Electron Beam Welding of Nickel Base Alloy 718

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ABSTRACT

As with inventions and evolutions of other manufacturing processes, requirements and developments of our present atomic and space-age worked together to accomplish continuing gains in welding technology, i.e. stronger welds with less heat affected zone by evolving exotic new metal joining processes like laser, diffusion and electron beam welding (EBW).

A detailed study of EBW process was made with its inherent advantages/attributes in making use of this process and its limitations in welding of Inconel 718. Optimum welding parameters were established making use of high vacuum mode of EBW's application for welding of Inconel-718. Welds so made were subjected to quality checks i.e. Radiographic Examination of Welds, Joint Efficiencies, Residual Stresses, Metallographic Examination of Welds & the Effect of Post Weld Heat Treatment (PWHT) on mechanical properties to qualitatively demonstrate capabilities of EBW.

Keywords: Electron Beam Welding, Evaluation, High vacuum mode, Laves Phase, Precision welding, Residual Stresses, Weld quality.

INTRODUCTION

EBW is one of the major technological innovations of 1950's, evolved to weld highly reactive materials for nuclear power industry. Subsequently because of its major advantage of offering stronger welds with less heat-affected-zone than the competitive methods, the process has been applied to a wide range of alloys used in critical applications in aircraft & aerospace industry, field of applications of EBW is stretching wider & wider with the developments made & being explored still further in the field of generation, beam optics and control of electron beams in association with deployment of higher efficiency vacuum generation equipments etc.

High purity environment, exceptional power densities and outstanding control capabilities are principally responsible for unique performance capabilities of EBW resulting in significantly lower heat inputs, low levels of distortion, higher depths to width ratio's, superior control over penetration and other mechanical properties etc.

EBW is best suited for welding of refractory materials. Other attributes of the process are long focus, wide range of thickness handled, welding of dissimilar metals, high accuracy of repeatability, high welding speeds. Major limitations being requirement of high vacuum placing limitations on the size of a component, high cost of equipment, precise fitment of joints. Metals or alloys having high gas content or high vapor pressure are difficult to weld by Electron Beam.

EBW being a precision welding process finds use in fabrication of nuclear energy systems & in aerospace industry.

THE MATERIAL

INCONEL-718 is one of many high temperature, high strength precipitation hardened Nickel base alloys, introduced in the late 1950's, developed by International Nickel Company of Canada, principally to cater to the requirements of fabrication of aero engine components i.e. for the aircraft gas turbine blades and rotors which were required to withstand high temperature plus large induced stresses, by virtue of their superior properties. Ref. Table I for a typical composition[12] of the alloy.

The alloy is suitable for service from 423^{0}F to 1300^{0}F, is now being widely used commercially in sheet, plate, bar & in forged or cast forms. On heat treating this alloy can attain room temperature mechanical properties[7] of greater than

Element	Composition, %
Nickel + Cobalt*	50- 55
Chromium	17- 21
Iron	16
Carbon	0.03- 0.10
Silicon	0.35
Manganese	0.35
Sulphur	0.015
Phosphorous	0.015
Molybdenum	2.8- 3.0
Columbium/ Niobium + Tantalum	5.0 - 5.5
Aluminum	0.40- 0.80
Titanium	0.70- 1.15
Copper	0.10
Boron	0.002- 0.006

* Cobalt being max of 1%

Table 1 : A Typical Composition of Inconel 718

200,000 psi UTS & 170,000 psi yields strength with elongation of greater than 20%. On heating to 1300°F the tensile strength drops to 130,000 psi, yield strength at this temperature is nearly the same (i.e. 128,000 psi). In addition to these very desirable high-temperature mechanical properties alloy 718 exhibits excellent strength & toughness at cryogenic temperatures.

Inconel 718 is finding its application as base line material for hot structures in recent development of faster and longer reaching missiles, requiring protection from aerodynamic heating & long soaking times resulting from required speed & long ranges, causing surface temperatures in excess of 1100°F (600°C). Secondly external thermal protection systems must be kept to a minimum to optimize the fuel capacity. Conventional missile systems that accelerate at extremely high rates during flight rely on external thermal protection systems to maintain the primary structural members at temperatures below 300°F (150°C).

Its seawater corrosion properties make it an attractive material for high strength marine applications. It is used as a material of construction in the liquid Sodium cooled fast breeder reactors in atomic power plants & nuclear industry, in the form of combustion cans and after burner liners in a wide variety of turbines & in fabrication of liquid rocket motors.

METALLURGICAL CONSIDERATIONS & THE PROCESS

Dr. Hrivnak[16] described an ideal weldable metal as one "which is neither sensitive to hot cracking, reheat cracking or lamellar tearing, nor susceptible to hydrogen induced cracking in the most advanced applications and which is not subject to transformation embrittlement in the heat affected zone, nor sensitive to notches & internal stresses."

The world of metallurgy has yet to discover revolutionary new concepts of steel production, and ideal weldable steel.

Whereas weldability describes the capacity of a metal to be welded under fabrication conditions imposed into a specific suitably designed structure & to perform satisfactorily in the intended service.

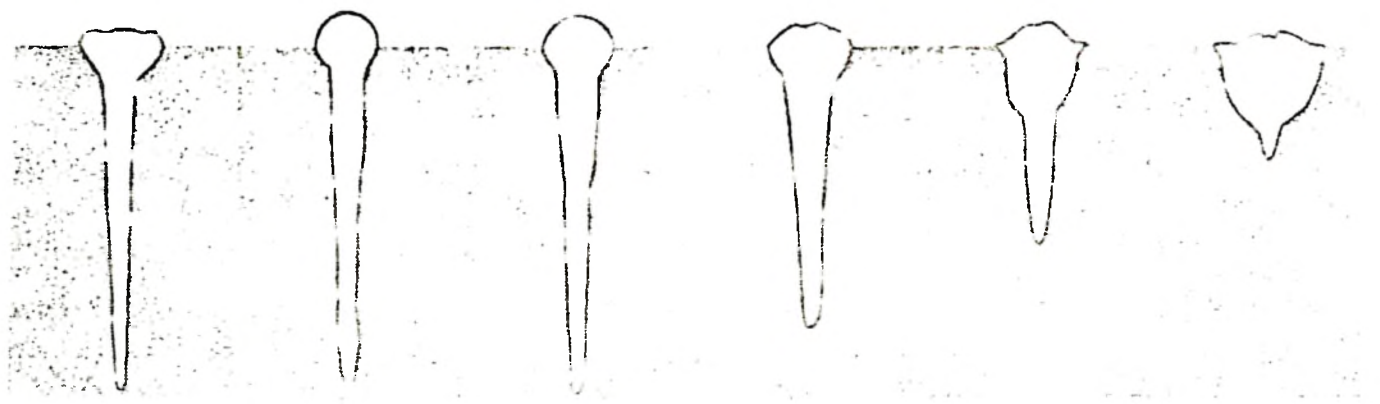
Of the more heat resistant members of the precipitation hardneable nickel base super alloys, one property unique to alloy 718 is the outstanding weldability of the material in either the age-hardened or annealed condition. The superior weldability is the result of strengthening by precipitation of Ni_3 (Nb Al Ti) Y` phase rather than by the usual $Ni_3$(Ti Al) Y` precipitation.

High strength alloy 718 has been considered the most weldable of the precipitation hardened, nickel base alloys because of its ability to resist post weld heat treat cracking (also called strain-age cracking).

The crack resistance of the alloy 718 in the heat affected zone arises from its low strength & higher ductility at the start of aging which permits more rapid relaxation of stresses & crack free accommodation of larger resulting strains. This is made possible by hardening with Columbium, which yields slower aging response than obtained with Aluminum & Titanium. A tendency towards over-aging however restricts the use of alloy hardened by Columbium to temperature below 1300°F (approx.).

Thermal strain & metallurgical effects are always inter-related, since it is impossible to heat and cool a metal locally without producing some strain.

Reducing thermal strain associated with Electron Beam Welding (approximately 1/10th in comparison with other conventional processes) together with narrow fusion and heat-affected zones, leads to two main metallurgical advantages, i.e. reduced incidence of cracking during & after welding, improved weld properties because of



For electron beam welds made on type 304 stainless steel, using a beam length of 16 in without changing focus. Maximum penetration shown in approximately ½ in. Welding conditions were : 150 kv, 30 ma. and 60 in. per minute. (J. W. Meier, Metal Progress, July 1966, p 63-64)

Fig. 1[23] Effect of welding-chamber pressure on penetration and weld shape

reduced metallurgical damage, in addition to low distortion levels achieved.

The extent of heat spread into work piece controls the extent of associated strain field. Narrow strain field reduces the risk of cracking.

The cracking tendency associated with welding is influenced by the strain field into the material, as also by the strain rate sensitivity of the material.

On both of these points the alloy 718 & the process score excellently well.

It has been suggested[12] after undertaking intensive investigations of weldments in alloy 718 that weld nugget shape and the associated stress patterns are also contributing to heat-affected zone cracking[4]. Welds made by high voltage (100-150 KV) EBW process, tend to produce a wedge shape weld nugget with less change in reentrant angle and are less crack sensitive than those made by the low voltage process (22-26 KV), like gas tungsten inert arc welding. Further the cracking susceptibility is drastically reduced if fine-grained materials are welded by the high voltage electron beam welding.

Flexibility afforded by variations of various welding parameters together with added features, for oscillation of beam parallel or perpendicular to welding direction, beam spinning, beam deflection, beam power pulsation, and post heating of weld with a defocused beam etc., the process can help to avoid detrimental micro-structural conditions in the weld metal or in the heat affected zone.

Electron beam welding with all beneficial characteristics, namely the smaller weld, the restricted heat-affected zone and lower residual stress levels, may be of help to eliminate micro cracking.

Power density is probably the most significant parameter of an electron beam as it controls the magnitude of heating in the irradiated material. Moreover refined electron optics can produce beams whose power density distribution is of a pre determined profile. In welding it has been claimed[3] that an annular power distribution ratter than the gaussian one normally produced with more convention units, reduces the incidence of porosity.

Additionally the high vacuum in the welding chamber results in deep penetration capability of the beam principally responsible for high depth to width ratio's (as illustrated in Figure1[23], for type 304 stainless steel)

OBJECTIVE

Investigations of previous researchers have shown that welding of Inconel 718 is beset with certain problems, i.e., microfissuring in the heat affected zone, poor impact & ductility properties of the weld fusion zone & poor penetration .

Objective of the experimented investigations was to see if electron beam welding of Inconel 718 would eliminate or minimize occurrence of these problems & to obtain optimum combination of mechanical properties Measurement of residual stresses & metallographic investigations were carried out to characterize the quality of welds.

Experiments were conducted with material in different heat treated conditions & appropriate effect of suitable post weld heat treatment investigated.

EXPERIMENTAL INVESTIGATION AND RESULTS

High Vacuum Electron Beam mode of welding had been applied to a Nickel base precipitation hardening supper-alloy, i.e. INCONEL-718, used for high temperature applications.

Welds were made on an Electron Beam Welding machine made by M/s HAWKER SIDDELEY DYNAMICS ENGG. LTD., UK, having following specifications: Maximum power rating of 25KW,

- Maximum accelerating voltage of 150KV,
- Maximum beam current of 167mA,
- Focusing range of 7.62 cms to 1.27 mtrs from base of the gun,
- Continuous variable speed of 10 - 300 cms/ min

ESTABLISHING WELD PARAMETERS

The starting point was establishing of welding parameters for 1mm thick solution treated specimens of Inconel 718.

After extensive melt runs on 1 mm thick plates in solution treated condition the plates were welded at operating parameters as detailed in the table II below:

While establishing weld parameters the following was kept in mind, i.e.

- The optimum combination of weld parameters for a deep penetration weld with the minimum of heat input is one that combines high power density with high total beam power to produce welds at the highest possible speed.
- The beam diameter is a critical parameter since it decides the power density of the beam & hence its penetration capabilities

Weld Parameters	Material	
	Sol'n trtd	Aged
Accelerating Voltage, KV	100	100
Beam Current, milliamps	5.5	6.5
Filament Current, amps	6.2	6.2
Vacuum Gun Chamber, torr	10-5	10-5
Vacuum Work Chamber, torr	10-4	10-4
Weld Speed, mm/sec	20	20
Gun to Work Distance, mm	595	595
Beak Spot diameter, mm	0.7	0.7
Heat Input per pass, joules/mm	27.5	27.5

Table 2 : Welding Parameters

The welds so obtained were subjected to visual and radiographic examination. The radiographs show complete freedom from welding defects such as cracks, under fill or undercut, lack of fusion or lack of penetration or porosity.

Welds were made on material in solution treated & aged condition and their mechanical properties were compared with those of base metal. Details of aging & solution treatment are as listed below.

Aging treatment consisted of the following steps :

i. 8 hrs at 1325°F,
ii. Furnace cool to 1150°F
iii. Hold for 8 hrs at 1150°F & then
iv. Air cool

Solution treatment consisted of the following steps :

i. 1 hr at 1750°F unless otherwise specified & then
ii. Air cool

Further effect of post weld heat treatment on the welds so made were investigated in respect of the mechanical properties as detailed in Table III, IV & V below

Test Details	Weld Specimen			Base Metal	
	#1	#2	#3	#1	#2
UTS, MPa	880	716.85	856	832	836.07
0.2% Proof Stress, MPa	448	387	408	432	442.62
% Elongation	58.2	25	62	60	58
jt as % of UTS	105.76	86.16	102.88	-	-
jt as % of 0.2 proof stress	103.70	89.95	94.44	-	-
Remarks	*	**	*	Gauge Length 5.65 $\overline{Ao}$	

- * Fractured Outside Weld - ** Broke in the Weld,
- Ao is the Original Area of Cross Section of the test specimen

Table 3 : Tensile Properties of Alloy 718 Weldments in comparison with Base Metal, in solution treated condition

Test Details	Welded Specimen				
	#1	#2	#3	#4	#5
UTS, MPa	930.33	1004.10	925.76	921.49	1000
0.2% Proof Stress, MPa	524.6	983.61	515.28	524.79	948.91
% Elongation	41.4	7.14	37	40.7	7.1
jt. as % of UTS	66.7	72	65.9	65.7	71.4
jt. as % of 0.2 proof stress	42.3	80.4	42.1	43.0	77.5
Remarks	*	*	*	*	*

- * Broke in the Weld

Table 4 (A) : Tensile Properties of Alloy 718 Weldments in comparison with Base Metal in aged condition

Test Details	Base Metal Specimen	
	#1	#2
UTS, MPa	1394.85	1400
0.2% Proof Stress, MPa	1223.18	1230
% Elongation	31.8	33.9
Remarks	Gauge Length 5.65 $\sqrt{Ao}$	

- Ao is the Original Area of Cross Section of the test specimen

Table 4 (B): Test Details of Alloy 718 Plates (Base- -Metal), in aged condition

Test Details	Heat Treatment 'A'	
	Weld #1	Base Metal
UTS, MPa	1360.56	1395.16
0.2% Proof Stress, MPa	1149.30	1233.87
% Elongation	30.9	22.9
jt. as % of UTS	97.5	--
jt. as % of 0.2 proof stress	93.1	--
Remarks	*	Gauge Length 5.65 $\sqrt{Ao}$

- * Broke in the weld,
- Ao is the Original Area of Cross Section of the test specimen
- 'A'- refers to specimen given 1800°F Solution treatment & aged at 1325°F/ 1150°F

Table 5 (A): Tensile Properties of Alloy 718 Weldments in comparison with Base Metal with Post Weld Heat Treatment 'A'

Test Details	Heat Treatment 'B'			
	Weld #1	Weld #2	Weld #3	Base Metal
UTS, MPa	1245.21	1135.37	1236.84	1235.77
0.2% Proof Stress, MPa	1022.99	1017.47	1008.77	1008.13
% Elongation	35.7	5	37	31
Jt as % of UTS	100.76	91.87	100.08	-
Jt as % of 0.2 proof stress	101.47	100.92	100.06	-
Remarks	*	**	*	Gauge Length $5.65\sqrt{Ao}$

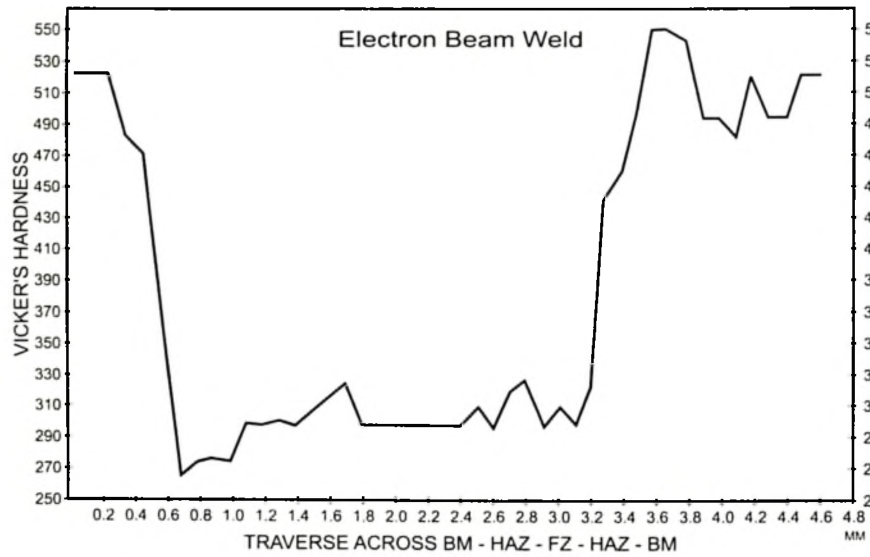
- * Broke outside weld,
- **Broke in the weld
- Ao is the Original Area of Cross Section of the test specimen
- 'B'- refers to specimen given 1900°F Solution treatment & aged at 1325°F/ 1150°F

Table 5 (B) : Tensile Properties of Alloy 718 Weldments in comparison with Base Metal with Post Weld Heat Treatment 'B'

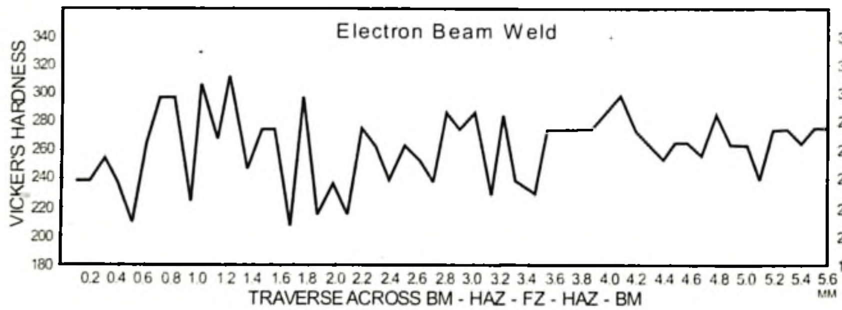
Test Details	Heat Treatment 'B'			
	Weld #1	Weld #2	Weld #3	Base Metal
UTS, MPa	1317.27	1229.85	1195.22	1158.33
0.2% Proof Stress, MPa	1176.71	1000	1007.97	94.67
% Elongation	7.14	40.63	27.9	30
jt as % of UTS	113.72	106.17	103.18	-
jt as % of 0.2 proof stress	124.96	106.19	107.04	-
Remarks	**	*	*	Gauge Length $5.65\sqrt{Ao}$

- * Broke outside weld;
- ** Broke in the Weld
- Ao is the Original Area of Cross Section of the test specimen
- 'C'- refers to specimen given 2000°F Solution treatment & aged at 1325°F/ 1150°F

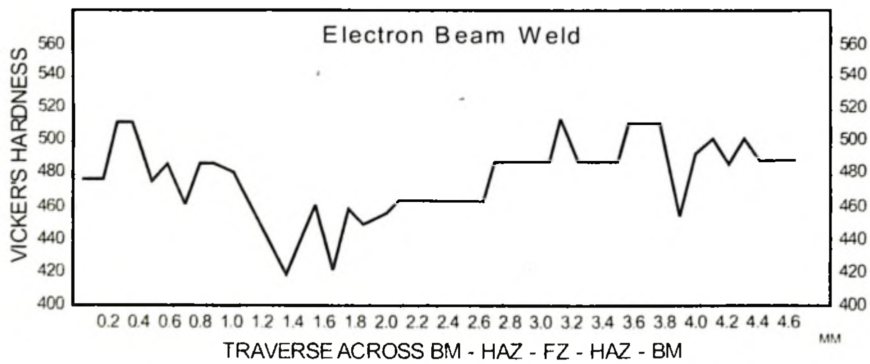
Table 5 (C): Tensile Properties of Alloy 718 Weldments in comparison with Base Metal with Post Weld Heat Treatment 'C'



Graph G1 : Micro Hardness Traverse for Welds made in Aged Plates.



Graph G2 : Micro Hardness Traverse for Welds made in Solution Treated Plates



Graph G3 : Micro Hardness Traverse for Welds made in Solution Treated Plates & given Post Weld Ageing Treatment.

Refer Graphs G1, G2 & G3 for Micro hardness traverse across the Base Metal - Heat Affected Zone - Fusion Zone - Heat Affected Zone - Base Metal, for welds made with material in aged & solution treated condition, taken with each successive reading at an interval of 0.2 mm, over a maximum traverse length of 2.8 mm on each side of the weld centre line. Vicker's hardness was obtained by converting micro hardness readings taken on cross section of the welded joints at their midpoints.

Results of the welds made in plates in aged condition demonstratively show the extent (i.e. small confinement), of heat affected zone on each side of the weld joint, whereas the welds made with plates in the solution treated condition show the profile across the weld zone of the specimen which is much smoother with very less variation in hardness.

Test Details	Experimental Observations #1	#2	#3	#4	#5	#6
Distance of gauge from weld joint, mm	1.3	1.56	1.80	0.56	0.80	1.58
Tangential Stress, kgf/mm^2	+0.4	+3.9	+3.95	-16.8	- 16.6	-35.3
Normal Stres, kgf/mm^2	-2.2	- 4.90	-42.4	-33.1	- 40.6	-55.4
Heat Input, joules/mm	27.5	27.5	55	55	55	55

a) +ve sign denotes tensile stresses,
b) -ve sign denotes compressive stresses,
c) Observations #1, #2, #3 & #4 are for plates welded in solution treated condition,
d) Observation #5 is for plates welded in aged condition,
e) Observation #6 is for plates welded in solution treated condition & given post weld 2000^0 F solution treatment + aging (1325^0 F/ 1150^0 F) treatment.

Table 6 : Measurement of Residual Stresses in electron Beam Weldments made in 1mm thick Inconel Alloy 718

MEASUREMENT OF RESIDUAL STRESSES

Residual stresses were measured by making use of the Strain- gauge hole drilling method[21,22].

The results (refer table VI) show that internal stresses remaining after post weld heat treatment were appreciably higher in magnitude than those in the "as welded" condition (applicable to welds made with plates in the solution treated and to the welds made with plates in aged condition). The stresses in "as welded" condition were negligible with respect to the base metal strength of 85kgf/ mm^2 in solution treated & 156kgf/ mm^2 in the precipitation hardened condition.

The results are a practical demonstration of the fact that EBW employs minimum heat input for making of sound quality welds, an essential requirement for critical applications for aerospace & nuclear industries.

Metallographic Examination of Weldments:

Photomicrographs 1 through 7 depict microstructure examination of welds as detailed below:

Figure 2 : (Photomicrograph 1) Fusion Zone Heat Affected Zone Base Metal, in solution treated specimen, Magnification: x50; Etchant: 10% Oxalic acid.

Figure 3 : (Photomicrograph 2) Fine Grained Dendritic Cast Structure of Metal in Fusion Zone, Magnification: x50, Etchant:: 10% Oxalic acid

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Metallographic Examination of Weldments:

Photomicrographs 1 through 7 depict microstructure examination of welds as detailed below:

Microstructure examination (Ref. Photomicrographs 1 through 7), shows that the welds made by EBW are essentially free from intergranular cracks / micro fissures as is expected of a fine grained material[11]

CONCLUSIONS

Specimens welded in solution treated condition and given post weld solution treatment at 1800^0F + aging at 1325^0F/ 1150^0F gave maximum

Figure 4 : (Photomicrograph 3) Segregation at Fusion Zone boundaries in solution treated specimen, Magnification: x100, Etchant: 5% Chromic acid

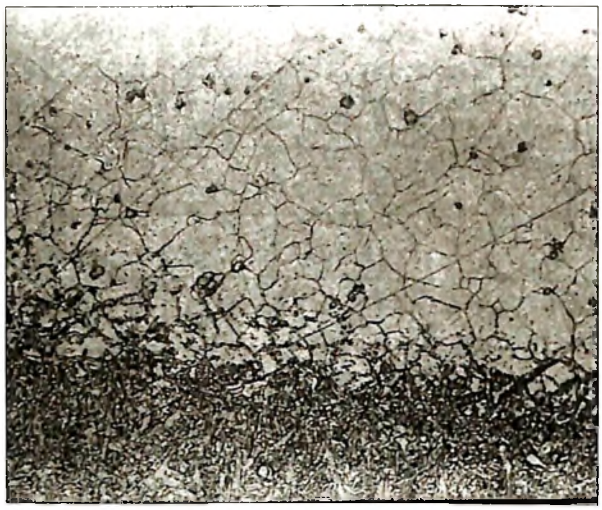

Figure 5 : (Photomicrograph 4) Segregation at Fusion Zone Heat Affected Zone, boundaries in soiution treated specimen, Magnification: x100, Etchant: 5% Chromic acid

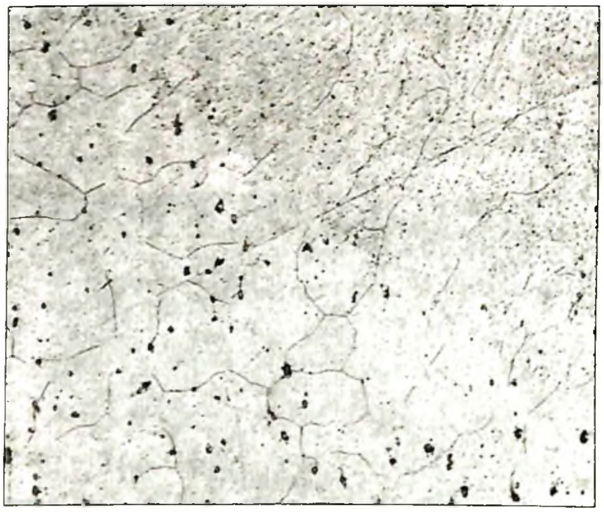

Figure 6 : (Photomicrograph 5) Fusion Zone Heat Affected Zone of welds made in solution treated specimen given post weld solution treatment, Magnification: x100, Etchant: 10% Oxalic acid

Figure 6 : (Photomicrograph 5) Laves Phase in the fusion zone of the weldment, Magnification: x1000, Etchant: 5% Chromic acid

value of UTS, along with better values of % elongation in comparison with what can be obtained with other processes of welding. This is because of lesser amount of heat input that goes in welding by Electron Beam (process).

Specimens given 2000°F post weld solution treatment showed the highest amount of % elongation (40%); this is expected as a more complete dissolution of Laves phase which occurs at 2000°F than at 1800°F / 1900°F.

Joint efficiencies recorded for all the specimens given post weld heat treatment were of the order of 100%, which proves capability of EBW process to obtain high joint efficiencies, coupled with high % elongation values at the high strength levels.

Metallographic examination of weldments has shown that the alloy is essentially free from intergra-nnular micro cracks in the heat-affected zone. This is expected of a fine-grained material (ASTM grain size 6.5 in the present case)

As expected presence of Laves phase has been detected in the Fusion Zone of weldments, which was dissolved by subsequent post weld solution treatment at 2000°F to effect improvement in ductility at high strength levels.

Residual stresses for electron beam welds were very small & insignificant which directly corroborates the principal

Figure 8 : (Photomicrograph 7) Laves Phase in dissolved dispersion, Magnification: x500, Etchant: 10% Oxalic acid

advantage of this process, i.e. accomplishing the weld with minimum heat input / resultant distortion and with least determinatal changes to the structural soundness of weldments.

Micro hardness traverse across the weld zone proves of narrow strain fields associated with the process, with consequent lesser heat affected zone & almost uniform micro hardness of the microstructure.

Foregoing investigations and results show the efficacy of Electron Beam Welding (EBW), in producing sound welds by subjecting the material to least micro-structural transformational changes and consequently the welds having better physical properties.

REFERENCES

1. Welding Handbook, Section 3A, Sixth Edition, 1970, Welding Cutting & Related Processes, American Welding Society.
2. Metals Handbook, Vol. 6, 8th Edition, 1971, Welding & Brazing, American Society for Metals.
3. Meleka A.H. 1971, Electron Beam Welding: Principles and Practices, McGraw-Hill Publishing Co. Ltd.
4. Schwartz Mel. M. 1969, Modern Metal Joining Techniques, John Wiley & Sons, Inc.
5. Woldman Norman E. & Gibbons Robert C. 1973, Engineering Alloys, 5th Edition, Litton Education Publishing Inc., USA
6. Colomber L. and Hochman J. 1967, Stainless and Heat Resisting Steels, Edward Arnold Ltd., UK
7. Everhart John L. 1971 Engineering Properties of Nickel and Nickel Alloys, Plenum Press, New York
8. Sims Chester T. and Hagel William C. 1972, The Super alloys, John Wiley & Sons.
9. Gordine J. Nov. 1970, Welding of Inconel-718, Welding J., Research Suppl. 531-S
10. Gordine J. Nov. 1971, Some Problems in Welding Inconel-718, Welding J. Research Suppl. 480-S
11. Thompson E. G. Feb. 1969, Hof Cracking Studies of Alloy 718 Weld Heat Affected Zones, Welding J. Research Suppl. 71-S
12. Lucas M. J. Jr. and Jackson C. E. Feb. 1970, The Welded Heat Affected Zone in Nickel Base Alloy 718, Welding J. Research Suppl. 47-S
13. Duvall D. S. and Owezarski M. A. Jan. 1969, Studies of Postweld Heat Treatment Cracking in Nickel-Base Alloys, Welding J. Research Suppl. 11-S
14. Mayor R. A. Sept. 1976, Selected Mechanical Properties of Inconel 718 & 706 weldments, Welding J. Research Suppl. 269-S
15. Douty R. A. and Schwartzbart H. Dec. 1973, Cobalt Base Surfacing of Inconel 718, Welding J. Research Suppl. 550-S
16. Grey Allen G. April 1979, Critical Point Metallurgy & Welding Technology, Metal Progress
17. Konkol P. J., Smith P. M., Willebrand C. F. & Connor L. P. Nov. 1971, Parameter Study of Electron Beam Welding, Welding J. pp. 765-776
18. Price I. G. July 1978, Electron Beam Welding 1, Engineering Materials and Design pp. 29-33
19. Bulcock Eric July 1978, E B Welding 2, Engineering Materials and Design, pp.34-38
20. Drew John Feb. 26, 1976, Electron Beams Tackle Tough Machining Jobs, Machine Design pp. 94-98
21. Sandstrom D. J., Buchen J. F. & G S Hanks July 1970, On the Measurement & Interpretation and Application of Parameters Important to Electron Beam Welding, Welding J. Research Suppl. 293-S
22. Render S. May 1974, Measurement of Residual Stresses By Blind Hole Drilling Method, Technical Bulletin TDG-5, Photolastic Inc., P. A., USA
23. Meier J. W. July 1966, Metal Progress, pp. 63-64

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