechanism of heat affected zone microfissuring not fully understood. However, researches understood that sensitive to (HAZ) in the base metal is dependent on thermo- mechanical processing (grain size), the severity of the welding processes used chemical composition of base metal. Coarser grain sizes are more sensitive to microfissuring. Annealing in the suitable temperatures (955-982^o C) produces fine- grained microstructure, which minimize microfissuring sensitivity.

3. Effect of alloying components Laves phase
Laves phase is a size effect intermetallic of general formula A_2B. A represents element Ni/Cr/Fe and B represents elements Nb/ Mo/Ti/Si. A, elements are approximately 20-30% smaller than B elements. The smaller atoms are responsible better packing along a specific direction. This result a complex lattice structure composed of close packed layers of atoms with larger inter-planar spacing. Laves phases will form in Inconel 718 when alloying elements Nb, Mo, Ti, and Si exceed their solubility limit in the austenite matrix. Hence, selection of proper proportion of alloying elements in Inconel 718 is necessary to minimize the formation of Laves phases. This in turn minimizes the Microfissuring.

4. Welding Process for Welding of Inconel 718
This section presents the various welding process used by researches for welding of Inconel 718 with either similar or dissimilar metals, which is tabulated in Table.2. Most of welding studies focused on reducing the grain size and Laves phases to minimize the defects.

4.1. Laser Welding (LW).
Researchers used different variations of Laser welding process for welding of Inconel 718 which include CO_2 laser [4, 10, 11], Cross-flow CO_2 continuous laser [8], Pulsed Nd-YAG laser [9] and Fibre laser [12]. Shinozaki, et al. [4] studied the effect of welding parameters on laser weldability of Inconel 718. Their results show that optimum laser welding conditions without defects were 6 kW with 2.5m/min and 8 kW with 4.0 m/min for the fine-grain sized (ASTM #10) specimens. However, for the same welding conditions, on the heat-affected zone (HAZ) of large-grain sized (ASTM #4) specimens micro-fissures were observed.

Table 2(a). Welding process used by researchers for Inconel 718

Welding Process	Description	Base metals condition and thickness/Filler material	Comments	Ref

LW	CO_2 laser (3 kW)	Inconel 718, 2 mm thick Solution Treated condition	High heating rates during laser welding caused grain boundary liquation in the HAZ. This is the primary cause for liquation cracking.	4
	Cross-flow CO_2 continuous laser (900W)	Inconel 718	Deformation at high temperature. tension is favourable to improving the microstructures of the weld seam	8
	Pulsed laser	2 mm thick Inconel 718	PWHT of solution treatment at 980ºC resulted better weld properties due to drastic dissolution of Laves phases	9
	CO_2 laser welding	Inconel 718, 5 mm thick	Welding speed of 2.5m/min for 6 kW and 4m/min for 8 kW laser power at produced full penetration welds without defects for a plate having fine grain size ASTM#10.	10
	Fibre laser welding (1 kW)	Inconel 718& Ti-6Al 4V of 2 mm thick	Best weld quality with less hardness variation and cracks obtained when laser beam with offset of 35 μm from the interface.	11
EBW	EBW	Cast Inconel 718	Initial size of the grain size influenced the weldability of cast alloys and both equilibrium and non-equilibrium boron segregation; increase in grain size caused reduction in micro-fissuring.	12
	EBW (Oscillated)	Inconel 718	Elliptical oscillated welds resulted in reduced Nb segregation, increased response to aging and mechanical properties	13
	EBW	Aged and solutionised cast Inconel 718	Laves phase in welds effect impact toughness, controlling the fraction and size of these phases is very important.	14
	EBW	Inconel 718 solution treated condition	Fine grain size and either medium or high heat input provides minimum microfissuring in HAZ	15

Table 2(b).

Welding Process	**Description**	**Base metals condition and**	**Comments**	**Ref**

		thickness/Filler material		
GTAW	GTAW	Cast Inconel 718	HAZ cracking found in TIG welds is liquation cracking; Laves of Fe_2Nb, NbC, γ', and γ" phases were observed	15,16
	Pulsed Current GTAW	2 mm thick Inconel 718	Pulsed current mode improved solidification structure, Nb concentration amount and size, tensile properties and also response to PWST	5
	A-GTAW	Inconel 718	Use of activating fluxes increased penetration, weld depth-to-width ratio and reduced hot cracking susceptibility of welds	17-19
	GTAW	Inconel 718,625 with 310 S with fillers 310S, Inconel 82	Best filler choice is Inconel 82 to obtain good mechanical properties	3
	Continuous Current and Pulsed Current GTAW	Aged Inconel 718 and austenitic stainless steel AISI 316L/ ER2553 and ERNiCu-7	PCGTA weldments with ERNiCu-7 filler exhibited better metallurgical and mechanical properties	20
FW	Friction welding	Inconel 718 rods	Better tensile properties were obtained with Solution treatment and then aging PWHT condition	21,22
CMT and traditional MIG	CMT and MIG	Inconel 718	CMT produced smaller width of HAZ in comparison with MIG welding process, but brittle phases were observed in the weld zone	23

This leads to a conclusion that grain size plays a key role in liquation cracking. Janaki Ram et al. [10] showed that laser welding pulsed form, and post- weld heat treatments of solution treatment at 980°C resulted better weld properties due to drastic dissolution of Laves phase. Hui-Chi et al. [11] studied weldability of Inconel 718 to Ti-6Al-4V using fibre laser. They proved that defect free welds were obtained with an IPG 1 kW fibre laser of higher values welding speed and power of the laser. Feng-sheng et al. [8] studied the tensile properties of laser welding of ultra-fine grained Inconel 718 at elevated temperatures. They result revealed that fine and equi-axed dendrites in welding zone. They observed that in fusion zone has columnar and coarser grains with Laves phases. From the above studies, concludes that Laves phase are main culprits for liquation cracking. Formation of this phase depends on initial grain and composition of the base metal. Proper pre/post heat treatment minimizes the liquation cracking.

4.2. Electron Beam Welding (EBW):

Huang et al. [12] studied weldability of Inconel 718 in cast form using EBW with a focus of effect of grain Size. They reported first time that the increasing the size of the grains with in a particular range of 90–3000 μm shows better weldability. They related this improved weldability with the chance/probability of grain boundaries intersecting with welds. When grain size increases this probability decreases leads to the reduction in grain boundary microfissuring. They concluded that this behavior is applicable to only chosen alloy with chosen range of grain size. This demands further study with other alloys with different grain sizes for generalisation. Hyun et al. [17] presented the effect of post weld heat treatment (PWHT) on cryogenic mechanical properties of electron beam welded cast Inconel 718. They concluded that for better strength of weldments at cryogenic temperature PWHT is necessary. As the presence of Laves phase in welds effect Charpy impact toughness, controlling the fraction and size of these phases is very important. Agilan et al. [15] studied weldability Inconel 718 with different welding processes GTAW & EBW and different solutionizing temperatures, 970°C and 1050°C. His results revealed that fine grain size, and medium heat input minimized the microfissuring. Madhusudan Reddy et al. [13] conducted experiments to study the effect of electron beam with different oscillation techniques and PWHT on mechanical properties of Inconel 718 weldments. They found that lowest amount of Laves phases found in the elliptical oscillated beam fusion zone and the use of 980°C post weld solution treatment gave better tensile properties

From the above studies concludes that proper pre/post weld heat treatment, elliptical oscillation techniques can minimize the Nb segregation and Laves formation to minimize the defects.

4.3. Gas Tungsten Arc Welding (GTAW):

Researchers used different variations of GTAW welding process for welding of Inconel 718 includes: Continuous current [3, 16- 19], Pulsed current [20], Activated flux [17-19]. These studies conclude that pulsed current mode improved solidification structure, Nb concentration amount and size, improved tensile properties and also response to PWST. The use of activating fluxes increase penetration, weld depth-to-width ratio and reduce hot cracking susceptibility of welds. Both continuous [3] and pulsed current [20] GTAW process were studied for welding Inconel 718 with austenite stainless steel 310S and AISI 316L with different filler materials and concluded that Inconel 82 and ERNiCu-7 filler metals exhibit better weldments. Agilan et al. [15] compared the welding processes GTAW & EBW and concluded that rapid cooling rate was the cause for grain boundary liquation in EBW.

4.4. Friction Welding(FW):

Damodaram, et al. [21] presented the influence of PWST on both mechanical and microstructural properties of FW Inconel 718 weldments. PWHTs used in their study were; aging after welding, and welding followed by solution treatment and aging. They concluded that former PWHT is recommended for FW of Inconel 718 as later PWHT caused in increase in grain size 4 to 27 µm. Song and Nataka [22] presented similar conclusion that PWHT improved properties of weldments.

4.5. Metal Inert Gas Welding (MIG):

Benoit et al. [23] used Cold Metal Transfer, MIG welding process for welding of Inconel 718. Their results revealed that, however CMT gave smaller width of HAZ in comparison with MIG welding process, but brittle phases were observed in the weld zone.

5. Conclusion and Scope for Future Research

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 (microfissuring) 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. Most of researchers [7, 10 and 11] concluded that finer grains minimize the tendency of microfissuring. Huang et al [12] presented that increasing the grain size improves the weldability and related this improved weldability with the chance/probability of grain boundaries intersecting with welds. When grain size increases this probability decreases leads to the reduction in grain boundary microfissuring and this behavior is applicable to only chosen alloy with chosen range of grain size. This demands further study with other alloys with different grain sizes for generalisation. Control of process parameters in different welding processes and selection filler materials for welding of Inconel 718 with other materials is still a challenge and a great scope for research.

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