Effect of frequency on Weldment and Microstructure of Pulsed TIG Welding of Inconel 718

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By

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ABSTRACT

Inconel 718 is the nickel based high strength super alloy suitable for service at temperature from (-252ºC) to (700ºC). It has been broadly used in components of gas turbines, nuclear plants and aircraft engines. Pulsed TIG welding is the main welding process adopted for welding of Inconel 718 alloy because of its welding quality and economy. Inconel 718 of 2mm thick plates was use as a base material.

If the base material is 2mm with single pass weld, pulsed TIG welding is preferred over conventional TIG welding process. The pulsed TIG welding parameters such as Peak current, Base current, Pulse on time, Frequency and Shielding gas are consider as the input parameters.

Inconel 718 is generally considered weldable, only in the context of PWHT cracking problem, which is known to occur in the age-hardenable Ni-base alloys containing 3 to 5% Al and Ti. The addition of Nb, which has averted the PWHT cracking problem, has rendered this alloy very much susceptible to hot cracking. The propensity of this alloy to such cracking has been a major persistent problem during the fabrication of sodium-water heat exchangers of fast breeder reactor steam generators. The cracking has been observed to occur in the HAZ as well as the weld metal.

ACKNOWLEDGEMENTS

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CHAPTER 1

1.1 Introduction

Inconel is a family of austenitic Nickel-Chromium based super alloy. Inconel alloys are oxidation and corrosion resistant materials well suited for service in 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 aluminum 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.

Inconel 718 is a precipitation hardenable nickel-based alloy designed to display exceptionally high yield, tensile and creep-rupture properties at temperatures up to 1300°F. The sluggish age-hardening response of Inconel 718 permits annealing and welding without spontaneous hardening during heating and cooling. This alloy has excellent weldability when compared to the nickel-base superalloys hardened by aluminum and titanium. This alloy has been used for jet engine and high-speed airframe parts such as wheels, buckets, spacers, and high temperature bolts and fasteners.

Inconel is often encountered in extreme environments. It is common in gas turbine blades, seals, and combustors, as well as turbocharger rotors and seals, electric submersible well pump motor shafts, high temperature fasteners, chemical processing and pressure vessels, heat exchanger tubing, steam generators and core components in nuclear pressurized water reactors, natural gas processing with contaminants such as H_2S and CO_2, firearm, sound suppressor, blast baffles, and Formula One, NASCAR, NHRA, and APR, LLC exhaust systems.

It is also used in the turbo system of the 3rd generation Mazda RX7, and the exhaust systems of high powered rotary engined Norton motorcycles where exhaust temperatures reach more than 1,000 degrees C. Inconel is increasingly used in the boilers of waste incinerators. The Joint European Torus and DIII-D (fusion reactor) tokamaks vacuum vessels are made in Inconel. Inconel 718 is commonly used for cryogenic storage tanks, downhole shafts and wellhead parts.

1.2 Composition of Inconel 718

Table 1: Composition of Inconel 718

Element	Min (%wt)	Max (%wt)
Nickel	50	55
Chromium	17	22
Iron	-	17
Niobium	4.75	5.5
Molybdenum	2.8	3.3
Titanium	0.65	1.15
Cobalt	-	1
Copper	-	0.3
Aluminum	0.2	0.8
Traces of Boron, Carbon, Phosphorus, Sulphur and Silicon		

1.3 Properties of Inconel 718

Inconel alloys are oxidation and corrosion resistant materials well suited for service in extreme environments subjected to high pressure and kinetic energy. When heated, Inconel forms a thick and stable passivating oxide layer protecting the surface from further attack. Inconel retains strength over a wide temperature range, attractive for high-temperature applications where aluminum 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 strengthening, depending on the alloy. In age-hardening or precipitation-strengthening varieties, small amounts of niobium combine with nickel to form the intermetallic compound Ni_3Nb or gamma prime (γ'). Gamma prime forms small cubic crystals that inhibit slip and creep effectively at elevated temperatures. The formation of gamma-prime crystals increases over time, especially after three hours of a heat exposure of 850 °C, and continues to grow after 72 hours of exposure.

Density: - 8220 kg/m^3
Melting Range: - 1210 to 1344 ºC
Electrical Resistivity: - 1210 microohm-mm
Modulus of Elasticity (E): - 208 x 10^3 MPa at room temperature

0.2% Yield Strength: - 1172 MPa at 200 ºF
Ultimate Tensile Strength: - 1407 MPa at 200 ºF

1.4 Heat Treatment of Inconel 718

Inconel 718, a FCC solid solution of Ni, Cr and Fe (γ, the matrix) is strengthened primarily by the coherent strains produced in its matrix by γ'' and γ' phases, γ'' is the main strengthening phase having a BCT crystal structure of the type Ni_3V. It is a solid solution rich in Nb having a formula $Ni_3(NbAlTi)$, while γ' has a FCC structure and is rich in Al having a formula $Ni_3(AlTiNb)$.

It is known from several studies that both high temperature solution annealing (1065 -1093°C) and age hardening (625-650°C) treatments promoted susceptibility of Inconel 718 to intergranular cracking. But a low temperature solution annealing at 927°C was found to greatly diminish intergranular cracking. Spot Varestraint crack measurements have shown that the solution annealed material (927°C) had better crack resistance than the high temperature solution annealed (1065-1093°C) and age hardened (625-650 ºC) materials.

The Inconel 718 sample of 2mm thickness was subjected to following heat treatment cycle

- Heating to 980 degree Celsius and soaking it for 8 hours.
- The specimen is then subjected to ice brine quenching till room temperature.
- Heating it again to 720 degree Celsius and soaking it for 8 hours.
- Temperature is reduced to 620 degree Celsius at the rate of 55 degree Celsius per hour.
- The specimen is allowed to be soaked at 620 degree Celsius for 8 hours.
- After 8 hours of soaking at 620 degree Celsius, the sample is furnace cooled to room temperature.
- Heat Treatment is done according to ASTM B637.

1.5 Phases formed during Heat Treatment

The application of heat treatment, by solid solution and precipitation hardening, is very important to optimize the mechanical properties of super alloys. The main phases present in Inconel 718 are: gamma prime γ′ face ordered $Ni_3(Al, Ti)$; gamma double prime γ″ bct ordered Ni_3Nb; eta η hexagonal ordered Ni_3Ti; delta δ orthorhombic Ni_3Nb intermetallic compounds and other topologically closed-packed structures such as μ and Laves phases.

The heat treatment applied to Inconel 718, precipitation hardening, has two steps: solid solution and aging treatment. In first step the secondary (hardening) phases are dissolved along the matrix, as well as carbides. It is important to note that after 650 °C and with long exposure times, γ″ transforms in the stable phase δ, which results in a loss of mechanical resistance.

The γ'' and γ' phases have distinctly different morphologies which help in their easy identification, γ'' precipitates are round shaped and about 20 nm in size while γ' precipitates are disc like with an aspect ratio of 5-6. 5 phase is mostly found as plates growing on the (111) planes or found nucleating on the grain boundaries.

The other phases which are found in Inconel 718 include carbides like Nb(Ta)C, TiC and M_6C, TiN, Laves and sigma. The Nb(Ta)C, TiC and TiN phases are inert while the Laves and sigma phases are brittle intermetallics detrimental to mechanical properties. These phases offer an ideal plate like morphology for easy initiation and propagation of fracture. Moreover they take away Nb from the matrix and hinder effective γ'' precipitation from occurring. Added to these undesirable features, these phases produce incipient melting and porosity during high temperature processing as they have a lower melting point than the matrix. They have a crystal structure characterized by close packed layers of atoms separated from one another by relatively large interatomic distances and are usually referred to as topologically close packed (TCP) phases. The Laves phase is a size effect intermetallic and has a chemical formula given by $(Fe,Ni,Cr)_2(Nb,Ti)$. The atoms of Fe, Ni and Cr are smaller and enable better packing with larger atoms of Nb and Ti.

1.6 Strength of the material post heat treatment

Surface hardness test was done on the sample post heat treatment using Rockwell Hardness C Scale. The following are the result of the hardness obtained.

Table 2: Hardness of the sample post heat treatment

SAMPLE 1			SAMPLE 2	
Test 1	54.5 HRC		Test 1	52 HRC
Test 2	61 HRC		Test 2	62 HRC
Test 3	61 HRC		Test 3	47 HRC
Test 4	53 HRC		Test 4	52 HRC
Test 5	56 HRC		Test 5	59 HRC
Test 6	57 HRC		Test 6	54 HRC
Average	57 HRC		Average	53.33 HRC

γ'' is the main strengthening phase having a BCT crystal structure of the type Ni_3V. It is a solid solution rich in Nb having a formula $Ni_3(NbAlTi)$, while γ' has a FCC structure and is rich in Al having a formula $Ni_3(AlTiNb)$.

CHAPTER 2

2.1 Introduction to Welding of Inconel 718

Inconel 718, a Ni base super alloy, was developed by Eiselstein of International Nickel Company, initially for use in the wrought condition. Now it is also used in investment cast form in great amounts as gas turbine blades because of its retention of high strength at temperatures ranging from 450 to 700°C complimented by excellent oxidation and corrosion resistance.

The excellent mechanical strength is attributed to the strengthening effect due to the precipitation of a unique Ni_3(NbAITi) phase. Since all investment castings are welded during their fabrication at one stage or the other and may also require some weld repair later, it is important that the material be easily weldable and free of cracking problems. It is in this context, Inconel 718 has gained recognition and its arrival, in fact, heralded the first weldable precipitation hardened super alloy.

One property unique to alloy 718 is its outstanding weldability in either the age hardened or annealed condition. While all the predecessor alloys of 718 could easily be welded in sheet-metal thicknesses, they suffered from strain-age cracking during welding or in the post weld aging treatment. These cracks were found in the heat affected zone (HA2) of the weldments. This is attributed to the fact that the majority of the super alloys contain 3 to 5 % (Al + Ti) and are strengthened by Ni_3(AITi) phase. This precipitation which is very effective in strengthening develops cracks in HAZ during welding as it forms very rapidly and reduces ductility.

This problem is avoided in Inconel 718 due to the delayed aging response when Nb is added to the base composition, while keeping rather low levels of Al and Ti compared to other super alloys. This addition of Nb results in the formation of a strengthening precipitate, Ni3(NbAITi) (γ''), distinctly different in morphology, composition and crystal structure from Ni3(AITi) (γ′). The sluggish age hardening response off improves the resistance to strain age cracking in Inconel 718 and enables to exploit the useful properties of this material in the welded condition.

Figure 1: TiG Welding Setup

2.2 Pulsed TiG Welding of Inconel 718

Inconel is a lightweight nickel- and chromium-based alloy used in a number of critical applications for its resistance to corrosion, as well as its ability to maintain its strength even when subjected to high temperatures.

There are two primary welding methods for welding Inconel: Gas Tungsten Arc Welding (GTAW, or TIG) of structural Inconel components, and Inconel cladding as made possible by the Gas Metal Arc Welding (GMAW, or MIG) process.

One common theme ties both practices together, however, and has benefited from recent technology advances: pulsed welding. In addition to the evolution of pulsing technologies, new features and capabilities of welding equipment have helped improve the processes and given operators more flexibility in dialling in the arc to work for them.

Inconel, like many nickel-based alloys, is highly susceptible to cracking and warping especially thin structures. As such, controlling heat input to the part is important, as well as controlling arc starts, providing proper shielding gas protection and averting crater formation at the end of the weld.

In the pulsed-current mode, the welding current rapidly alternates between two levels. The higher current state is known as the pulse current while the lower current level is called the background current. During the period of the pulse current, the weld area is heated and fusion occurs. Upon dropping to the background current, the weld area is allowed to cool and solidify. Pulsed-current TiG has a number of advantages, including lower heat input and consequently a reduction in distortion and warpage in thin workpieces.

In this project TiG welding is done with following constant welding parameters:

- Peak Current 90 A.
- Background Current 15 A.
- Welding Speed 6mm/sec.
- Shielding Gas Argon at 15l/min.

Figure 2: Sample after welding

As we are going to study the effect on the weldment, HAZ and base metal due to the change in frequency of pulsed TiG welding. The test is conducted on two different ranges of frequencies

Low range frequencies compromises of 2- 10 Hz with an interval of 2 Hz and the high range frequencies compromises of 100-500 Hz with an interval of 100 Hz.

- Low frequency range (2Hz, 4Hz, 6Hz, 8Hz, 10Hz).
- High frequency range (100Hz, 200Hz, 300Hz, 400Hz, 500Hz).

2.3 Macrostructure of the Weldament

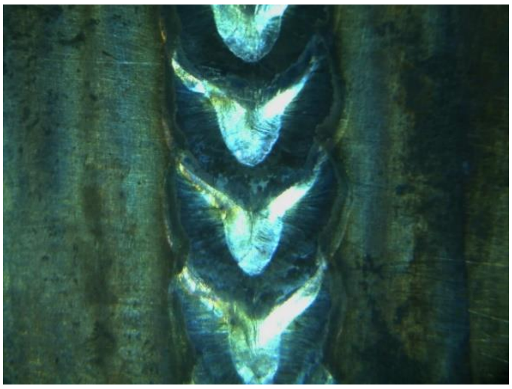

Figure 3: Frequency **2Hz**

Figure 4: Frequency **4Hz**

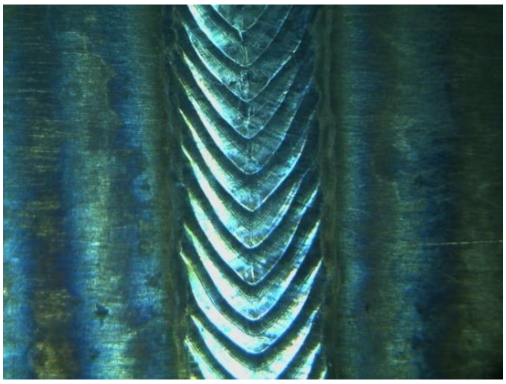

Figure 5: Frequency **6Hz**

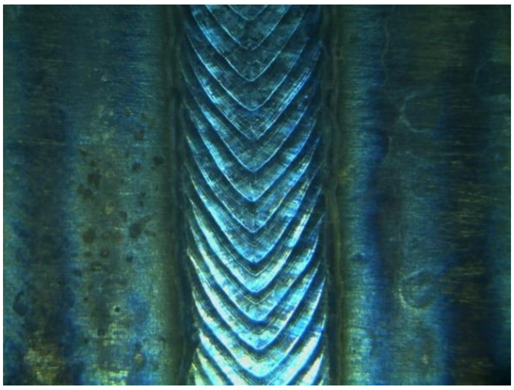

Figure 6: Frequency **8Hz**

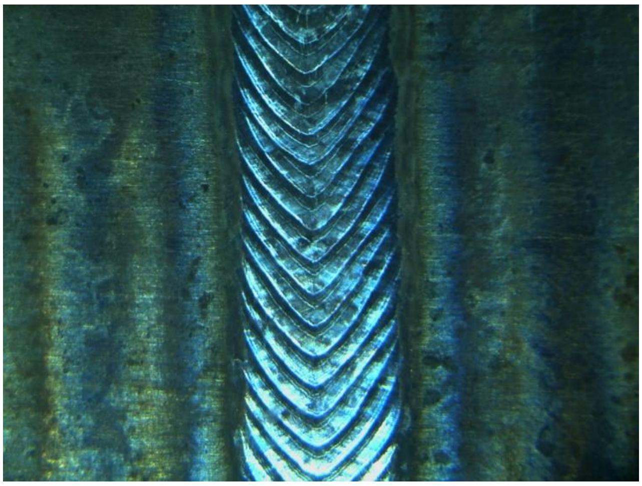

Figure 7: Frequency **10Hz**

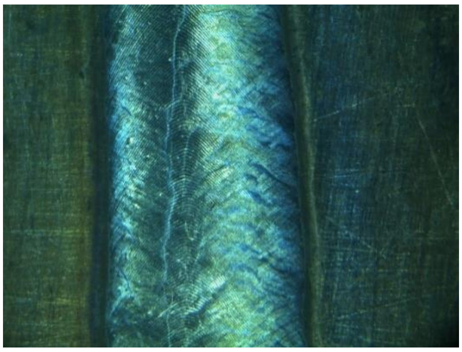

Figure 8: Frequency **100Hz**

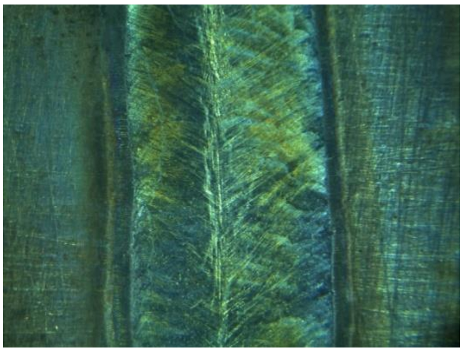

Figure 9: Frequency **200Hz**

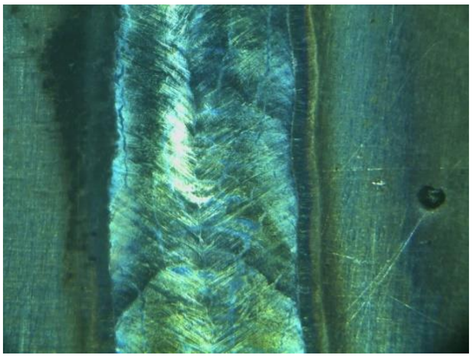

Figure 10: Frequency **300Hz**

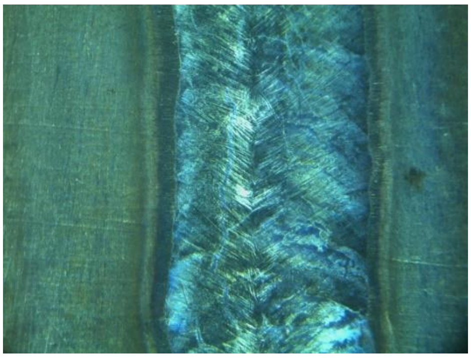

Figure 11: Frequency **400Hz**

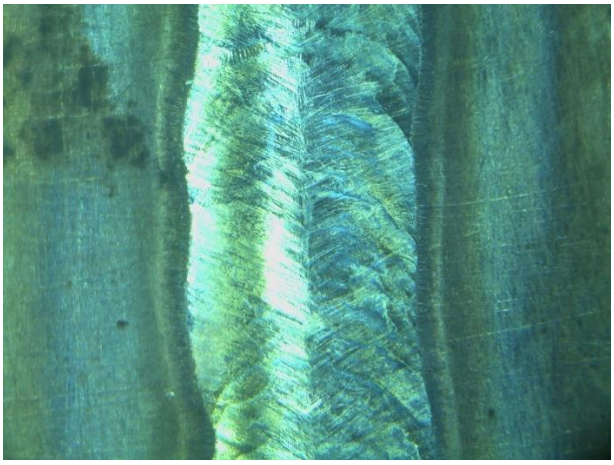

Figure 12: Frequency **500Hz**

2.4 Problems faced during TiG welding of Inconel 718

The main problems that occur during TiG welding of IN 718 alloys are

1. Poor penetration during welding.
2. Micro fissuring in the heat affected zone.
3. Poor impact and ductility properties of the weld fusion zone.

2.4.1 Poor penetration during welding

The one problem always encountered was the difficulty of obtaining good penetration with the root pass. This is encountered in most nickel-base alloys and is due to the poor fluidity of the molten metal.

Penetration may be defined as joint penetration or root penetration. Joint penetration is the minimum depth a groove weld extends from its face into a joint, exclusive of reinforcement. Root penetration is defined as the depth a groove weld extends into the root of a joint measured on the centre line of the weld cross section.

Penetration was influenced by the following four factors:

- shielding gas
- groove geometry
- root gap
- heat input

2.4.2 Micro fissuring in the heat affected zone.

Another problem encountered in welding Inconel 718 was microfissuring in heat affected zone. Microfissures are fine cracks which is usually only 1 or 2 grains in length,that form in the heat affected zone of the weld adjacent to the fusion zone. These cracks are intergranular and seem to form along the boundaries of the partially melted grains close to the fusion zone. The solution treatment temperature before welding has an important influence upon microfissuring susceptibility.

Figure 13: Microfissure in IN718 weldament. Mag 1000X [4]

2.4.3 Poor impact and ductility properties of the weld fusion zone

A further problem encountered in the welding of Inconel 718 was development of adequate ductility in the weld. The results of the welding clearly show that the ductility and impact properties of the weldments were poor in comparison to the base metal. The white phase formed in the inter dendritic regions of the weld metal was identified by its appearance and by electron probe microanalysis as the Laves phase, and it is this phase that is thought to be responsible for embrittlement that occurs in Inconel 718 weldments.

CHAPTER 3

3.1 Electro Discharge Machining

Electro Discharge Machining (EDM) is an electro-thermal non-traditional machining process, where electrical energy is used to generate electrical spark and material removal mainly occurs due to thermal energy of the spark.

EDM is mainly used to machine difficult-to-machine materials and high strength temperature resistant alloys. EDM can be used to machine difficult geometries in small batches or even on job-shop basis. Work material to be machined by EDM has to be electrically conductive.

In EDM, a potential difference is applied between the tool and workpiece. Both the tool and the work material are to be conductors of electricity. The tool and the work material are immersed in a dielectric medium. Generally kerosene or deionized+-+ water is used as the dielectric medium. A gap is maintained between the tool and the workpiece. Depending upon the applied potential difference and the gap between the tool and workpiece, an electric field would be established. Generally the tool is connected to the negative terminal of the generator and the workpiece is connected to positive terminal. As the electric field is established between the tool and the job, the free electrons on the tool are subjected to electrostatic forces. If the work function or the bonding energy of the electrons is less, electrons would be emitted from the tool (assuming it to be connected to the negative terminal). Such emission of electrons are called or termed as cold emission. The "cold emitted" electrons are then accelerated towards the job through the dielectric medium. As they gain velocity and energy, and start moving towards the job, there would be collisions between the electrons and dielectric molecules. Such collision may result in ionization of the dielectric molecule depending upon the work function or ionization energy of the dielectric molecule and the energy of the electron. Thus, as the electrons get accelerated, more positive ions and electrons would get generated due to collisions. This cyclic process would increase the concentration of electrons and ions in the dielectric medium between the tool and the job at the spark gap. The concentration would be so high that the matter existing in that channel could be characterized as "plasma". The electrical resistance of such plasma channel would be very less. Thus all of a sudden, a large number of electrons will flow from the tool to the job and ions from the job to the tool. This is called avalanche motion of electrons. Such movement of electrons and ions can be visually seen as a spark. Thus the electrical energy is dissipated as the thermal energy of the spark. The high speed electrons then impinge on the job and ions on the tool. The kinetic energy of the electrons and ions on impact with the surface of the job and tool respectively would be converted into thermal energy or heat flux.

Such intense localized heat flux leads to extreme instantaneous confined rise in temperature which would be in excess of 10,000 ^{o}C. Such localized extreme rise in temperature leads to material removal. Material removal occurs due to instant vaporization of the material as well as due to melting. The molten metal is not removed completely but only partially.

Thus to summarize, the material removal in EDM mainly occurs due to formation of shock waves as the plasma channel collapse owing to discontinuation of applied potential difference.

3.2 Hot mounting

Hot mounting takes place under pressure in a mounting press, where the specimen is placed in a cylinder together with the appropriate mounting resin. A temperature of up to 200°C, and a pressure of up to 50kN are then applied during the embedding of the specimen.

The resin used for Inconel 718 sample is Bakelite and the following steps are involved in the hot mounting of the sample

- It is subjected to the temperature of 117 ^{o}C.
- Then allowed to soak for a time period of 10 mins.
- Finally left to cool down for 10 mins.

Figure 14: Hot mounted sample

3.3 Electro polishing

Electro polishing is an electrochemical process that removes material from a metallic work piece. Typically, the work-piece is immersed in a temperature-controlled bath of electrolyte and serves as the anode; it is connected to the positive terminal of a DC power supply, the negative terminal being attached to the cathode.

A current passes from the anode, where metal on the surface is oxidized and dissolved in the electrolyte, to the cathode. At the cathode, a reduction reaction occurs, which normally produces hydrogen. Electrolytes used for electro polishing are most often concentrated acid solutions having a high viscosity.

Initially the sample is etched with Kalling's No.2 etchant ($CuCl_2$ + HCl + ethanol) and the resulted grain structure of HAZ is not clear. Hence electro polishing is done for obtaining a better microstructure of the Inconel 718.

Electro polishing of Inconel 718 is done with 0.1M oxalic acid as the electrolyte and the sample is immersed in the oxalic acid and a time of 10 sec is given for etching.

Figure 15: Electro polishing

3.4 Microstructure

The etched samples were observed under optical microscope at 200X magnification. The following are the microstructure of the samples welded with different pulsed frequencies.

Microstructure of sample welded at 2Hz

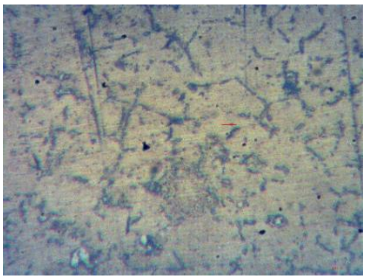

Figure 16: Base metal

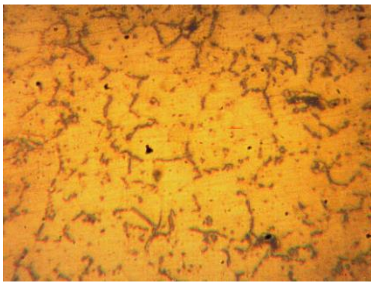

Figure 17: HAZ

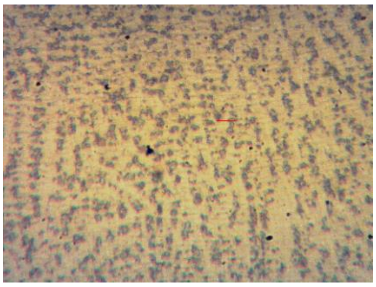

Figure 18: Weld

Microstructure of sample welded at 4Hz

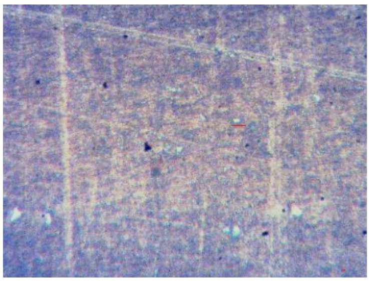

Figure 19: Base metal

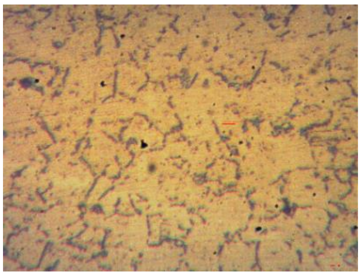

Figure 20: HAZ

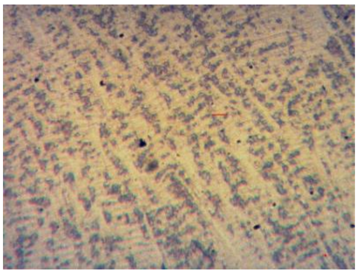

Figure 21: Weld

Microstructure of sample welded at 6Hz

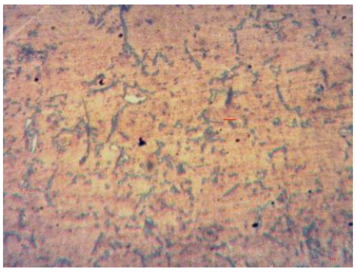

Figure 22: Base metal

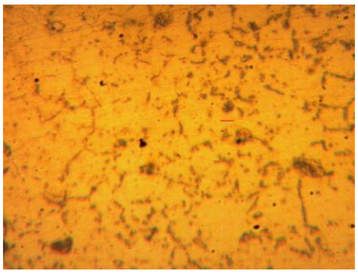

Figure 23: HAZ

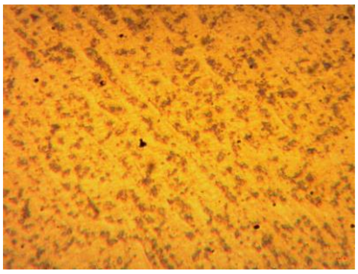

Figure 24: Weld

Microstructure of sample welded at 100Hz

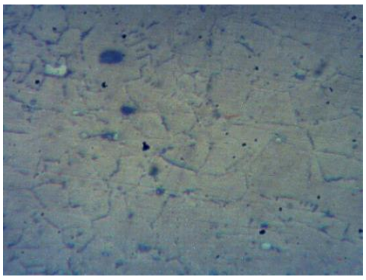

Figure 25: Base metal

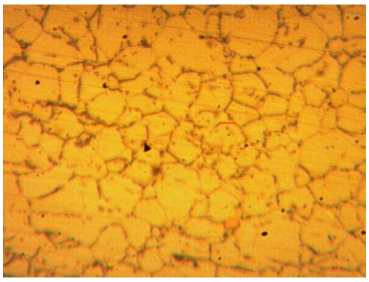

Figure 26: HAZ

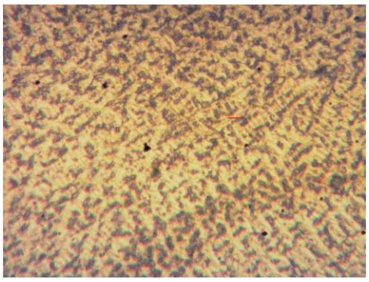

Figure 27: Weld

Microstructure of sample welded at 200Hz

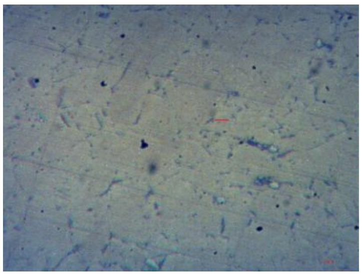

Figure 28: Base metal

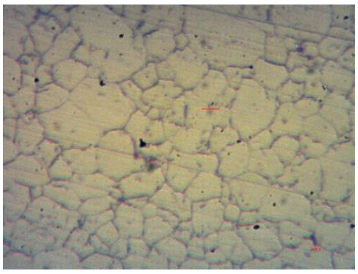

Figure 29: HAZ

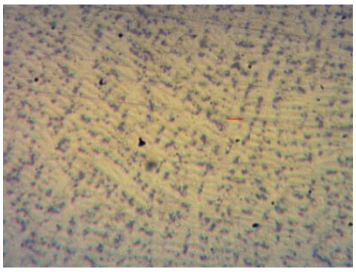

Figure 30: Weld

Microstructure of sample welded at 300Hz

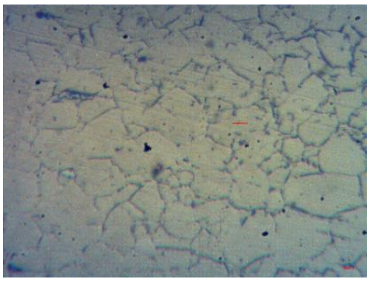

Figure 31: Base metal

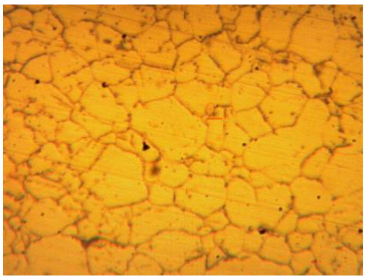

Figure 32: HAZ

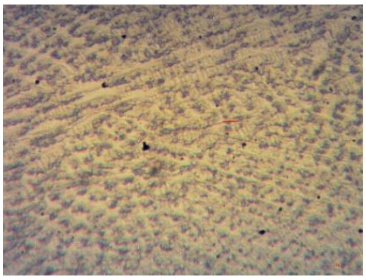

Figure 33: Weld

3.5 Micro hardness of the weld

Table 3: Macro hardness

Frequency	Base (HV)	HAZ (HV)	Weld (HV)
2	442.9	241.4	224.5
4	400	242.7	233.4
6	423.6	252.3	239.3
8	402.5	244.5	243.7
10	432.7	248.3	239
100	424.1	239.1	234.6
200	401.3	229.8	223.3
300	414.1	229.6	241.9
400	437.7	236.5	229.2
500	416.3	242.6	234.1

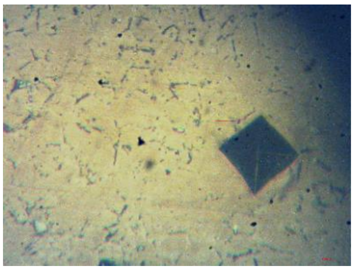

Figure 34: Indentation in base metal

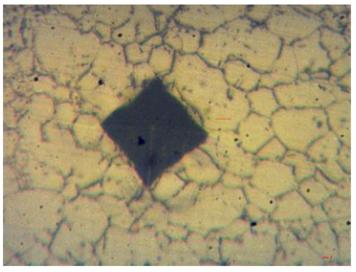

Figure 35: Indentation in HAZ

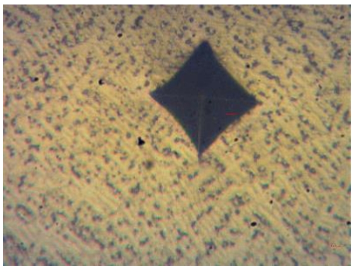

Figure 36: Indentation in weld

3.6 Macrostructure of the cross-section

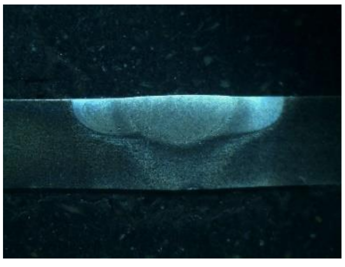

Figure 37: 2 Hz

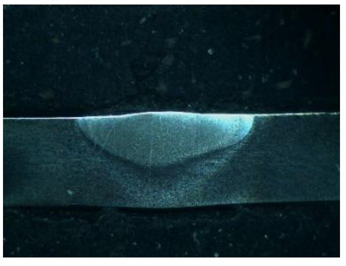

Figure 38: 4 Hz

Figure 39: 6 Hz

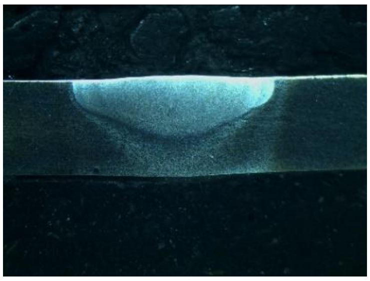

Figure 40: 8 Hz

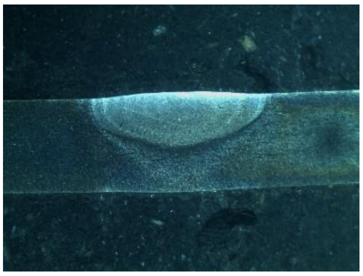

Figure 41: 10 Hz

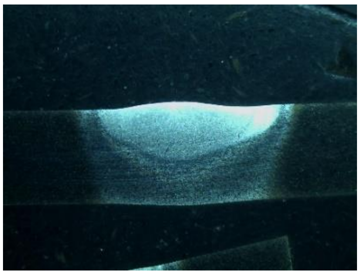

Figure 42: 100 Hz

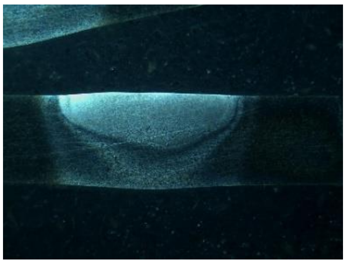

Figure 43: 200 Hz

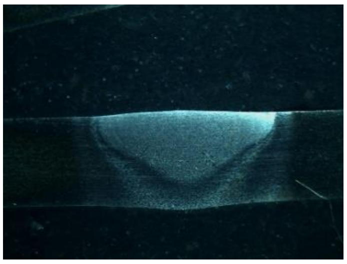

Figure 44: 300 Hz

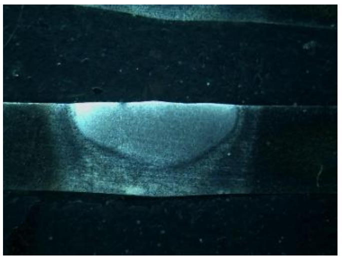

Figure 45: 400 Hz

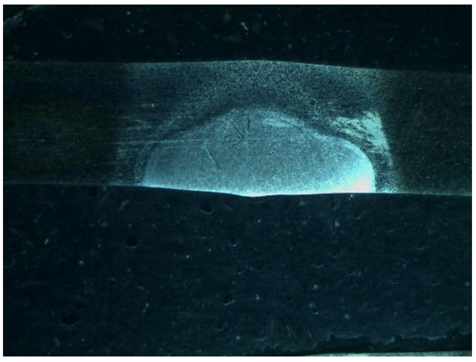

Figure 46: 500 Hz

CHAPTER 4

4.1 Results and analysis

Performing a comparative analysis on the Macro image of weld, reveals that ripples on the weld tends to increase along with frequency. In 2 Hz, the ripples are more widely placed than the 4 Hz. This trend is followed by subsequent weld frequency. At higher frequency of 400 Hz, 500 Hz the ripples are nearly indistinguishable and appears as a continuous weld pattern.

By observing the microstructure of 2 Hz, 4 Hz, 6Hz, 100 Hz, 200Hz, 300 Hz there is not much difference between. These resulting microstructure are similar. The weld region has a medium sized grain with directionality towards the base metal. The HAZ region has fine grained structure as it is heated to recrystallisation temperature. The base metal has a similar base and HAZ microstructure. This suggest that there is no difference in terms energy/input heat in this region and temperature profile has been similar.

Table 4: Depth and width of different zones

Frequency (Hz)	Depth (mm)	Bead width (mm)
2	1.2	4.7988
4	1.17	4.315
6	1.17	4.26
8	1.17	4.265
10	1.07	3.724
20	0.9331	3.465
40	0.9331	3.3325
60	0.9331	3.3325
80	0.9331	3.3325
100	0.9331	3.8657

200	1.07	3.8657
300	1.17	3.8657
400	1.33	3.7324
500	1.17	3.7324

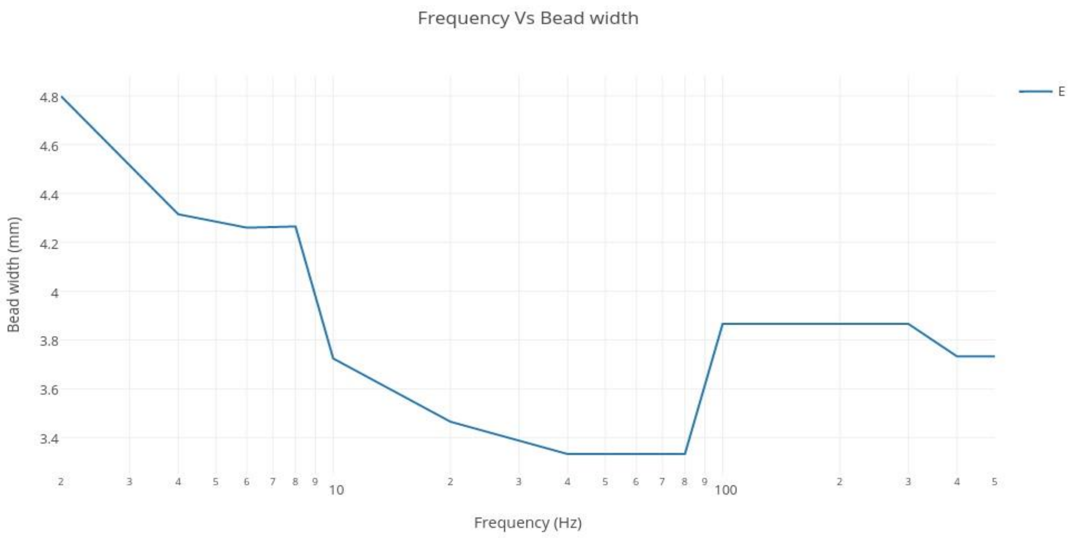

Figure 47: Frequency Vs Bead Width

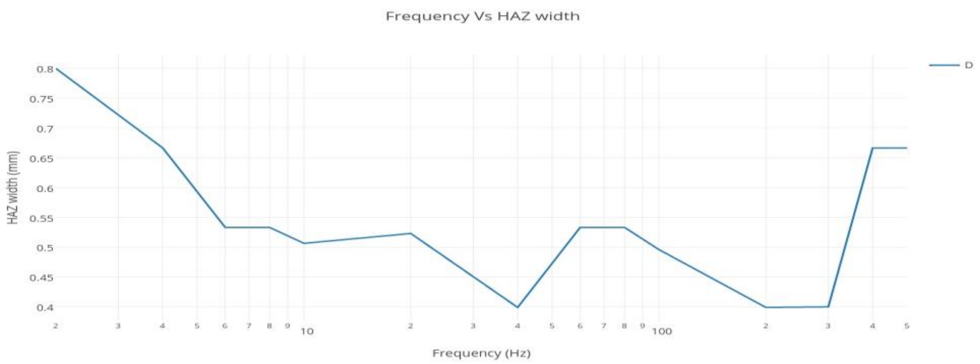

Figure 48: Frequency Vs HAZ Width

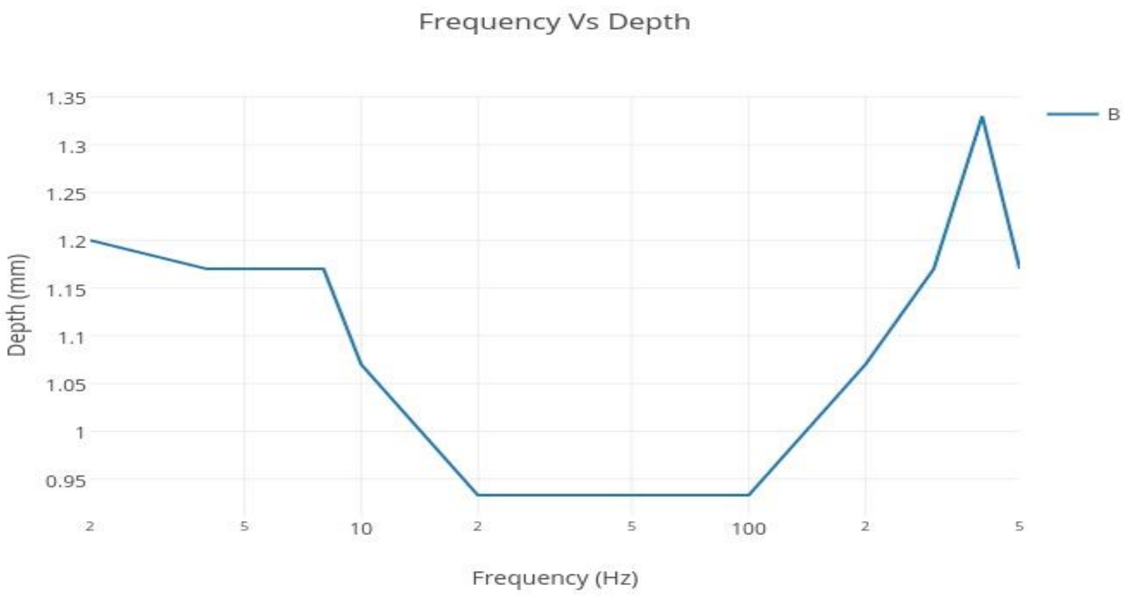

Figure 49: Frequency Vs Depth

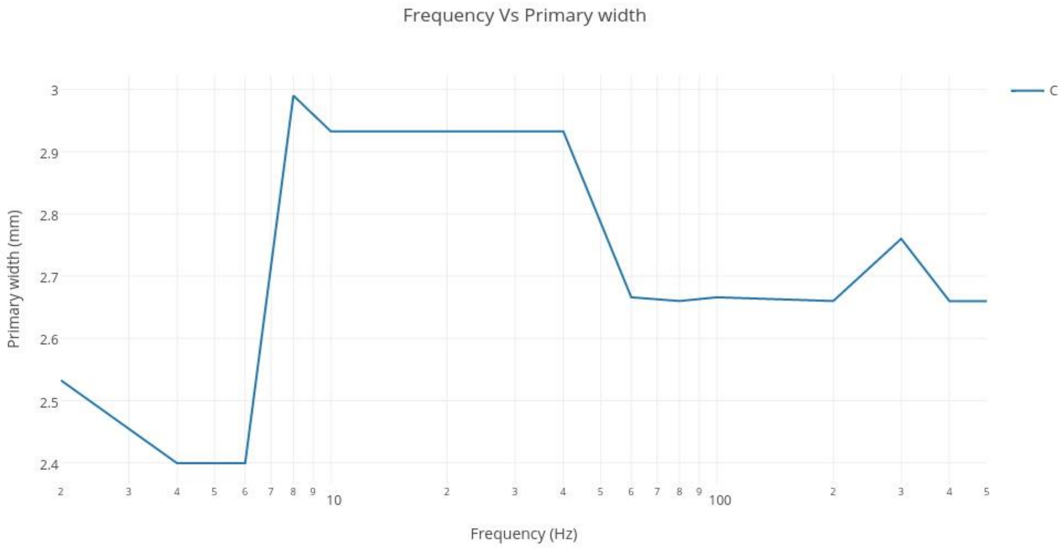

Figure 50: Frequency Vs Primary Width

It can be observed that depth, HAZ and Bead width decreases upto a certain point due to various factors like skin effect, heat dissipation and then saturates expect depth which increases again. Primary width decreases till 6 Hz then later increases and saturates at 10 Hz.

From the macrostructure of lower frequency (2Hz) pulse welded specimen there are two distinguishable weld region. One would be wider and shallow and another would be narrow and deep. These structures are formed due to changing welding current at that specific instant. The peak current forms the deeper weld regions and background current forms the shallow ones. But this distinguishable regions tend to merge together when the frequency of the pulse is increased. At higher frequencies of 400Hz and 500Hz, there is no separable region for peak current weld and background current weld. There will be a single weld region at the higher frequencies.

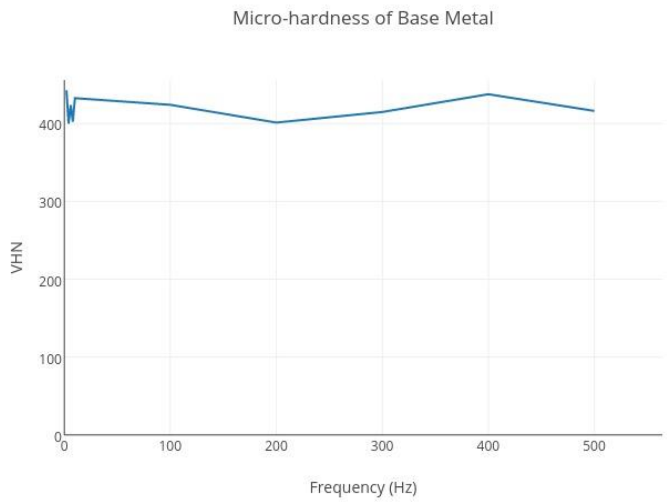

Figure 51

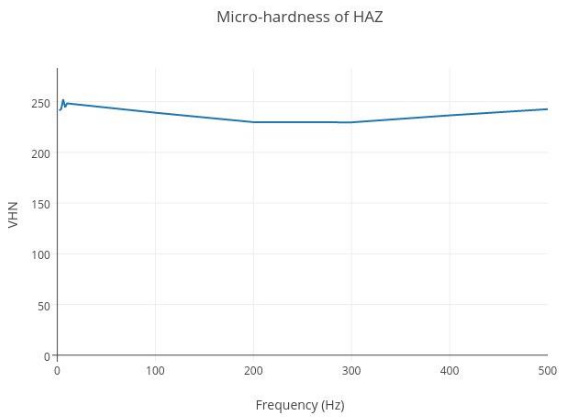

Figure 52

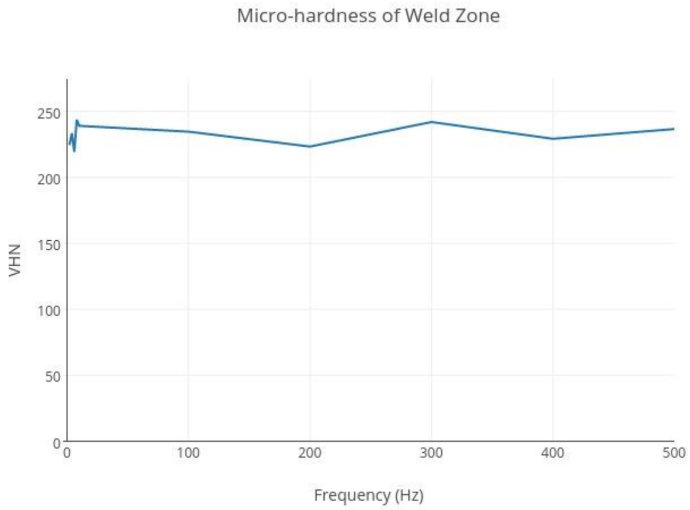

Figure 53

From the hardness plot, we can see that there isn't a much notable difference between the values at different frequencies. The plot remains constant for frequency changes. This implies that the mechanical property of weld is not affected at the microstructural level. The hardness of the base metal is higher compared to other regions and weld region is weaker because precipitates has been lost during the weld cycle. HAZ is bit harder compared to weld region. This trend is followed for every frequency.

4.2 Conclusion

Based on the result obtained from the experiments conducted to study the mechanical properties of Inconel 718 alloy using PTIG welding the following findings were made, the effect of PTIG frequency on Microstructure, Macrostructure and hardness in welding of Inconel 718 alloy has been studied. From the study it has been observed that changing frequency does not affect the microstructure of the weld region. Whereas depth of penetration and width of different regions shows distinguishable variations with frequency change. The micro hardness shows a constant trend towards frequency change in different regions. Considering all these factors, PTIG welding with higher frequency are suggested to get uniform weld structure and desired properties.

References

[1] Appa Rao G, Mahendra Kumar, Srinivas M. and Sharma D.S. (2003) ‘Effect of standard heat treatment on the microstructure and mechanical properties of hot isostatically pressed superalloy Inconel 718’

[2] Devendranath Ramkumar K, Monoj Kumar B, Gokul Krishnan M, Sidarth Dev, Aman Jayesh Bhalodi, Arivazhagan N. and Narayanan S. (2015) ‘Studies on the weldability, microstructure and mechanical properties of activated flux TIG weldments of Inconel 718’

[3] Garat V, Deleume J, Cloué J. M. and Andrieu E. (2005) ‘High temperature intergranular oxidation of alloy 718’

[4] Gordine J. ‘Problems in Welding Inconel 718’

[5] Jerold Jose P. and Dev Anand M. (2016) ‘Effect of Process Parameters on Mechanical Properties and Modeling of Pulsed TIG Welding of Inconel 718 Alloy’

[6] John J. Schirra ‘Effect of Heat Treatment Variations on the Hardness and Mechanical Properties of Wrought Inconel 718’

[7] Muralidharan B.G, Shankar V. and Gill T. P. S. (1996) ‘Weldability of Inconel 718 - A Review’