Weldability, Mechanical Properties and Microstructure of Nickel Based Super Alloys: a review

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Abstract. Welding of Nickel Based Super Alloys has been challenging due to the cracking and microstructure segregation of alloying elements. These super alloys are often used in extreme environments like in Turbine Blades, Boilers of Waste incinerators, Seals, Turbocharger rotors, high temperature fasteners, pressure vessels etc. The major application include Aerospace and Automobile Industry. The current paper will cover the relevant published work on welding processes and the challenges that were faced to weld nickel based super alloys. The review will go on to describe the weldability, microstructure and mechanical properties that are produced during and after the welding process. This paper will mainly focus on nickel based super alloys and poses many challenges which need to be focused and solved to produce an operational system in an acceptable time frame.

1. Introduction

Welding of Nickel based super alloys is a challenging job since it is exposed to high temperature and high corrosive environments. The weld that has been created must perform similarly to that of the base metal. The weldability addresses the issues that raise during welding, fabrication and the ability of the material to work properly in the environment. Most of the alloys possess very high tensile strength, yield strength and creep rupture properties up to high temperatures [1]. These alloys are used for high temperature applications where some materials would succumb to creep. These super alloys have high melting temperatures, high heat resistance and have good mechanical properties at high temperatures and thermal fatigue. They play a key role in gas turbine engines, aircraft, marine, industrial, nuclear, power plants and other high temperature applications. Nickel has a Face-Centered-Cubic(FCC) austenite structure and when alloyed with many other elements these would produce alloys with good and superior properties when compared with other materials [2].

Nickel is produced from the deposits of sulphide and laterite ores. These superalloys are so demanding that the industry have to look out for multiple options to find materials that are having high strength and higher material removal rates [3] and nickel based super alloys also have good mechanical properties and high temperature when compared with other superior materials. Fig 1 shows that almost 2/3rd of the super alloy production is used for aerospace applications [4].

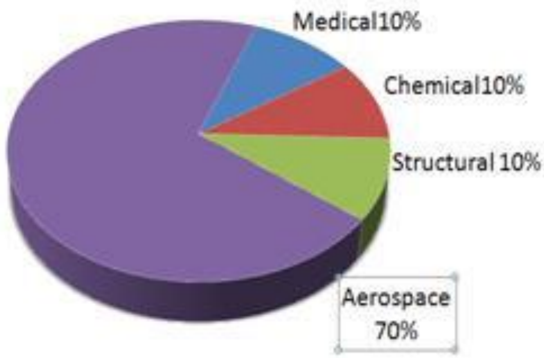

Fig 1: Nickel Based Superalloy Consumption [5]

Commercial Nickel and Nickel based super alloys have come into existence in 20th century and these materials are used in major industrial applications. Special metals corporation and Haynes international Inc have developed many alloys which can be used for high temperature

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applications and also corrosion resisting environment. Table 1 provides an overview of important nickel based super alloys and its commercial examples and also the weldability concerns of these alloys [6].

Table 1: Commercial Nickel Based Alloys and Main Weldability Concerns

Alloy family	*Alloy system*		*Commercial alloy examples*	*Main weldability concerns*
Corrosion-resistant	Solid-solution strengthened	Ni	Nickel 200	WM porosity
		Ni–Cu	400, K-500	WM porosity, solidification cracking
		Ni–Mo	B-2, B-3®	WM and HAZ corrosion
		Ni–Cr–Mo	G-35®, 59	WM and HAZ corrosion
		Ni–Cr–Mo–W	C-276, C-22®, 686	WM and HAZ corrosion
		Ni–Cr–Mo–Cu	C-2000®	WM and HAZ corrosion
		Ni–Mo–Cr	HYBRID-BC1®	WM and HAZ corrosion
High-temperature	Solid-solution strengthened	Ni–Fe–Cr	800H, RA330®, HR-120®	Liquation cracking
		Ni–Cr–Fe	600, 690	Ductility-dip cracking
		Ni–Cr–Fe–Mo	HASTELLOY X	Liquation cracking
		Ni–Cr–Mo–Nb	625, 625SQ®	Solidification cracking
		Ni–Cr–Co–Mo	617	Liquation cracking
		Ni–Cr–W–Mo	230®	Solidification and liquation cracking
		Ni–Co–Cr–Si	HR-160®	Solidification cracking
	Precipitation-strengthened	Ni_2(Mo,Cr)	242®, 244®	Solidification cracking
		γ'	Waspaloy, René 41, 282®	Strain-age cracking
		γ''	718, 718 Plus®	Solidification and liquation cracking
	Nickel aluminides	Ni_3Al	IC-25, IC-218	Solidification and liquation cracking
	Oxide-dispersion strengthened	Y_2O_3	MA754, MA6000	Oxide agglomeration/flotation
	Single-crystal superalloys	N/A	CMSX-4, TMS 162	Stray grain formation, solidification cracking

2. Classification of super alloys

The major applications are in the area where there are high temperature applications and high temperature components. The melting point of Nickel is very high (1453°C) and has a FCC crystal structure and is a ductile material. The super alloys in general can be categorised into nickel based, iron based and cobalt based which is shown in Fig 2. And they are further categorised into cast, wrought and powder metallurgy alloys. Nickel based super alloys contain nickel as the major constituent which is more than 50%. Out of the commercial nickel based super alloys, Inconel 718 is the most dominant one which is having more production when compared with rest of the other super alloys.

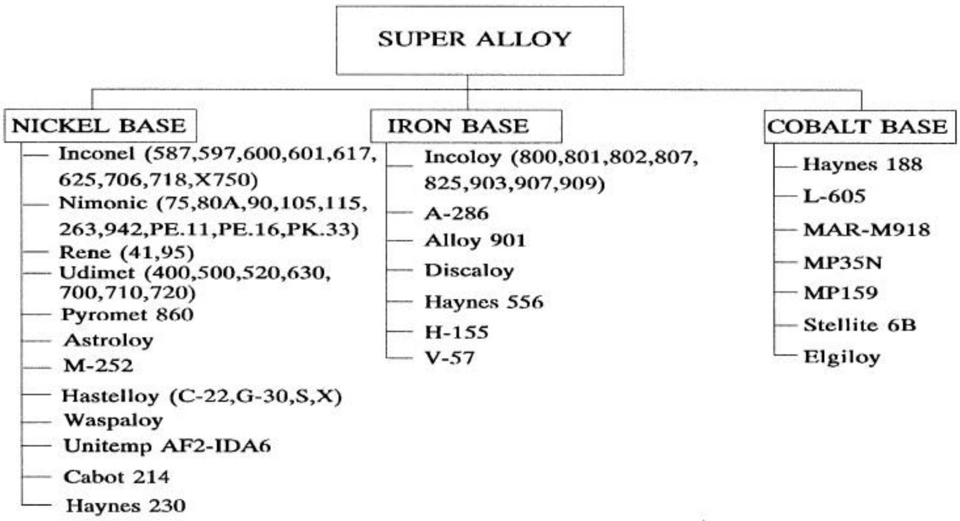

Fig 2: Classification of super alloys [7]

The alloys which were being developed for many years has always kept on increasing the high temperature resistance [8]. Most of the Nickel alloys are costly due to the presence of costly alloying elements. Most of the components which are developed are lighter in weight. The Weldability of these alloys will be discussed first and Mechanical Properties and Microstructures will be further discussed in the following sections.

3. Weldability

The main issues in weldability of nickel based alloys is that they have a tendency to develop hot cracking of crystallization and they may even develop in the transverse direction and form micro cracks [9]. Liquid phases are usually present on the grain boundaries, due to which hot cracks are created and also there is a decohesion of the metal due to shrinkages during the weld while it is getting cooled [10-16]. The nickel based super alloys is weldable and has a significant resistance to cracking [17]. Cleanliness is another important challenge during welding process, where the weld has to be defect free joint. The contaminants during the welding process is one of the major thing these contaminants can be of carbon, oxygen, sulphur etc.

Similar matching filler material is often used while welding these alloys. Nickel has a high thermal expansion coefficient which is in between low alloy steels and austenitic stainless steel. This is one of the reason why these alloys are used for dissimilar weld also to reduce residual stresses and strains in the joints [18]. A proper weld joint and a weld angle can be possible by using any of the cutting methods i.e mechanical or thermal. Before welding process the surface should be cleaned with any solvent. Some of the welding processes that have been already used for are gas tungsten arc welding(GTAW), submerged arc welding(SAW), metal inert gas welding(MIG), electron beam welding(EBM), laser beam welding(LBM) and Plasma arc welding(PAW). LBW and EBW are having an ability to make deeper welds and has very good production rates also. Some of the nickel super alloys weld joint designs are shown below in Fig 3.

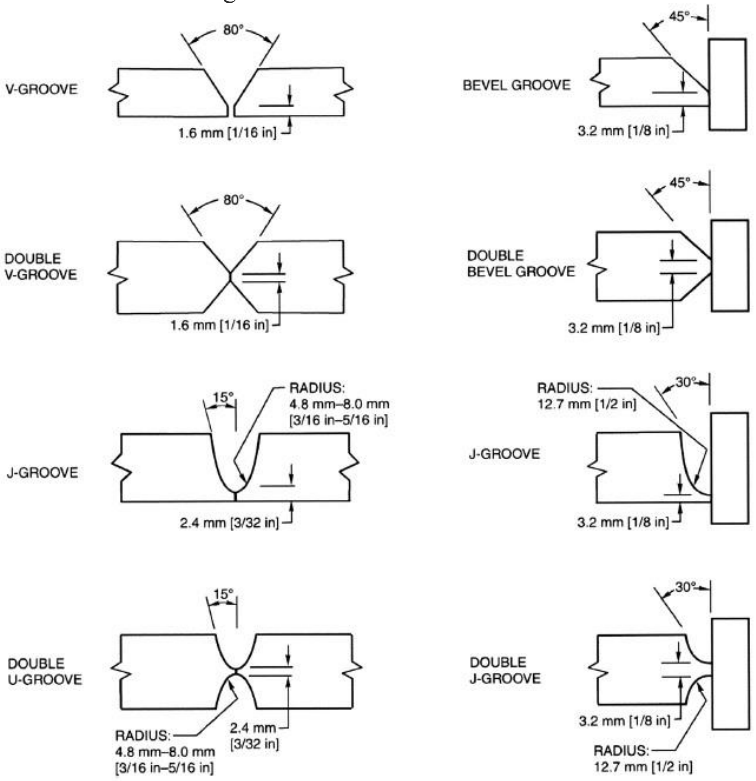

Fig 3: Nickel based super alloys weld joint designs

Selection of a welding processes is based on to improve the mechanical strength and metallurgical quality of the weld joints [19]. Conventional gas tungsten arc welding process can surpass the phenomena of hot cracking and mechanical properties, this can be done by using liquid nitrogen and spraying itw hile the welding process is going on [20], this will make the heat affected zone to be reduced drastically. It was also found out in pulsed GTAW the faster cooling rates has also developed microstructure for these alloys [21]. TIG welding is the best available methods for joining advanced nickel alloys and preferably it is used to weld Inconel 617 alloy due to high quality welds. [22, 23]. When welding advanced nickel alloys, it is always preferable to use as low heat input as possible to prevent welding incompatibilities, eg. crackings [22-25].

The other method which was employed for welding of nickel based super alloys was continuous current gas tungsten arc welding (CCGTAW) method, where nickel alloy Inconel 718 was welded with AISI 310 stainless steel [26]. The results have shown that by using suitable filler material(Inconel 82) the properties of the weld has improved. Damage at the HAZ mainly occured for the nickel alloy welds [27]. Based on the above investigation, TIG is proved to be one of the effective welding method for Nickel based superalloys which is because of the heat inputs that were provided and also better quality.

Electron beam welding is another process which is the most commonly used process for welding nickel based superalloys. It is a fusion welding process which can generate very high energy densities. At a very high beam power densities the deep welding effect occurs. Hot cracking of both liquation and crystallization type are some of the issues. Electron beam power has an important role to play during weldability of the joint, both the thickness and width of the remelted zone surface increases with increase in electron beam power [9]. EBM process should be carried out in vacuum environment and porosity can be one of the major issues of this welding processand it can also generate single layer welds with no filler material.

Laser Beam Welding is another process which is used to weld nickel based super alloys. This process has the ability to create narrow and deep penetration during the welding process. It also generated low heat input for a given depth of penetration. LBW and EBW processes are capable of producing better weld properties when compared with arc welding process and moreover these processes are best suited for those applications where arc welding is not possible. LBW and EBW processes can produce much higher thermal gradients that therefore it shortens the time period for solidification to occur [9].

Plasma Arc Welding is one of the other processes which is used to weld nickel alloys. During the welding process welding current and welding speed will have a major impact on bead geometry when compared with other process parameters like gas flow rate [28]. Most of these alloys are subjected to the formation of laves phase during the weld metal solidification [29]. This will effect the weld quality, lower heat input will form a high temperature gradient during solidification which therefore will result in higher cooling rates. Plasma welding process is one of the process which produces constricted arc of very high energy densities. The mechanical properties and microstructures of nickel based super alloys will be discussed in the following sections.

4. Mechanical Properties and Microstructure

Solid Solution Strengthening welds of nickel alloys which are used for corrosion resistance usually possess the mechanical properties which are similar to that of the base metal. Changing the grain sizes will result in various effects in regards with the different mechanical properties. The tensile properties are usually refrained by fine grain microstructure whereas creek and fatigue properties are optimised by coarse grain microstructure at elevated temperatures.

The chemical composition of nickel based super alloys creates a phase constitution, which inturn creates the microstructure changes. The allowable stresses for AUSC candidate nickel alloys are shown in the Fig 4. Fig 5 shows the graph between Creep rupture strength versus temperature of some of the common materials that are used in power plants. Power plants use austenitic steels and super alloys like Inconel 617 in the areas of highest temperature. These alloys usually contain 10% Mo, which is used to develop creep resistant ferritic steels. M. Bemani et.al [30] discussed about the factors affecting the mechanical properties of a certain nickel based super alloys using resistance spot welding, it had a major impact in the properties of the material and the mechanical properties were found to be improved by increasing the welding current.

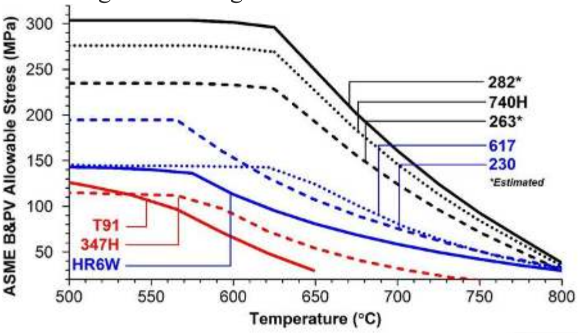

Fig 4: Allowable stresses for AUSC candidate nickel based super alloys [31]

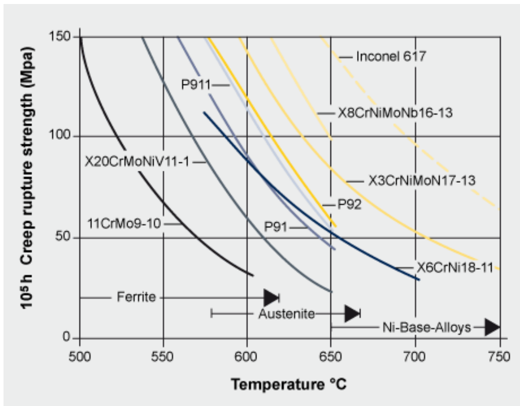

Fig 5: Creep rupture strength of some common materials used in power plants

Some of the properties that are achievable for the nickel based super alloys are shown below in the Table 4.

Table 2: Properties achievable for Nickel based super alloys

Nickel	Property
+ Aluminium, Titanium	High Temperature Strength
+Chromium, Iron, Molybdenum, Tungsten, Tantalum	High Strength
+ Boron, Carbon, Zirconium	Creep Resistance
+ Aluminium, Chromium,	Oxidation

Tantalum	Resistance
+ Hafnium	Intermediate Temperature Ductility

The major constituents or phases of the nickel based super alloys are

The Gamma Phase, γ is the solid solution of the alloying elements in Ni, at the temperatures nearing to the melting point. Elements like Chromium, Cobalt, Iron, Tungsten and Molybdenum in the Nickel based alloys does contain this phase as the matrix. Molybdenum and Tungsten were proved to be solid solution strengtheners in Nickel based super alloys. Most Nickel based superalloys would contain more Chromium than either Tungsten or Molybdenum or a combination of both, Chromium improves the strength of the Nickel matrix by solid-solution hardening. The FCC matrix present in it will be as a solvent for a multiple alloying additions. Fig 7 shows the microstructure of nickel based super alloys.

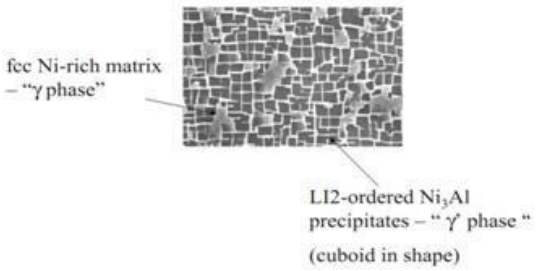

Fig 6: Microstructure of Nickel based super alloys [5]

The Gamma Prime Phase, γ' will form cubic crystal which will be subjected to slip and creep at elevated temperatures. Formation of these crystals increases after heat exposure and will continue to grow. Aluminum, Titanium and Niobium are added which have a tendency to form fine dispersion and precipitate FCC γ'. Cobalt will increase the solubility temperature of γ', so that the alloy can withstand maximum temperature where it can be used. Nickel based super alloys gain maximum strength through precipitation of gamma prime phase, which is an intermetallic phase based on Ni_3Al, Fig 8 shows the electronic images of secondary and tertiary γ' phases of nickel based super alloys.

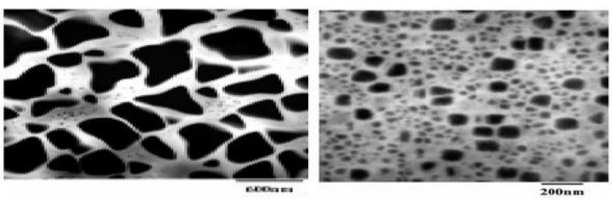

Fig 7: Secondary and Tertiary γ' phases in nickel based super alloys [5]

The Gamma Double Prime Phase, γ'' will form Body Centered Tetragonal(BCT) structure in which Nickel along with Niobium will combine in the presence of Iron. This phase will provide high strength at low temperatures and intermediate temperatures.

Carbide Phase, in most ferrous alloys, and even nonferrous alloy systems, carbide formations usually have adverse effects on mechanical properties. Any high temperature deformations present in the alloy will be stabilized when carbides are added. When they are subjected to high temperature, the effect on properties will be decided upon the amount of carbides present and the morphology ot it [32].

Minor Phases, in addition to the previous phases are also present in small quantities in these superalloys. Some of them are nitrides, carbonitrides borides and Laves phases. Sometimes we can also see some of the oxide precipitates in these superalloys but these are limited to only few specific type of super alloys. Hydrogen is also found in these alloys and it is present in solid solution. Nitrides are also observed usually in commercial superalloys [32].

Boron presence has shown to increase stress-rupture properties. It consists of boron and zirconium, which will improve the strengthening mechanism in the solution. σ-phase is also present and it is the hard and brittle phase. Presence of σ-phase in the alloy will usually tend to decrease the impact strength, creep strength and rupture life of the alloys. As the temperature decrease the ductility of the material does not decrease drastically [33]. Another phase that is usually found is the μ-phase which are present in some conditions only. Presence of these are also found to have lowered ductility and rupture strength in these super alloys.

5. Conclusions

The Weldability, Properties and Microstructure aspects of Nickel based super alloys has been discussed in this review paper. These alloys have good material properties like high corrosion resistance, high toughness, high heat resistance, resistance to thermal fatigue, good mechanical properties at elevated temperatures, high melting temperatures, creep and erosion.

The Quality of the weld of the Nickel based superalloys will depend upon various process parameters. The most suited welding processes are gas tungsten arc welding(GTAW), electron beam welding(EBW), laser beam welding(LBW) and plasma arc welding(PAW) processes. Nickel-based superalloys consists of intermetallic phases(γ'), carbides, and several other minor phases in a F.C.C matrix designated γ, minor phases which include borides, nitrides, carbonitrides, and, occasionally, relatively inert oxides.

Microstructure of these alloys which are in the heat-treated condition are metastable and when they are subjected to elevated temperatures it will approach equilibrium conditions. A detailed review has been presented and with the development of many more different alloys, there will be a wide range of applications for these alloys in the future.

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