RESEARCH ARTICLE

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Effect of Delta Current Frequency (DCF) on Microstructure and Tensile properties of Gas Tungsten Constricted Arc (GTCA) welded Inconel 718 Alloy Joints

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Abstract

Inconel 718 is a nickel-based superalloy mostly used in high temperature applications in aerospace sector due to its extensive mechanical properties and weldability. Gas Tungsten Arc Welding (GTAW) process is widely used for joining of Inconel 718 alloy for cleaner, precise and high-quality welds. However, due to the high heat input and wider arc associated with this process, it is having certain metallurgical problems in welding, such as coarse dendritic structure and segregation of alloying elements in weld metal region which significantly reduces the mechanical properties of the joints. To overcome these limitations, a newly developed Gas Tungsten Constricted Arc Welding (GTCAW) process is employed to join Inconel 718 alloy. It is the advanced configuration of GTAW process, based on magnetic arc constriction induced by high frequency pulsing of the current known as Delta Current. The main objective of this investigation is to study the effect of Delta Current Frequency (DCF) on the weldability of Inconel 718 alloy for its viability in aerospace applications. The joints welded at 4 kHz showed superior tensile properties due to the refinement of grains in fusion zone. Increase in DCF results in decrease in tensile properties of the joints due to the coarsening of dendritic fusion zone microstructure. It is attributed to the stacking of heat input during welding.

Keywords: Gas Tungsten Constricted Arc Welding; GTCAW; Delta Current Frequency; Inconel 718; Tensile properties; Microstructure.

1.0 Introduction

Inconel 718 is a nickel-based superalloy originally developed for gas turbine engine applications in the late 1950's [1]. It is of great interest in aerospace sector because of its extensive mechanical properties and weldability. It contains Nb, Al and Ti as principal strengthening elements for the precipitation of gamma prime and gamma double prime precipitates. Most of the high temperature strength is achieved by the precipitation of gamma double prime precipitates [2]. Inconel 718 offers greater resistance to strain age cracking due to its sluggish response to aging treatment [3]. The outstanding property of Inconel 718 is its ability to get welded in either solution treated or aged condition. It is suitable for service temperature ranging from -252°C to 750°C. It has widened its application areas from cryogenic to high temperature service conditions [4]. It's high temperature strength, creep and stress rupture properties, corrosion and oxidation resistance makes it a suitable material for use in high temperature sections of rocket engines for fuel oxidizer, injector plates, forged rings, thrust chamber, jackets and turbine wheels etc. It finds major applications in lightweight welded frames and other parts in aircraft turbojet engines [5]. For the fabrication and assembly of such parts, welding is a major concern for joining of this alloy. Thus, an investigation on the weldability of this alloy is of a great significance to produce stronger and sound welds.

Gas Tungsten Arc welding (GTAW) process is widely used for joining of Inconel 718 alloy. It provides better control over the welds as compared to the other competing fusion welding processes to produce precise and high-quality welds. This provides a competitive advantage for its use in aerospace applications. The process has certain limitations in joining of Inconel 718 alloy due to its high heat input, wider arc, lower arc penetration and slower welding speed. Inconel 718 alloy being a highly alloyed solid solution, is more prone to the metallurgical problems in welding, such as segregation of alloying elements and laves phase formation in interdendritic regions [6-8]. It also makes it susceptible for HAZ microfissuring [9, 10]. This significantly reduces the strength and ductility of welded joints as compared to the base metal. To overcome this problem, heat input in the GTAW process needs to be reduced. In this investigation, a recently developed Gas Tungsten Constricted Arc Welding (GTCAW) process is used to join Inconel 718 alloy to reduce the heat input and refine the fusion zone microstructure for increasing the strength and ductility of welded joints. Gas Tungsten Constricted Arc Welding (GTCAW) is an advanced configuration of GTAW process with magnetic arc constriction introduced by high frequency pulsing of the Delta Current [11].The Delta Current Frequency (DCF) is a significant parameter in controlling the magnetic arc constriction. It is the pulsing of Delta Current from higher amperage to lower amperage up to 20 kHz in saw tooth shape wave form rather than square wave form as in pulsed current GTAW. **Fig. 1** shows the Delta Current pulsing wave form. It controls the rise time and fall time of the arc. Hence the study of DCF on the weldability of Inconel 718 alloy is important for its viability in aerospace applications.

The published research works on the welding of Inconel 718 alloy are mainly focussed on GTAW process [12-14]. Researchers attempted to make the use of low heat input processes such as Electron Beam Welding (EBW) [15-17] and Laser Beam Welding (LBW) [18-20] to attain finer grains in the fusion zone. Few investigations were reported on the use of magnetic arc oscillation [21] and current pulsing technique [22] in GTAW to reduce the segregation effect and enhance the mechanical properties of Inconel 718 alloy joints. However, there is a major research gap in literature about the use of magnetic arc constriction technique in GTAW process. Also, the information available on the high frequency pulsing of the Delta Current is very less [23]. Hence, this research work aims to investigate the effect of DCF on tensile properties and microstructure of GTCA welded Inconel 718 alloy joints.

2.0 Experimental Methodology

Rolled sheets of 2 mm thick Inconel 718 alloy at 980°C solution treated condition was selected for the present investigation. The chemical composition and mechanical properties of the base metal are shown in **Table 1** and **2** respectively.

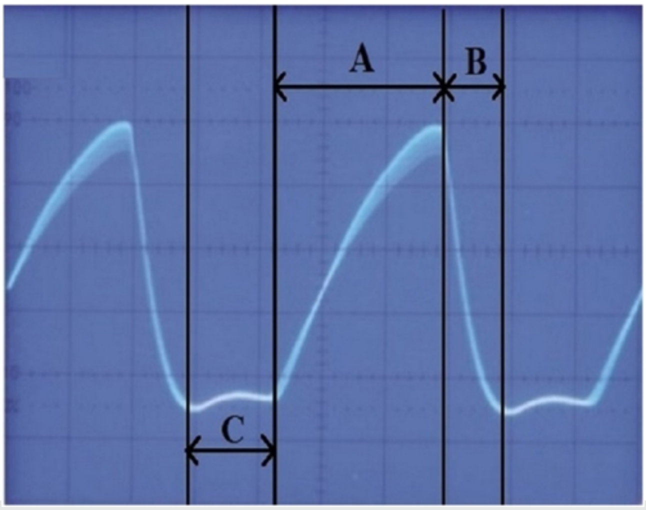


Fig. 1 : Delta Current Frequency waveform
(A= Rise time, B= Fall time and C= Agitation)

Table 1 : Chemical composition of base metal (% by weight)

Ni	Cr	Fe	Co	Mo	Nb	Ti	Al	C	Mn	Si	B	Cu	S
55.5	17.7	21.8	0.04	3	4.96	0.93	0.44	0.43	0.017	0.06	0.003	0.001	0.004

Table 2 : Mechanical properties of base metal

Tensile Strength (MPa)	0.2% Offset Yield Strength (MPa)	Elongation in 50 mm gauge length (%)	Microhardness ($HV_{0.5}$)
870	580	38	292

Autogenous welds were produced in a square butt joint configuration using Gas Tungsten Constricted Arc Welding (GTCAW) machine (Make: VBC UK; Model: InterPulseTIG E 175i) with pure Argon gas as a shielding gas at a constant flow rate of 10 l/min. Tungsten electrode 2 % thoriated of diameter 1.6 mm was used at an arc length of 0.8 mm. **Fig. 2** represents the square butt joint configuration for welding of Inconel 718 alloy joints.

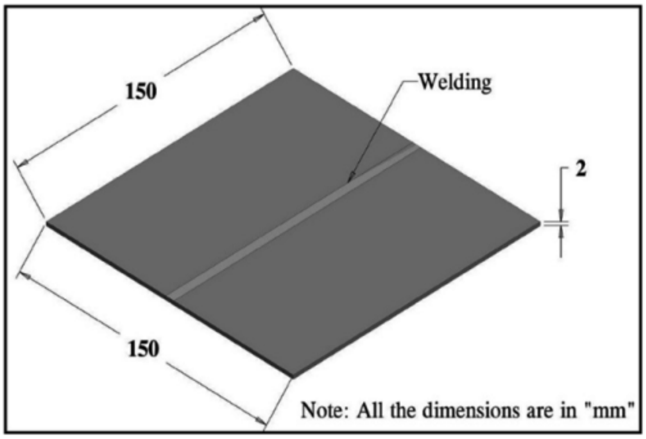


Fig. 2 : Square butt joint configuration used to fabricate the joints

The welding was done in a transverse direction of rolling. The GTCAW machine set up is shown in **Fig. 3**. The photograph of the welded joints is shown in **Fig. 4**.

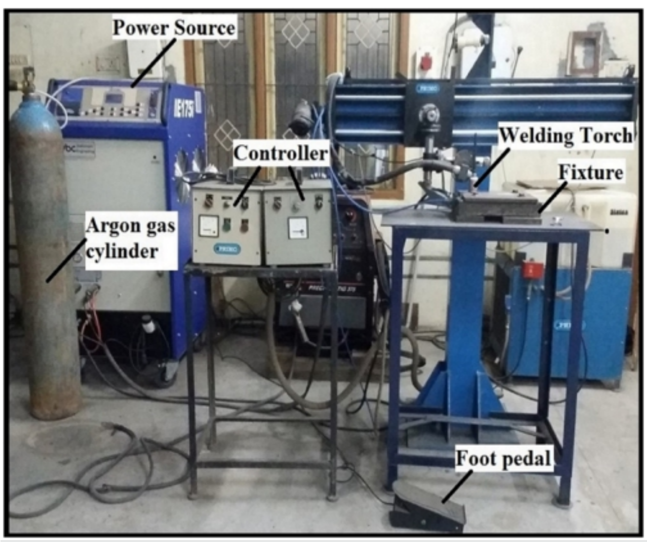


Fig. 3 : GTCAW machine set up

One factor at a time strategy of experimentation was selected to investigate the main effect of Delta Current Frequency (DCF). It was varied from 4 kHz to 20 kHz at 5 distinct levels while other parameters were kept at constant level. A number of trials were done to set the minimum and maximum working limit of DCF to produce defect free sound welds. **Table 3** shows GTCAW parameters and levels selected for this investigation.

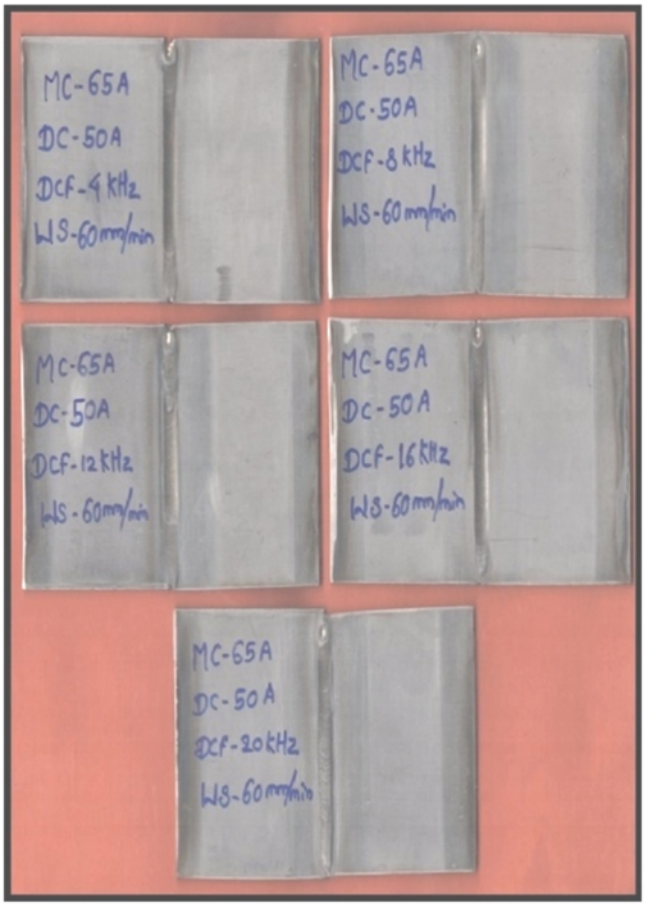


Fig. 4 : Photograph of welded joints

Table 3 : Welding parameters for GTCAW of Inconel 718 alloy joints

Sl. No.	Delta Current Frequency (kHz)	Main Current (A)	Delta Current (A)	Welding Speed (mm/min)	Heat Input (J/mm)
1.	4	65	50	60	518
2.	8	65	50	60	518
3.	12	65	50	60	518
4.	16	65	50	60	518
5.	20	65	50	60	518

The smooth sub-size tensile specimens were extracted from the butt joint to determine the transverse tensile properties. The tensile test was carried out on the welded joints as per ASTM E8M Standard. The dimensions of the tensile specimen are shown in **Fig. 5**.

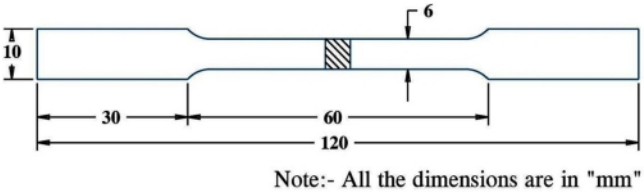


Fig. 5 : Dimensions of tensile specimen as per ASTM Standard

Three specimens for each level were tested by a 50 kN servo-controlled tensile testing machine (Make: Tinius Olsen, Horsham, Pennsylvania; Model: H50KL) at a crosshead speed of 2 mm/min as per ASTM specifications. The average of the results was taken as the final reading. The 0.2% offset yield strength was derived from engineering stress-engineering strain diagram. The tensile elongation was measured at 50 mm gauge length.

The cross section of the metallographic welded samples was mirror polished for measurement of Vickers microhardness. The microhardness testing was performed as per ASTM E384-17 standard at a testing load of 5.0 N and 15.0 s dwell time using a Vickers Microhardness Testing machine (Make: Shimadzu; Model: HMV-2T). The microhardness distribution across the different regions of welded joints was recorded at mid-thickness region from the weld centre at an interval of 0.1 mm to study the variation in hardness values due to the segregation of alloying elements and correlated with the tensile failure of joints. The average microhardness values were measured for different regions of the weld (FZ and HAZ).

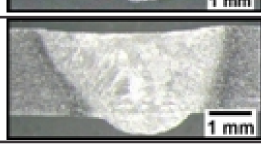
The cross-sectional surface of the metallographic welded samples was subjected to specimen preparation and mirror polishing. It was then etched with a Kalling's standard reagent to reveal both macro and microstructure of the welds. The macrostructure was analyzed using Stereo zoom microscope and the microstructure was taken using Optical Microscope (Make: MEJI, Japan; Model: MIL-7100). The microstructure was observed at different magnifications of 50 X, 100 X, 200, 500 X and 1000 X to find the extent of refinement and dendrite growth. It was correlated to the tensile properties and microhardness. The fractographs of the tensile specimens were analysed with the help of Scanning Electron Microscope (SEM).

3.0 Results

3.1 Macrostructure

The macrostructure of the joints for different levels of DCF is displayed in **Table 4**. All the joints are defect-free except minor undercutting observed at 8 kHz and 20 kHz. The weld bead shows a cup shape with narrowing bottom at each joint.

Table 4 : Effect of Delta Current Frequency on Weld Bead Geometry

Delta Current Frequency	Macrograph	Bead width (mm)	Bead depth (mm)	FZ area (mm^2)	Avg. HAZ width (mm)	Observation
4 kHz		4.24	2.00	7.32	0.37	Excess Penetration
8 kHz		4.85	2.00	8.10	0.43	Correct Penetration
12 kHz		4.37	2.00	7.46	0.46	Correct Penetration
16 kHz		4.60	2.00	7.75	0.51	Excess Penetration
20 kHz		5.10	2.00	8.30	0.56	Excess Penetration

The results show that there is an increase in weld bead geometry due to the increase in DCF. The Fusion zone area is increased significantly by 13.38% at higher level (20 kHz) as compared to the lower level (4 kHz). The width of weld bead and HAZ increases with increase in DCF. It is attributed to the increase in average heat input during welding with increase in DCF. This shows that weld bead geometry is sensitive to the changes in levels of DCF. Thus, the selection of DCF is important in producing the optimum weld bead size.

3.2 Tensile Properties

The effect of DCF on the transverse tensile properties of welded joints is shown in **Table 5**. The tensile strength and elongation are comparatively lower than the base metal. It is due to the microstructural difference in the welded joints and base metal. The fusion zone solidifies in cast dendritic form resulting in less strength at the grain boundaries than that of wrought base metal. It is correlated to the segregation of alloying elements resulting in laves phase formation in interdendritic regions of fusion zone. The laves phase offers microvoid nucleation in welds and also facilitates a low energy fracture path, contributing in lower ductility [18].

The tensile strength decreases with increase in DCF. The decrease in tensile strength up to 12 kHz is not significant. The joints welded at 4 kHz showed higher tensile strength of 863 MPa and yield strength of 548 MPa. The tensile elongation increases slightly with increase in DCF up to 12 kHz. Further increase results in slight reduction in tensile elongation. The tensile elongation is higher up to 29.64% at 12 kHz. The decrease in tensile properties with increase in DCF is attributed to the accumulation of heat input during welding with increase in DCF. The failure of the tensile specimens after testing is shown in **Fig. 6**. The failure occurred in the fusion zone of all the joints.

Table 5 : Effect of Delta Current Frequency on transverse tensile properties of joints

Delta Current Frequency	Tensile Strength (MPa)	0.2% Offset Yield Strength (MPa)	Elongation in 50 mm gauge length (%)	Joint Efficiency (%)	Failure Location
4 kHz	863	548	27.93	99.20	FZ
8 kHz	857	534	28.72	98.50	FZ
12 kHz	854	532	29.64	98.16	FZ
16 kHz	838	520	28.23	97.44	FZ
20 kHz	834	517	26.22	95.86	FZ

Fig. 6 : Photograph of tensile specimens after testing

3.3 Microhardness

The microhardness distribution across the welded joints in the mid-thickness region is shown in **Fig.7**. It shows the variation in microhardness of the fusion zone from the weld centre. The microhardness is observed to be considerably less than HAZ and base metal at some points from the weld centre. These are the points responsible for failure of the joints in fusion zone only. It is attributed to the segregation of alloying elements in interdendritic regions of fusion zone, which depletes the strengthening alloying elements from the matrix.

Table 6 shows the effect of DCF on microhardness of various regions. The average microhardness of FZ and HAZ is less than the base metal in all the joints. The microhardness of FZ and HAZ decreases with increase in DCF. There is no appreciable change in microhardness of the fusion zone up to 12 kHz. Further increase in DCF results in decrease in microhardness considerably. The microhardness of FZ and HAZ decreases by 7.40% and 5.86% respectively at 20 kHz as compared to 4 kHz. The decrease in microhardness of fusion zone is attributed to the segregation of alloying elements which rises at incremental levels of DCF.

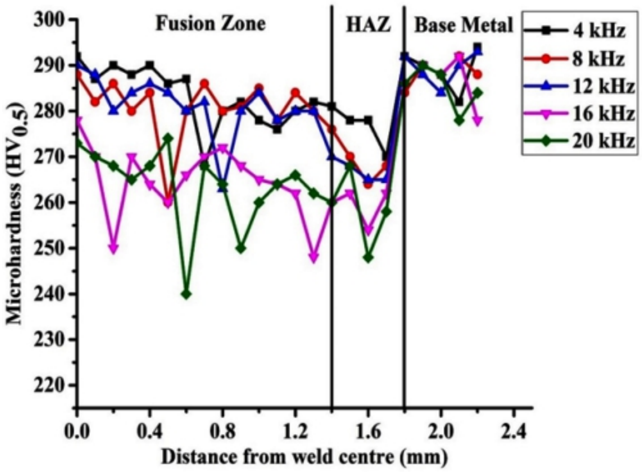


Fig.7 : Microhardness distribution of the welded joints at mid-thickness region

Table 6 : Effect of Delta Current Frequency on microhardness of various regions

Delta Current Frequency	FZ ($HV_{0.5}$)	HAZ ($HV_{0.5}$)	BM ($HV_{0.5}$)
4 kHz	284	273	292
8 kHz	279	267	292
12 kHz	280	265	292
16 kHz	265	260	292
20 kHz	263	257	292

3.4 Microstructure

The microstructure of the base metal in 980°C solution treated condition is shown in **Fig.8 a**). It consists of fine equiaxed grains in the nickel austenitic matrix. Mechanical twinning is observed across the grains. The primary carbides are present in grains and across the grain boundaries. **Fig.8 b) to f)** shows the microstructure of the fusion zone at incremental levels of DCF. The fusion zone shows dendritic structure in the dark austenitic matrix. The growth of the dendritic structure is dependent on the heat input. As the DCF increases the dendritic structure of the fusion zone becomes coarser. This results in increases in interdendritic regions. The interdendritic regions are the preferential sites for the segregation of alloying elements. The fusion zone of the joints welded at 4 kHz shows finer dendritic structure as compared to the other levels. The refinement in fusion zone is observed up to 12 kHz. Further increase results in coarsening of the dendrites. The fusion zone at higher level of DCF (20 kHz) shows coarser dendritic structure. This clearly infers that the average heat input rises during welding. The coarsening of dendritic structure with increase in DCF is attributed to the stacking of heat input during welding in weld thermal cycle.

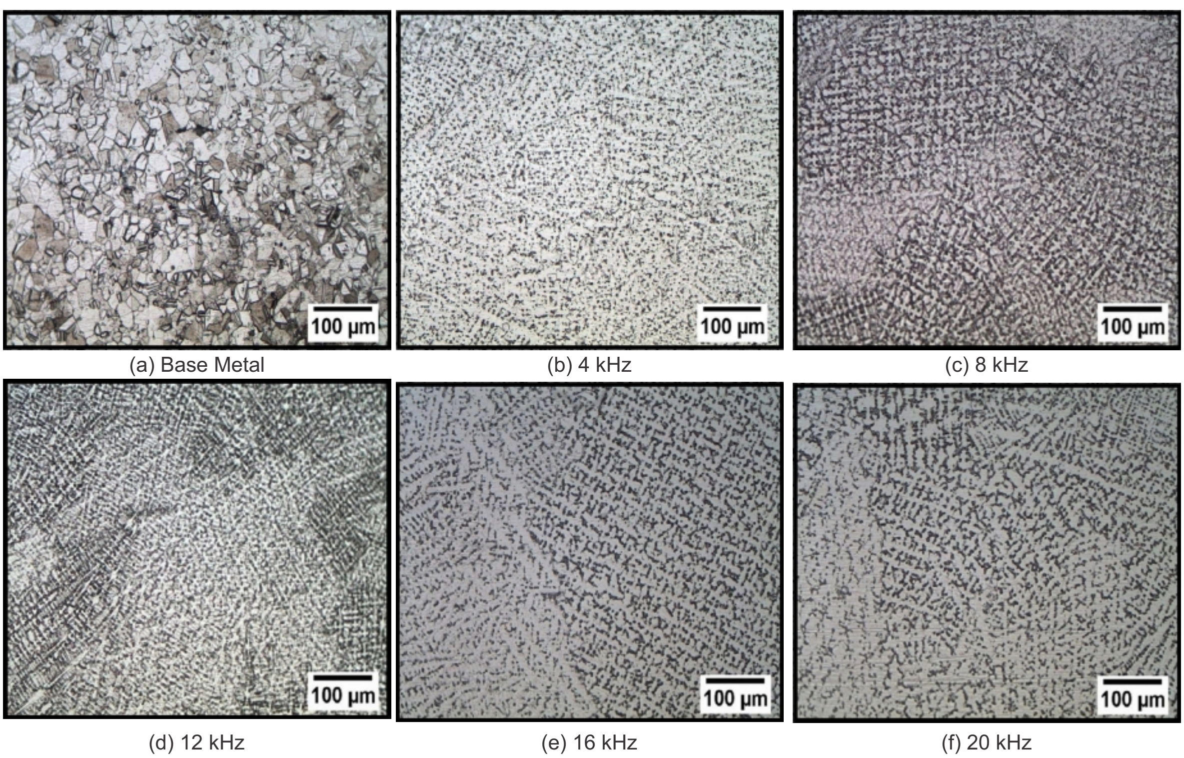


Fig. 8 : Effect of Delta Current Frequency on microstructure of fusion zone (FZ)

The fractograph of the tensile specimen of base metal is shown in **Fig. 9 a**). The base material fractured surface exhibited completely dimpled rupture and showed no favourable fracture path. **Fig. 9 b**) **to f)** shows the fractographs of the tensile specimens at incremental levels of DCF. The fusion zone fractured surface exhibits dendritic pattern and shows favourable fracture path. The fracture occurs along the interdendritic regions. The joints welded using DCF of 12 kHz shows finer and deeper dimple regions, where as it was observed to be coarser and shallower at 16 kHz and 20 kHz. The joints welded using DCF of 20 kHz shows the presence of more tear ridges and brittle regions. Hence the tensile properties are observed to be inferior at higher level of DCF. It is due to the increase in segregation and laves phase formation because of higher heat input.

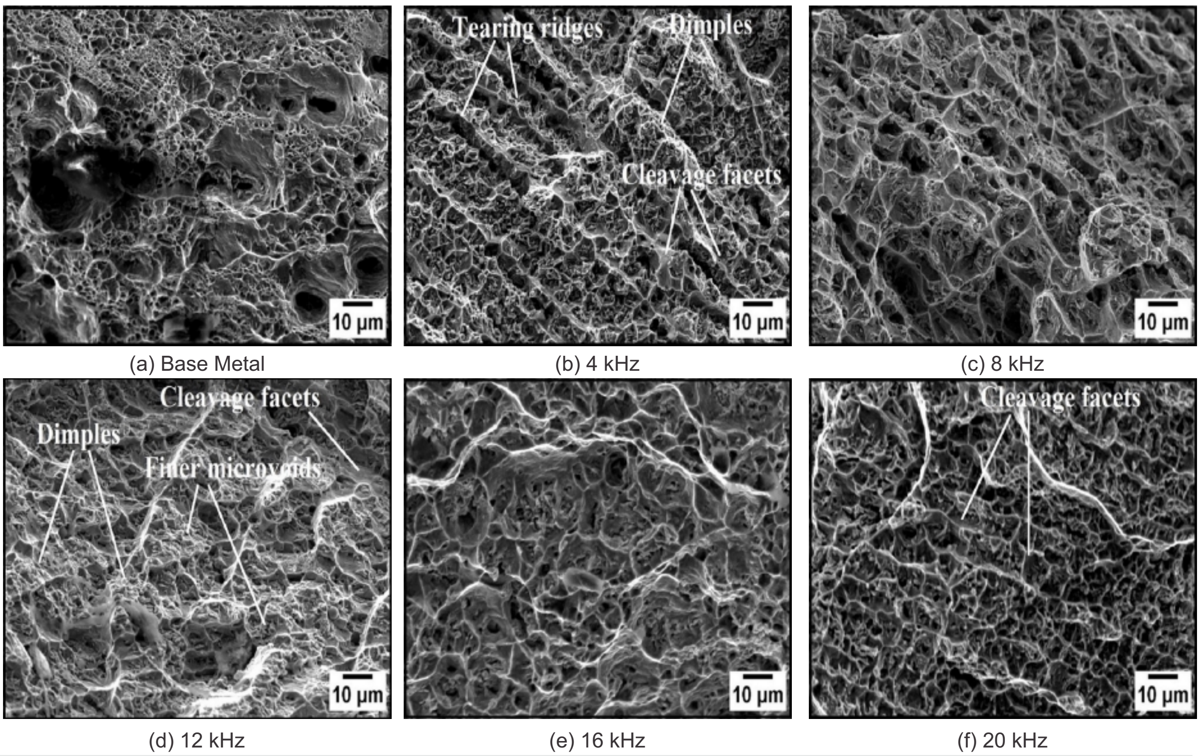


Fig. 9 : SEM fractograph of tensile specimens

4.0 Discussion

4.1 Effect of DCF on Macrostructure

The weld bead geometry is directly proportional to the welding heat input. As the heat input increases the melting of metal at the joint increases, which results in an increase in bead width, fusion zone area and HAZ width. GTCAW process is characterized by the magnetic arc constriction and high frequency pulsing of Delta Current. The DCF modifies the magnetic field around the arc for arc constriction. The magnetic arc constriction is associated with changes in magnetic field. Thus, DCF have considerable influence on the rise time and fall time of the magnetic arc constriction. As the DCF increases, rise time and fall time decreases, which results in less time available for the magnetic arc constriction and release. The magnetic arc constriction is mainly responsible for the localized heating of metal at the joint. As the arc constriction rise and fall time is reduced with incremental levels of DCF, the localized heating of the metal at the joint reduces and the arc does not reduce the heat input during welding.

From the results, it is inferred that the average heat input increases with increase in DCF. As DCF increases, the distance between the adjacent peaks of the Delta Current decreases. This results in decrease in rise time and fall time of the magnetic arc constriction. Thus, less time is available for the heat transfer during each weld thermal cycle. This in turn causes the increase in piling of heat input during welding. The increase in stacking of heat input during welding with increase in DCF is mainly responsible for the increase in melting of the metal at the joint and thus the weld bead geometry increases.

4.2 Effect of DCF on Tensile Properties

Inconel 718 alloy is heavily alloyed to achieve excellent mechanical properties at high temperature [24]. The strengthening is provided by the formation of gamma prime and gamma double prime precipitates. Nb is the alloying element which is mainly used for high temperature strengthening. But the main problem is, it is having a high partition coefficient [25]. It results in segregation of Nb in interdendritic regions, causing depletion of alloying elements from the matrix [26]. It reduces the strength of the joints in depleted regions. The tensile failure was observed in the fusion zone only. It is attributed to the presence of laves phase in the fusion zone due to the segregation of alloying elements. The tensile properties decrease with increase in DCF. This effect is not significant up to 12 kHz. Further increase results in significant decrease in tensile properties of the joints. The decrease in tensile strength is attributed to the coarsening of dendritic structure with incremental levels of DCF. The coarsening of dendritic structure increases the size of interdendritic regions which are preferential sites for segregation. As segregation is time dependent phenomenon, the increase in average heat input during each weld thermal cycle increases the segregation of alloying elements in interdendritic regions. Thus, there is an increase in depletion of alloying elements from the matrix. This reduces the strength and ductility by void formation at the depleted regions. The laves phase composition is A_2B type, where A = Ni, Cr, Fe and B=Nb, Mo, Si and Ti [6]. The laves phase is rich in Mo, Nb, Ti and Si. It does not extend tensile deformation along with the matrix and ensues rapid initiation and propagation of cracks [22].The cleavage facets formed during tensile deformation are due to the presence hard and brittle lave phases in interdendritic regions of the fusion zone resulting in significant deterioration in tensile properties of joints especially at 20 kHz. The welded joints showed higher tensile properties at 4 kHz due to the significant refinement in dendritic structure of the fusion zone. The finer the dendritic structure the smaller will be the interdendritic regions. This reduces the segregation of alloying elements in interdendritic regions and increases the tensile properties.

4.3 Effect of DCF on Microhardness

The microhardness of fusion zone is dependent on the solidification rate. The solidification rate governs the dendritic structure refinement and segregation of alloying elements [8]. Inconel 718 alloy have large solidus and liquidus temperature range. This makes it more pronounced for the segregation of alloying elements [27]. The microhardness survey showed variation in microhardness of the fusion zone from weld centre. The significant variation in microhardness is allocated to the segregation effect. The strengthening alloying elements get depleted from the matrix and segregate in the interdendritic regions for laves phase formation. This results in lowering the microhardness values at some points in the fusion zone from the weld centre. These are the regions which are responsible for the failure of the welded joints in fusion zone only.

The average microhardness of the fusion zone decreases with increase in DCF. It is attributed to the coarsening of dendritic structure with increase in stacking of heat input during welding with incremental levels of DCF. The microhardness is higher at 4 kHz. It is attributed to the finer dendritic structure due to optimum heat input and thermal oscillation of the weld pool.

4.4 Effect of DCF on Microstructure

Inconel 718 alloy solidifies in the cast dendritic mode by constitutional supercooling and the growth of the dendrites is dependent on heat input and cooling rate [27]. The results showed an increase in the growth of the dendrites and interdendritic regions with incremental levels of DCF. This clearly indicates that the average heat input increases with increase in DCF. It is attributed to the reduction in rise time and fall time with increase in DCF. As the DCF increases, the distance between the two adjacent peaks of the Delta Current decreases, which reduces the time available for the heat to transfer in the next welding thermal cycle. Thus, there is piling of heat input in each welding thermal cycle. The end effect is an increase in average heat input during welding with incremental levels of DCF. The piling of heat input increases the thermal gradient between the weld pool and the base metal. Thus, there is enough time available for the heat transfer due to the reduced cooling rate. This provides the preferential conditions for the growth of the dendrites. The coarsening of dendritic structure is mainly responsible for the reduction in mechanical properties of the welded joints at 20 kHz. The increase in growth of the dendrites is not significant up to 12 kHz. This is the reason that there is no notable reduction in mechanical properties up to 12 kHz.

The optimum heat input and thermal oscillation of the weld pool increases the cooling rate by increasing the fluid motion and convective force in the weld pool especially at 4 kHz to impart grain refinement in fusion zone. The ratio of thermal gradient and growth rate is inversely proportional to the degree of undercooling in solidifying weld pool [16]. The reduced thermal gradient between the weld pool and the base metal results in significant undercooling and leads to the formation of nuclei on the molten pool surface and produces the finer dendritic structure [23]. The DCF up to 12 kHz is showing better results in breaking of dendrites. The broken dendrites also act as nuclei for refinement in the fusion zone during solidification. Thus, the refinement in fusion zone is the combined effect of magnetic arc constriction and optimum thermal oscillation of the weld pool.

5.0 Conclusions

1. Delta Current Frequency (DCF) is observed to have significant effect on the microstructure and tensile

properties of Gas Tungsten Constricted Arc Welded (GTCAW) Inconel 718 alloy joints. Hence, the optimum selection of DCF is important to achieve the potential benefits of magnetic arc constriction.

2. Increase in DCF from 4 kHz to 20 kHz results in decrease in tensile properties and coarsening of the dendritic structure of fusion zone. It is attributed to the increase in stacking of heat input during welding at incremental levels of DCF.
3. The joints made by using DCF of 4 kHz yielded superior tensile properties. It is attributed to the formation of finer dendritic structure due to the optimum heat input supplied and thermal oscillation experienced by the weld pool.
4. The joint efficiency is comparatively higher (above 94%) for all the joints. The higher joint efficiency and elongation can be taken as a measure of reduced segregation of alloying elements and laves phase formation in fusion zone of GTCA welded Inconel 718 alloy joints.

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