Effect of delta current on the microstructure and tensile properties of gas tungsten constricted arc welded Inconel 718 alloy joints

Tushar Sonar[1*], V Balasubramanian[2], S Malarvizhi[3], T Venkateswaran[4] and D Sivakumar[5]

[1,2,3] Centre for Material Joining and Research (CEMAJOR), Dept. of Mfg. Engg., Annamalai University, Annamalai Nagar, Tamilnadu
[4, 5] Vikram Sarabhai Space Centre (VSSC), ISRO, Thiruvananthapuram, Kerala

ABSTRACT

Keywords:
Gas Tungsten Constricted Arc Welding (GTCAW),
Delta Current,
Tensile Properties,
Microstructural Characteristics

Inconel 718 is a nickel-based superalloy which is of potential interest in high temperature applications in rocket and gas turbines. This alloy is mostly joined by Gas Tungsten Arc Welding (GTAW) process for clean and precise welds and it is economical and shop friendly. However, due to the high heat input associated with this process, the joints are more prone for metallurgical problems such as coarse dendritic structure and segregation in weld metal region and liquation cracking in heat affected zone (HAZ) which significantly reduces the mechanical properties of the welded joints. To overcome these shortcomings, a recently developed Gas Tungsten Constricted Arc Welding (GTCAW) process is used for joining Inconel 718 alloy. It is the advanced variant of GTAW process with magnetic arc constriction achieved by introducing high frequency pulsing Current (known as Delta Current). Delta Current pulsing at a very high frequency is controlling factor for the rise and fall of magnetic arc constriction during welding. The main objective of this investigation is to make the potential use of Magnetic Arc Constriction to reduce the heat input for minimizing metallurgical problems and enhancing the mechanical properties of the joints. To achieve this, main effect of Delta Current on tensile properties and microstructural characteristics of Inconel 718 alloy is investigated.

1. Introduction

Inconel 718 is a precipitation hardened Ni-Cr-Fe based superalloy containing Nb, Al and Ti as principal strengthening elements. It possesses excellent mechanical properties and weldability. It is having high temperature strength, creep and stress rupture properties, excellent resistance to oxidation and corrosion at elevated temperature. The high temperature strength is achieved mainly by the precipitation of gamma prime γ'- $Ni_3(Ti,Al)$ and gamma double prime precipitates γ'' - Ni_3Nb. It shows excellent resistance to strain age cracking as compared to other superalloys due to sluggish precipitation kinetics of γ''- Ni_3Nb [1]. It is used in rocket engines for rocket combustors and nozzle, in gas turbine for turbine blades and casings, in high temperature system of cryogenic rocket engines etc [2].

However, this material has some metallurgical problems when subjected to high heat input processes like GTAW. It is subjected to HAZ liquation cracking or microfissuring in HAZ due to the high heat input which tends to form low melting point eutectics at the grain boundaries. It is also more prone for segregation of alloying element in the interdendritic regions. The segregation of Nb leads to the formation of hard and brittle intermetallic phase known as laves phase in the interdendritic regions. The laves phase formation is detrimental to weld mechanical properties. It does not assist in plastic deformation and causes voids and crack initiation and propagation which leads to the reduced strength [3-5]. The laves phase formation is proportional to the coarsening of dendritic structure. Increase in size of dendrites provides preferential sites for segregation in interdendritic regions and subsequent laves phase formation [6]. Any technique which can refine the

*Corresponding author,
E-mail: tushar.sonar77@gmail.com (Tushar Sonar)

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

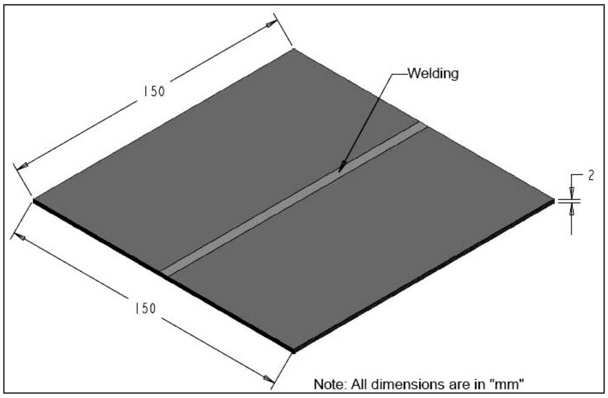


Fig. 1. Square butt joint configuration for the fabrication of the Inconel 718 joints.

dendritic structure can reduce the segregation effect and laves phase formation. In this investigation Gas Tungsten Constricted Arc Welding is used to join Inconel 718 alloy. It is the advanced modification of GTAW with magnetic arc constriction produced by high frequency pulsing of the Delta Current. The arc constriction reduces the wastage of heat on outer flare and increase heat intensity of the arc and thereby reduces the heat input and enhance the cooling rate.

S. Rao et al. investigated the local deformation behavior of Inconel 718 GTAW weldments at room temperature and at 550°C and observed that GTAW welded joints showed 22 % reduction in tensile strength and 50 % reduction in ductility as compared to the parent material [7]. Sivaprasad et. al studied the influence of magnetic arc oscillation and pulsing on microstructure and high temperature tensile strength of alloy 718 TIG weldments and concluded that refinement in laves phase and less interconnectivity was obtained by magnetic arc oscillation technique. however, the benefits of current pulsing were not obtained in refinement due to the high heat input used in the welding process [8]. Jankiram et. al. studied control of laves phase in Inconel 718 GTA welds with current pulsing and observed higher tensile properties and refinement in fusion zone due to current pulsing as compared to constant current GTAW. The tensile elongation was observed to be 11.5% as compared to 4% in GTAW for 16% elongation of base metal [9]. Radhakrishna et al. observed significant amount of depletion of Nb upto 2.5 % in dendrite core regions as against 5% in the base metal and concluded that slow cooling rate in GTAW results in more segregation and formation of coarse and interconnected laves phase in weld microstructure [10].

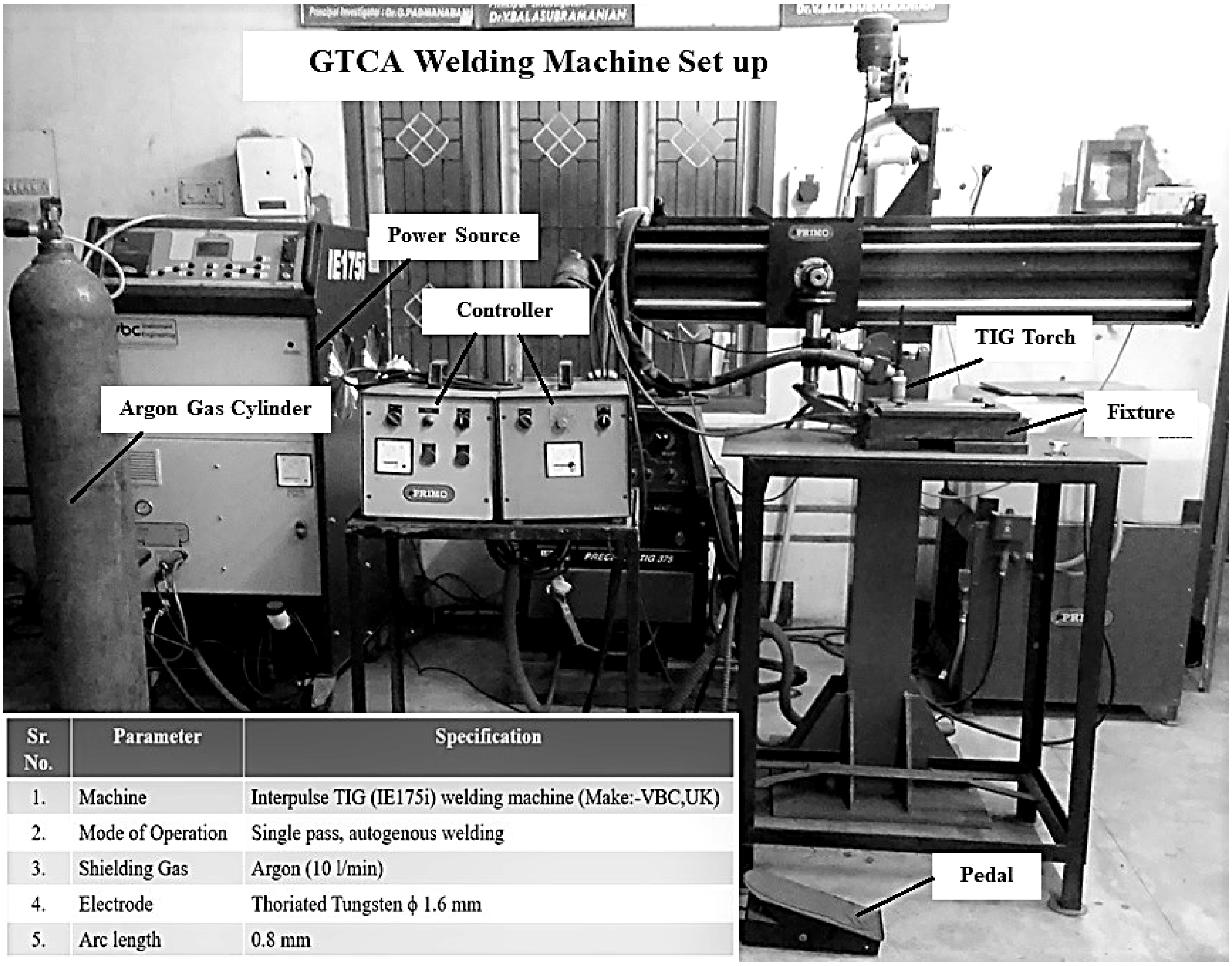
Table 2
Mechanical properties of base metal.

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

Till now, the research is mainly focussed on the constant current and pulse current GTAW of Inconel 718 alloy. Investigators reported the use of magnetic arc oscillation technique and compound current pulsing for refinement in fusion zone. However, there is a lack of systematic investigation on the use of arc constriction technique to reduce the heat input and enhance the cooling rate in GTAW of Inconel 718 for the refinement in dendritic structure and improvement in mechanical properties of the welded joints. As Delta Current is the significant factor responsible for the magnetic arc constriction in GTCAW, the main objective of this investigation is to study the effect of Delta Current at various levels on the microstructure and mechanical properties of Gas Tungsten Constricted Arc Welded Inconel 718 alloy joints.

2. Experimental Methodology

Autogenous square butt-welded joints were prepared in rolled 2 mm thick sheets of Inconel 718 alloy using Gas Tungsten Constricted Arc Welding machine (Make: -VBC, UK; Model: - InterPulse IE175i;). The square butt joint configuration is shown in Fig. 1 The chemical composition and mechanical properties of Inconel 718 alloy is depicted in Table. 1 and 2 respectively. The one factor at a time approach was used to study the main effect of Delta Current in which Delta Current



Sr. No.	Parameter	Specification
1.	Machine	Interpulse TIG (IE175i) welding machine (Make:-VBC,UK)
2.	Mode of Operation	Single pass, autogenous welding
3.	Shielding Gas	Argon (10 l/min)
4.	Electrode	Thoriated Tungsten ϕ 1.6 mm
5.	Arc length	0.8 mm

Fig. 2. GTCAW machine set up.

Table 3
Welding parameters for GTCAW of Inconel 718 alloy.

Sr. No.	Main Current (A)	Delta Current (A)	Delta Frequency (kHz)	Welding Speed (mm/min)	Heat Input (J/mm)
1.	65	40	12	60	472
2.	65	45	12	60	495
3.	65	50	12	60	517
4.	65	55	12	60	540
5.	65	60	12	60	562

was varied from 40 A to 60 A keeping other parameters at a constant level as represented in Table 3 so that the interaction effect is neglected and main effect is taken in to consideration. The lower and higher levels of Delta Current was set after extensive trials of welding with defect free joints. The Delta Current was varied at 5 levels of interval in between lower and higher level. Welding was performed in a direction normal to the rolling direction. The set up of the Gas Tungsten Constricted Arc Welding machine and mechanical clamping of the joints is shown in Fig. 2 and 3.

The tensile testing was carried out as per ASTM E8M-05 Standard. Fig. 4 shows the dimensions of the standard tensile specimen. The smooth

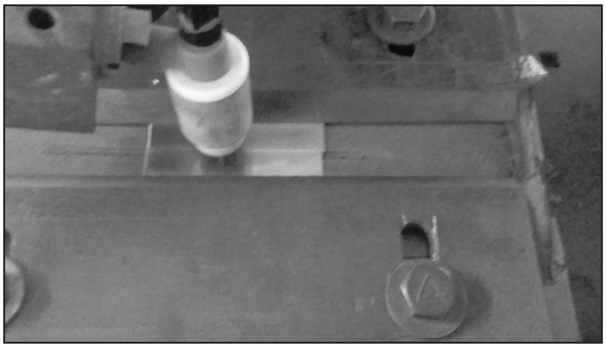


Fig. 3. Clamping of joint for welding.

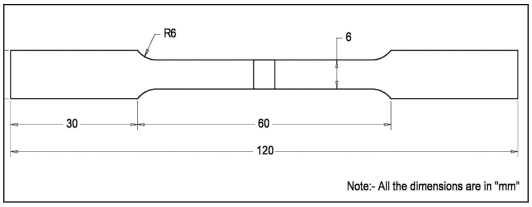


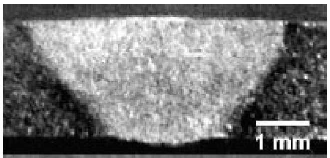
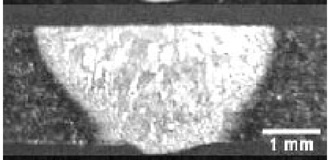
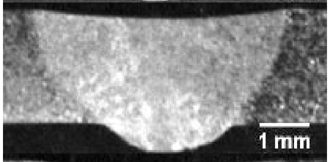
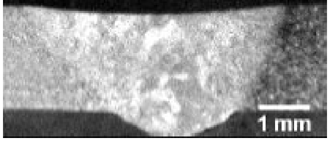
Fig. 4. Dimensions of the tensile specimen as per ASTM Standard.

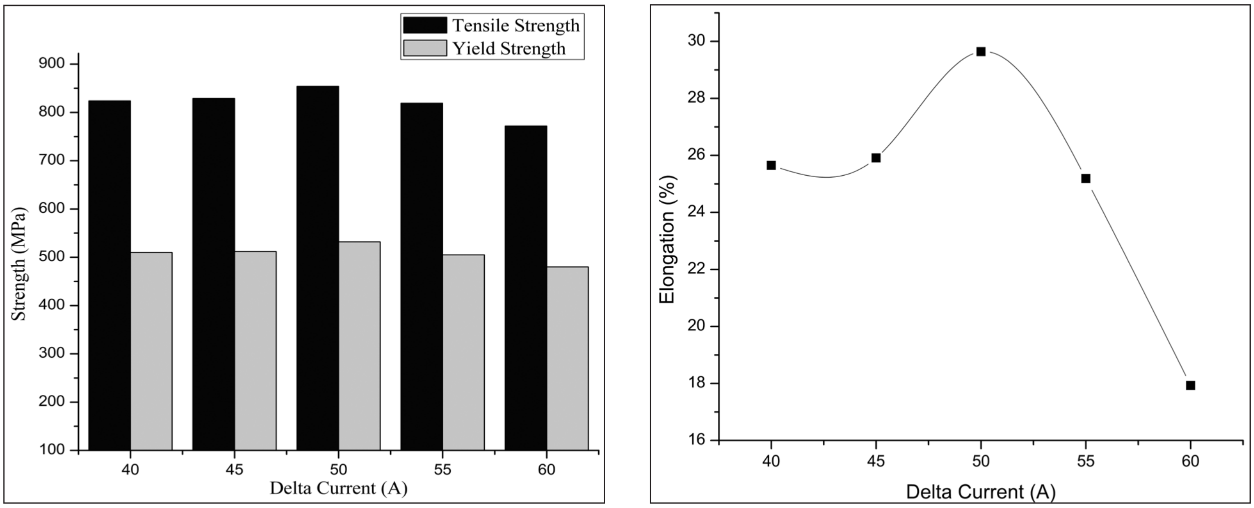
tensile specimens (3 Nos) were extracted from the welded joint and subjected to a tensile oading at a cross head speed of 2 mm/min by a 50 kN servo-controlled tensile testing machine (Make: Tinius Olsen, Horsham, Pennsylvania; Model: H50KL). The average of 3 readings was reported in tensile properties. The ductility was measured with an elongation in gauge length of 50 mm. The 0.2 % offset yield strength was measured from the stress strain curve.

The Vickers microhardness was measured on a mirror polished specimen in the weld centre region by using Vickers Microhardness testing machine (Make & Model: - SHIMADZU HMV-2T) at a testing load of 0.5 Kg and 15 s dwell time as per ASTM 384 standard. The microhardness survey was made at a distance of 0.1 mm from the weld centre at mid-thickness region.

The cross section of metallographic specimens was carefully mirror polished using emery papers and diamond paste with 0.25 um size. The metallographic specimens were etched using a

Table 4
Effect of delta current on weld bead geometry.

Delta Current A	Macrograph	Bead width (mm)	Bead depth (mm)	Avg. HAZ width in (mm)	FZ area (mm^2)	Observations
40		4.725	2.00	0.314	7.680	Correct Penetration
45		4.455	2.00	0.333	7.564	Correct Penetration
50		4.378	2.00	0.384	7.466	Correct Penetration
55		5.168	2.00	0.430	8.378	Excess Penetration
60		4.911	2.00	0.461	8.271	Excess Penetration



a) Delta Current (A) vs Strength (MPa)

b) Delta Current (A) vs Elongation (%)

Fig. 5. Effect of Delta Current on tensile properties of Inconel 718 GTCA welded joints.

Table 5
Effect of delta current on transverse tensile properties of the joints.

Delta Current (A)	Tensile Strength (MPa)	0.2% Offset Yield Strength (MPa)	Elongation in 50 mm gauge length (%)	Joint Efficiency (%)	Failure Location
40	824	510	25.65	94.93	FZ
45	829	512	25.91	95.51	FZ
50	854	532	29.64	98.39	FZ
55	819	505	25.19	94.35	FZ
60	772	480	17.93	88.94	FZ

Kalling's regent to revel both macro and micro structure. The macro structure was taken using sterozoom microscope and microstructure was observed under optical microscope (Make: MEJI, Japan; Model: MIL-7100). The fractographs of the tensile specimens were analysed by SEM.

3. Results

3.1. Bead geometry

The weld bead geometry at different levels of Delta Current is presented in table. 4. All the joints were observed to be defect free. Delta Current showed significant effect on the weld bead at various levels. The increase in Delta Current from lower level 40 A to higher level 60 results increase in weld bead size. The heat input was calculated using the formula [((V x I_{avg} x efficiency)/speed) x1000] where I_{avg} is the average of Main Current and Delta Current. As Delta Current increases theoretical average heat input increases. Increase in weld bead size is due to the increase in heat input in between lower level and higher level of Delta Current during welding. Increase in Delta Current from lower level 40 A to mid-level 50 A results in decrease in weld bead geometry. It is attributed to the increase in magnetic arc constriction with increase in Delta Current. The magnetic arc constriction causes the localized melting of the metal at the joint and reduces the weld bead geometry. However further increase in Delta Current above 50 A results in significant increase in weld bead geometry. Because increase in magnetic arc constriction with incremental levels of Delta Current raises the heat intensity of the arc and reduces the time for the melting of the metal at the joint. As the welding speed is kept constant, there is more melting of the metal due to the increase in heat input during welding.

The heat input effect is more pronounced at higher level 60 A. Increase in Delta Current also results in increase penetration. The joints welded above 50 A showed increase in concavity on the top surface and excess penetration at the bottom. The increase in Delta Current is associated with increase in arc force which tends to increase penetration.

3.2. Tensile properties

The transverse tensile properties of the welded joints are presented in table 5. It is lower than the base material at all levels due to the difference in microstructural characteristic of base metal and fusion zone. The effect of Delta Current on tensile properties of Gas Tungsten Constricted Arc Welded Inconel 718 joints is shown in Fig. 5 The increase in Delta current from lower level to higher level results in decrease in tensile properties. As Delta Current increases the tensile and yield strength increases up to 50 A. Further increase results in decrease in tensile and yield strength of the welded joints. The tensile strength and yield strength are decreased by 6% and 5.88 % when welded at higher level of Delta Current as compared to the lower level. Increase in Delta Current from lower level 40A to mid-level 50 A results in increase in tensile elongation. Further increase results in significant reduction in tensile elongation of the welded joints. Delta Current at higher level 60A results in 30 % reduction in ductility of the welded joints as compared to the lower level 40 A. Higher tensile strength of 854 MPa, Yield strength 532 MPa, ductility 29.64% was achieved at mid-level of Delta Current at 50 A. It is 1.83%, 8.27 % and 22% less as compared to the base metal respectively. Fig. 6 shows the photograph of tensile specimens after testing. All the joints welded at different levels of Delta Current failed in fusion zone. The failure of the Inconel 718 welds in fusion zone are consistent with the observations reported in literature. It is attributed to the segregation of alloying elements resulting in the formation of hard and brittle laves phase in fusion zone which does not assist in plastic deformation [2] [4-10].

3.3. Microhardness

The effect of Delta Current on microhardness of various regions is shown in Table 6. The average microhardness of fusion zone (FZ) and heat affected zone (HAZ) of all the joints is lower than the base metal. Fig. 7 shows the effect of Delta Current on average microhardness of fusion zone (FZ) and heat affected zone (HAZ). It follows the trend of tensile strength at incremental levels of Delta Current. As Delta Current increases from lower level 40 A to mid-level 50 A the average

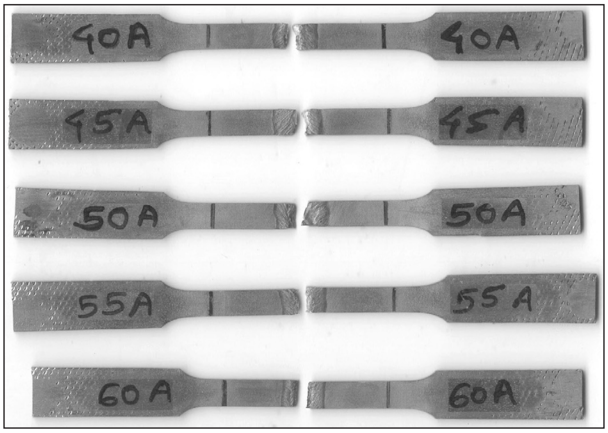


Fig. 6. Photograph of tensile specimens after testing.

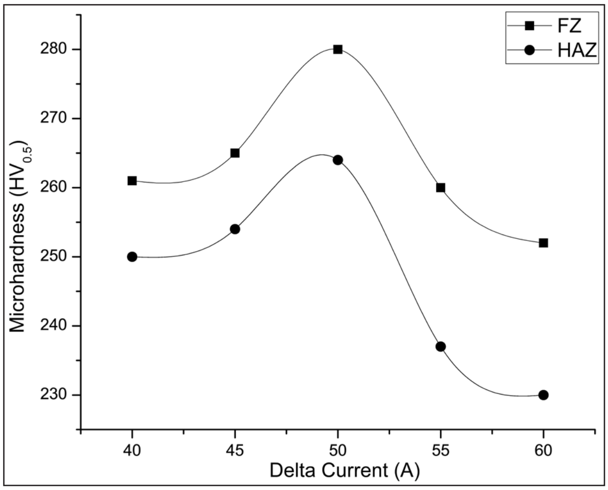


Fig. 7. Effect of delta current on average microhardness of FZ and HAZ.

Table 6
Effect of delta current on microhardness of various regions.

Delta Current (A)	FZ ($HV_{0.5}$)	HAZ ($HV_{0.5}$)	BM ($HV_{0.5}$)
40 A	261	250	292
45 A	265	254	292
50 A	280	265	292
55 A	260	237	292
60 A	250	230	292

microhardness of fusion zone (FZ) and heat affected zone increases (HAZ). However further increase in Delta Current results in decrease in average microhardness values. The results showed 4.21 % and 8% reduction in average microhardness of FZ and HAZ at higher level as compared to the lower level of the Delta Current. The microhardness distribution across the welded joints at mid-thickness region is shown in fig.8. The microhardness values of fusion zone vary away from the weld centre due to the segregation of alloying elements. In fusion zone some region shows considerably lower microhardness values than HAZ and BM. The failure in fusion zone is due to these lower hardness regions observed near the weld centre.

3.4. Microstructure

The microstructure of base metal in solution treated condition is shown Fig. 9 (a). It shows equiaxed grains in austenitic nickel matrix with presence of primary carbides at the grain boundaries. Twinning is observed across some grains. Fig. 9 (b to f) shows the effect of Delta Current on microstructure of fusion zone (FZ). The dendritic structure of fusion zone gets coarsen with increase in Delta Current when compared in between lower level and higher level. Increase in Delta Current from lower level 40 A to mid-level 50 A, showed refinement in dendritic structure of fusion zone. It is attributed to the increase in magnetic arc constriction which reduces the heat input during welding and increase the cooling rate. This results in increase in nucleation and also reduces the time available for the growth of the dendrites thereby refining the dendritic structure of the fusion zone. However further increase in Delta Current results in coarsening of Dendrites. The dendritic structure is much coarser at higher level 60 A. It shows larger interdendritic spacings which are preferential sites for segregation of alloying elements. It is mainly due to the increase in heat input associated with constant welding speed at incremental levels of Delta Current. As increase in magnetic arc constriction reduces the time for the melting of the metal at the joint, the heat input effect is more significant at higher level of Delta Current due to the constant welding speed. Fig. 10 a) shows the fractographs of the tensile

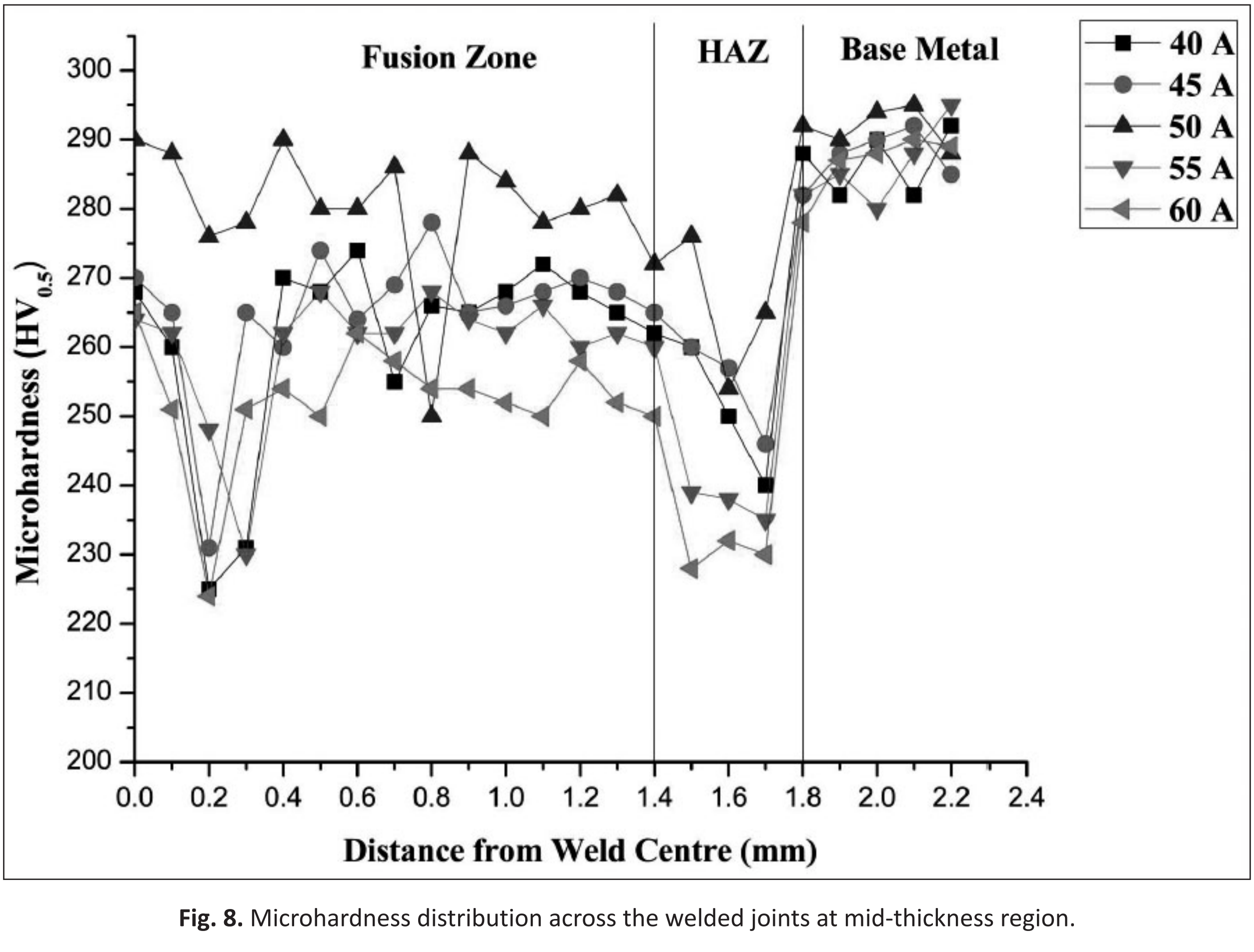
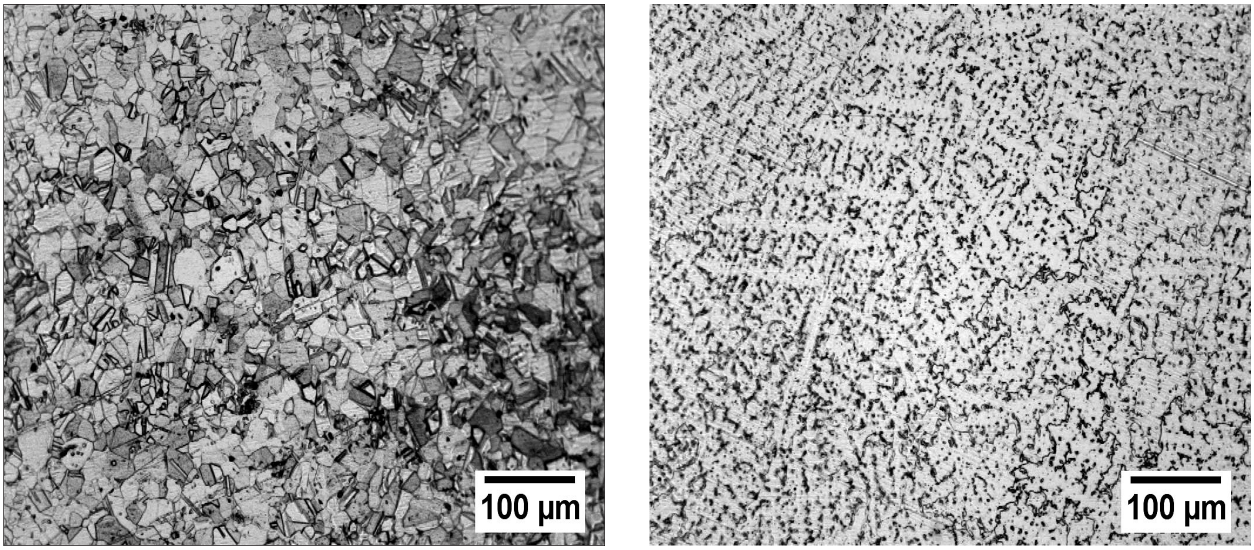
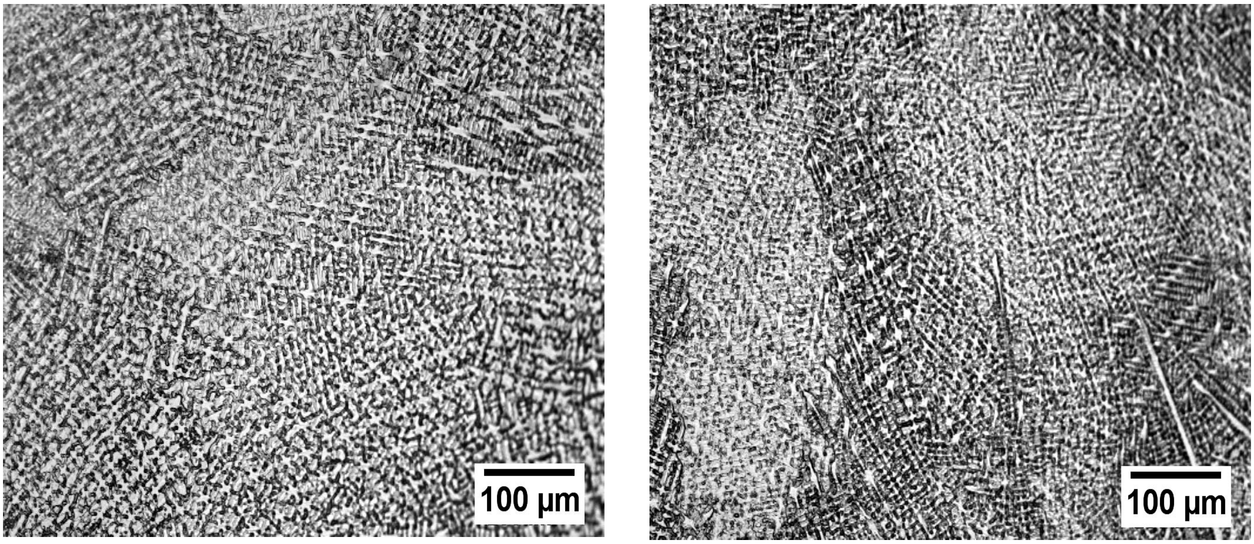


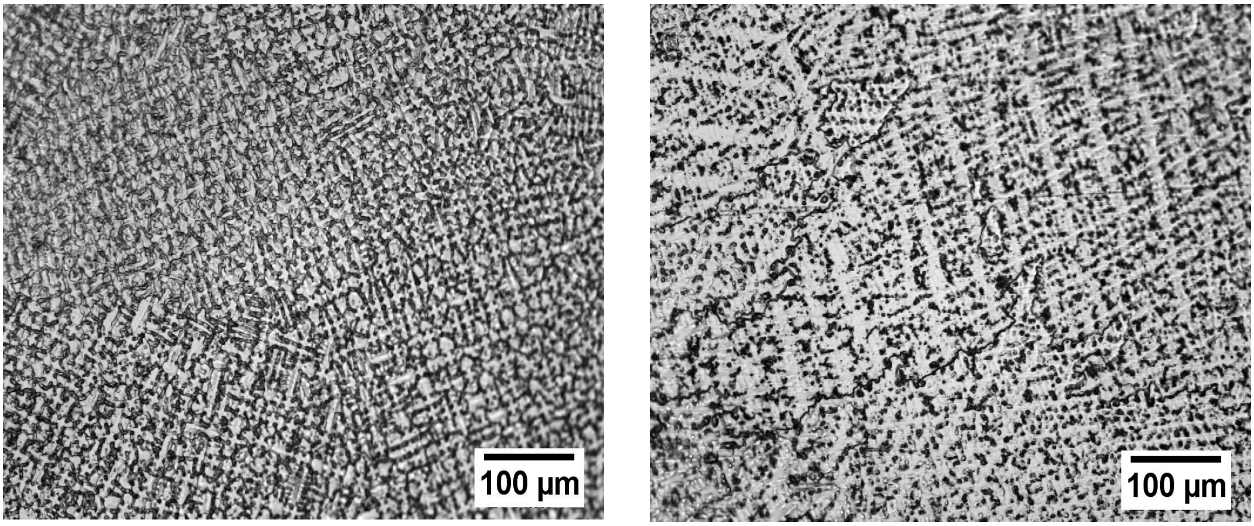
Fig. 8. Microhardness distribution across the welded joints at mid-thickness region.



a) Base Metal b) 40 A

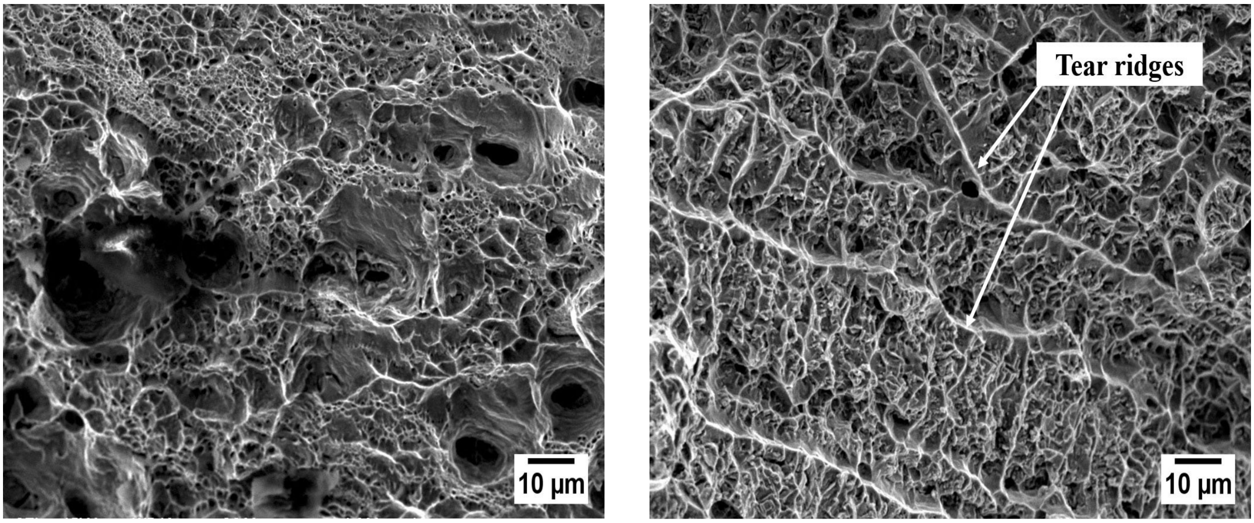


c) 45 A d) 50 A

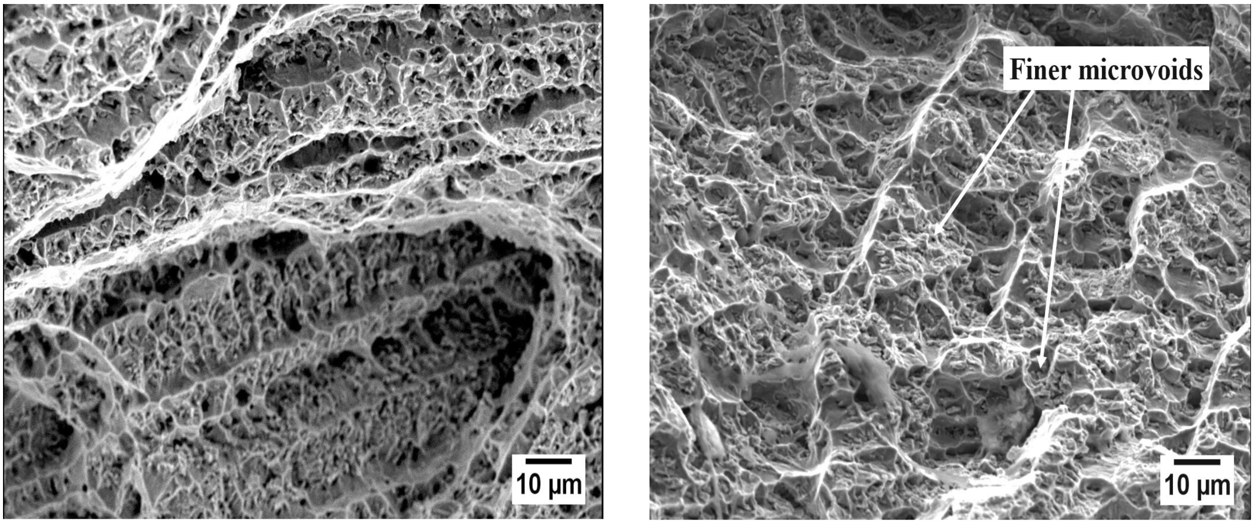


e) 55 A f) 60 A

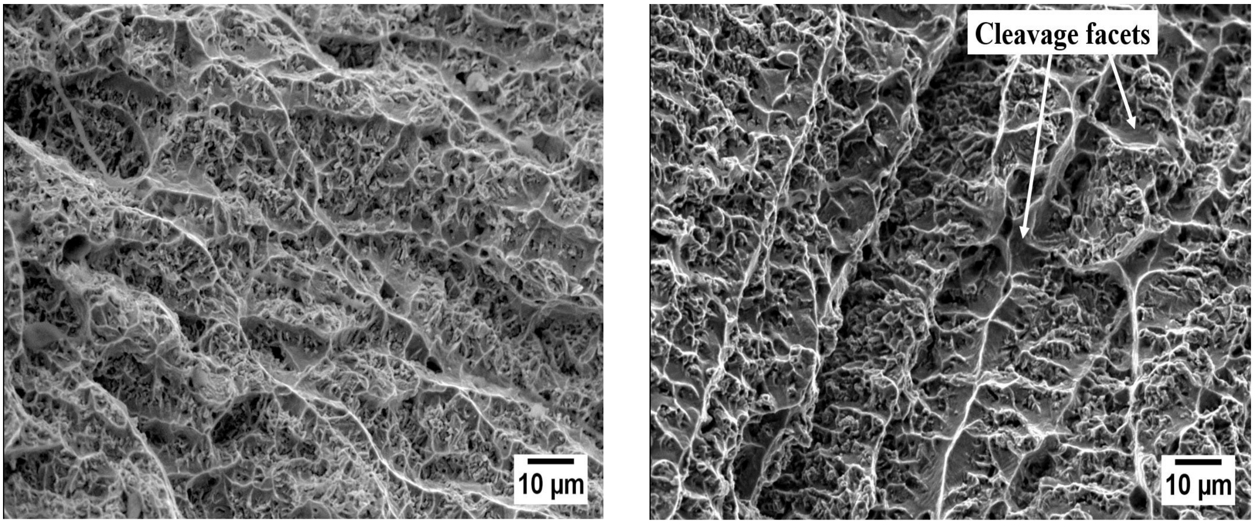
Fig. 9. Effect of delta current on microstructure of fusion zone (FZ).



a) Base Metal b) 40 A



c) 45 A d) 50 A



e) 55 A f) 60 A

Fig. 10. SEM fractographs of the tensile specimens a) Basemetal and b) to f) Welded joints at incremental levels of delta current.

specimen of the base metal. The fracture surface of the base material showed no preferential fracture path and exhibited completely dimple regions. The fractographs of the welded joints at incremental levels of Delta Current is shown in (Fig. 10 b to f). The fracture surface of the fusion zone showed dendritic pattern and exhibited preferential fracture path. The fracture occurred along the interdendritic regions. The joints welded at 50 A Delta Current showed finer and deeper dimple regions where as it was observed to be coarser and shallower at higher level of Delta Current 60 A.

4. Discussions

4.1. Weld bead geometry

Gas Tungsten Constricted Arc Welding is the advanced GTAW process in which the welding arc is constricted by the magnetic field produced by the high frequency pulsing of the Delta Current. Delta Current is the controlling parameter which showed significant effect on the weld characteristics of the joint. As Delta Current increases, there is increase in average theoretical heat input during welding at incremental levels due to the constant welding speed. When the Delta Current increased from lower level 40 A to mid-level 50 A the fusion zone area decreased. It is attributed to the increase in magnetic arc constriction with increase in Delta Current which reduces the wastage of heat on outer flare and increases the heat intensity of the arc. This results in localized heating of metal at the joint and the average heat input is reduced during welding. Thus, the time required for melting of the metal at the joint is reduced. This indicates the interaction effect between the Delta Current and Welding Speed. In this investigation, to study the main effect of Delta Current, the interaction effect of welding speed with Delta Current is neglected i.e. welding speed is kept constant. Further increase in Delta Current above 50 A resulted in increased weld bead geometry. It is attributed to the increase in magnetic arc constriction with incremental levels at constant welding speed resulting in more melting of the metal at the joint. The benefits of the magnetic arc constriction are not achieved at higher level of Delta Current due to the increased heat input effect and constant welding speed. The increase in Delta Current must be associated with increase in Welding Speed to attain the full beneficial effects of magnetic arc constriction.

4.2. Tensile properties

The tensile properties of the welded joints depend on heat input, chemical composition and microstructure. As Delta Current increases the average heat input during welding decreases. This results in increase in cooling rate. The increase in cooling rate provides less time for the growth of the dendrites and solute redistribution. This causes refinement in fusion zone. As the dendritic structure becomes finer, the interdendritic spacing reduces which are the preferential sites for segregation of alloying elements and laves phase formation. Thus, the magnetic arc constriction reduces the depletion of alloying elements from the matrix and core of dendrites to interdendritic regions. The reduced segregation effect provides better strength properties. The increase in tensile strength from lower level 40 A to mid-level 50 A is attributed to the refinement in dendritic structure of fusion zone. However, the tensile properties decrease significantly above 50 A. The benefits of magnetic arc constriction with increase in Delta Current at constant Welding Speed are not obtained at higher level 60 A due to the fact that heat input effect is becoming dominant which reduces cooling rate. It provides enough time for the growth of the dendrites and solute distribution. This results in increase in interdendritic spacing with more segregation of alloying elements. The depletion of alloying elements from matrix and core of the dendrites in interdendritic regions reduces the strength of the welded joints [4][5] [8-10]. Thus, the reduced tensile properties at higher level of Delta Current is attributed to the coarser dendritic structure.

4.3. Microhardness

Segregation and growth of dendrites are temperature-time dependent. The average microhardness of fusion zone increases with increase in Delta Current from lower level 40 A to mid-level 50 A due to the decrease in average heat input and enhancement in cooling rate. It is attributed to the increase in magnetic arc constriction which provides refinement in fusion zone and decreases the segregation of alloying elements from matrix in the interdendritic regions. The microhardness increases due to the reduced depletion of alloying elements from the matrix. Higher microhardness of 281 HV observed at 50 A Delta Current is attributed to the finer dendritic structure due to the optimum heat input. The microhardness of fusion zone decreases significantly above mid-level 50 A due to the increase in heat input effect and reduced cooling rate. The lower microhardness of fusion zone at higher level of Delta Current is attributed to the coarser dendritic structure and segregation of alloying elements in interdendritic regions. The microhardness of fusion zone varies when measured along the weld centre at an interval of 0.1 mm. It is due to the segregation of alloying element. As Inconel 718 is heavily alloyed material, it is having large thermal gradient in between solidus and liquidus. Solidification takes place by constitutional supercooling. This causes segregation of alloying elements in fusion zone during solidification [1]. Thus, some regions showed lower hardness values which are depleted of the strengthening alloying elements from the matrix. These are the regions where strength is less andfailure takes place. The failure in the fusion zone is attributed to the lower microhardness values observed in fusion zone.

4.4. Microstructure

The Inconel 718 alloy being heavily alloyed with large number of alloying elements have large solidification range and solidifies in dendritic mode. The growth of the dendrites is directly proportional to heat input. Increase in Delta Current from lower level 40 A to mid-level 50 A showed refinement in dendritic structure of fusion zone. The increase in magnetic arc constriction minimizes the heat input during welding and enhance the cooling rate by increasing the heat intensity of the arc. Thus, the thermal gradient towards the weld centre and base metal reduces. As there is no steep thermal gradient between the weld centre and base metal, it results in significant undercooling which leads to the refinement of dendritic structure. As the magnetic field is imposed on the arc and periodically reversed, it results in generation of circular internal motion in the weld pool around the electrode axis [11]. This results in stirring of the molten pool and reduces the segregation of alloying elements in the weld pool. The arc constriction and release also enhance the cooling rate by increasing the fluid motion in the weld pool. This provides increase in the nucleation sites and refinement in fusion zone. The finer dendritic structure observed at 50 A Delta Current is attributed to the increased magnetic arc constriction and optimum interaction effect of Delta Current and Welding Speed. As the magnetic arc constriction raises the heat intensity of the arc, it reduces the time required for the melting of the metal at the joint. But as the welding speed is kept constant to understand the main effect of Delta Current, there is more melting of metal at the joint at incremental levels of Delta Current. Increase in Delta Current at constant Welding Speed increases the theoretical average heat input during welding. The heat input effect is more pronounced at higher level of Delta Current due to the constant Welding Speed. This results in increase in thermal gradient between the weld centre and base metal. This in turn reduces the heat transfer rate and provides enough time and conditions for the growth of the dendrites. The significant coarsening of dendritic structure is observed at higher level of Delta Current 60 A.

Increase in Delta Current from lower level 40 A to mid-level 50A resulted in decrease in the size of the dimples and microvoids. It is attributed to the refinement in dendritic structure which provides resistance to the microvoid formation and tearing. This resulted in increase in tensile properties up to 50 A. The joints welded at 50 A Delta Current showed finer dimple region and microvoids. Further increase resulted in the formation of smaller cleavage facets in the dimpled regions which provides easy crack initiation and propagation. The joints welded at higher level of Delta Current 60 A showed the presence of more cleavage facets in dimpled regions along the tear ridges. It is attributed to the coarser dendritic structure. Segregation of the alloying element and the laves phase formation is more pronounced in interdendritic regions of coarse fusion zone due to the high heat input. The cleavage facet regions are formed during tensile loading due to the incoherent, hard and brittle lave phases as it does not assist in plastic deformation and weakens the interface between the matrix and dendrites due to the depletion of alloying elements. This provides the brittle crack initiation and propagation regions. This is the main reason that the joints welded at 60 A Delta Current showed significant reduction in tensile properties. The benefits of magnetic arc constriction are not achieved at higher level of Delta Current due to the constant welding speed increasing the heat input significantly.

5. Conclusion

1. Delta Current is observed to have major effect on the tensile properties and microstructural characteristics of Inconel 718 alloy welds. Thus, the optimum selection of Delta Current is necessary for the better mechanical properties.
2. Increase in Delta from lower level 40 A to mid-level 50 A results in increase in tensile properties and microhardness of the welded joints. It is attributed to the refinement in dendritic structure of fusion zone. Further increase results in decrease in mechanical properties due to the coarsening of dendritic structure of fusion zone.
3. The magnetic arc constriction increases with increase in Delta Current which provides better control on weld bead geometry up to mid-level of Delta Current 50 A. The benefits of magnetic arc constriction are not achieved at higher level of Delta Current.
4. The interaction effect exists between Delta Current and Welding Speed. The welding Speed must be increased with increase in Delta Current.
5. The joints welded at 50 A Delta Current showed higher tensile properties and microhardness. It is attributed to the finer dendritic structure and reduced segregation of alloying elements due to the optimum heat input and interaction effect of Delta Current and Welding Speed.

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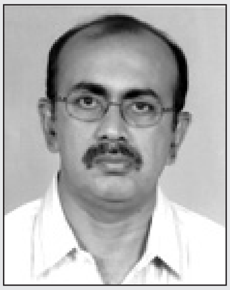
Tushar Sonar is a Research Scholar in the Centre for Materials Joining and Research (CEMAJOR), Dept. of Manufacturing Engineering, Annamalai University, Annamalai Nagar, Tamilnadu. He is working on ISRO RESPOND project in Gas Tungsten Constricted Arc (InterPulse TIG) welding of Aerospace alloys. He graduated from Sir Visvesvaraya Institute of Technology Nashik in 2013 and completed his post-graduation from Maharashtra Institute of Technology Aurangabad in 2015. He has presented 5 research papers in international conferences. His areas of interest are welding of Nickel and Titanium alloys, Heat treatment and Additive Manufacturing. (E-mail: tushar.sonar77@gmail.com)

Dr. V Balasubramanian is working currently as Professor & Director of Centre for Materials Joining & Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar, Tamilnadu. He graduated from Government College of Engineering, Salem, University of Madras in 1989 and obtained his post graduation from College of Engineering, Guindy, Anna University, Chennai in 1992. He obtained his Ph.D from Indian Institute of Technology Madras (IITM), Chennai in 2000. He has 26 years of teaching experience and 20 years of research experience. He has published more than 300 papers in SCOPUS indexed Journals and supervised 23 Ph.D scholars. His areas of interest are Materials Joining, Surface Engineering and Nanomaterials. He has completed 25 R&D projects worth of Rs. 10.00 crores funded by various funding agencies such as DST, DRDO, UGC, AICTE, DAE NRB & ARDB, Ministry of Environment & Forest.
(E-mail: visvabalu@yahoo.com)

Dr. S Malarvizhi is working currently as Professor, Centre for Materials Joining & Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar, Tamilnadu. She obtained her Ph.D from Annamalai University, Chidambaram 2008. She has published several research papers in National and International Journals and Conferences. She has 20 years of teaching experience and 14 years of research experience. Her areas of interest are: Welding Technology and Material Science. She has completed various Sponsored R & D projects from many agencies such as AICTE, UGC, DST, DRDO, CSIR & MEF (as Principal Investigator). (E-mail: jeejoo@rediffmail.com)

Dr. T Venkateswaran is a Scientist at Materials and Metallurgy Group (MMG) of Vikram Sarabhai Space Centre (VSSC), ISRO, Thiruvananthapuram, Kerala. He obtained his under graduate and post graduate degrees from Government College of Engineering (2002), Salem and Indian Institute of Technology, Kanpur (2005) respectively. He obtained his Ph.D. from Indian Institute of Technology, Madras, (2018) in the area of metal joining. He served as visiting research scholar at Seoul National University (SNU), South Korea before joining VSSC. He has authored/co-authored more than 25 publications in international journals. At present, engaged in various developmental activities connected to the upcoming launch vehicles of Indian Space Research Organization (ISRO). His research interest includes brazing of metallic and ceramic materials, welding of aerospace materials, high temperature materials, and ultra high temperature ceramics.
(E-mail: tvenkateswaran@gmail.com)



Dr. D Sivakumar is a Scientist at Materials and Metallurgy Group (MMG) of Vikram Sarabhai Space Centre (VSSC), ISRO, Thiruvananthapuram, Kerala, India. He obtained his undergraduate degree from IIT Madras and Ph.D from IIT Mumbai in the area of welding. He is currently heading the Heat Treatment and Welding Metallurgy division in VSSC, Trivandrum.He has more than 25 years of research and industrial experience in welding and brazing of stainless steels and superalloys.He has authored/ co-authored 55 publications in the areas of steels, welding and brazing. His research interests include development of high strength steels, maraging steels, welding of steels, superalloys and aluminium alloys and vacuum brazing. (E-mail: dsivakumar@yahoo.com)