EFFECT OF CONSTRICTED ARC WELDING ON TENSILE PROPERTIES OF THIN SHEETS OF AERO ENGINE GRADE TITANIUM ALLOY

Vaithiyanathan V[1*], Balasubramanian V[2], Malarvizhi S[3], Vijay Petley[4], Shweta Verma[5]

Research Scholar[1], Prof[2], Assoc. Prof[3], Centre for Materials Joining & Research (CEMAJOR),
Dept. of Mfg. Engg., Annamalai University, Annamalai Nagar, Tamilnadu
Scientist - E[4], Scientist - D[5], Materials Group (MTG)
Gas Turbine Research Establishment (GTRE), Bengaluru
Corresponding Author*: vaithimfg@gmail.com

Abstract: *Titanium and its alloys have been considered as one of the best engineering materials for aero-engine applications, because they possess many good characteristics such as high specific strength, superior corrosion resistance and good high temperature strength. Gas tungsten arc welding (GTAW) welding process is generally preferred because to repair aero-engine blades of its high versatility and easy applicability. Gas Tungsten Constricted Arc welding (GTCAW) is a new variant of GTAW process. It generates very high frequency (20 kHz) and alters the magnetic field of the arc, thus enabling the control of constriction of arc and leading to less heat input, narrow heat affected zone (HAZ), reduced residual stresses and distortion compared to conventional GTAW process. This paper reports the tensile properties of GTA and GTCA welded thin sheets (1.2 mm) of Ti-6Al-4V alloy used in aero-engine applications. The joints were characterized using optical microscopy, scanning electron microscopy and microhardness survey. From this investigation, it is found that GTCAW joints exhibited superior tensile properties compared to GTAW joints due to reduction of prior beta grain boundary, higher fusion zone hardness and narrow heat affected zone. Hence, it is preferred that GTCAW process can be employed to repair aero-engine components over GTAW process.*

Keywords: *Titanium Alloy, Gas Tungsten Arc Welding, Gas Tungsten Constricted Arc Welding, Tensile Properties, Microstructure.*

1. INTRODUCTION

Titanium alloys have been widely used in the field of aviation and aerospace by virtue of its high strength to weight ratio, heat resistance and corrosion resistance [1-2]. More over the Ti-6Al-4V alloys have significant applications owing to combination of high strength and toughness [3-4]. Gas Tungsten Arc Welding (GTAW) process is usually chosen to repair aero-engine components due to simple operation and low cost. However, the common problems due to the GTAW process are the degradation of mechanical properties like strength and ductility [5-6]. Over heating in the fusion zone and heat affected zone resulting intergranular microstructure and large prior beta grain occurred [7]. In addition formation of coarse columnar grains in the fusion zone leads to solidification cracking [8].

Above problems can be rectified by using pulsed current GTAW process because of lower heat input involved in the process. Variation of the welding current with frequency, the pulsed current GTAW process had excellent stable arc with deeper penetration and refined grains in the fusion zone [9]. Current pulsing offers many advantages over conventional GTAW process such as refinement of prior beta grains that leads to improvement in strength, hardness and ductility also. The frequency of inverter welding power source had a significant impact on the refinement of fusion

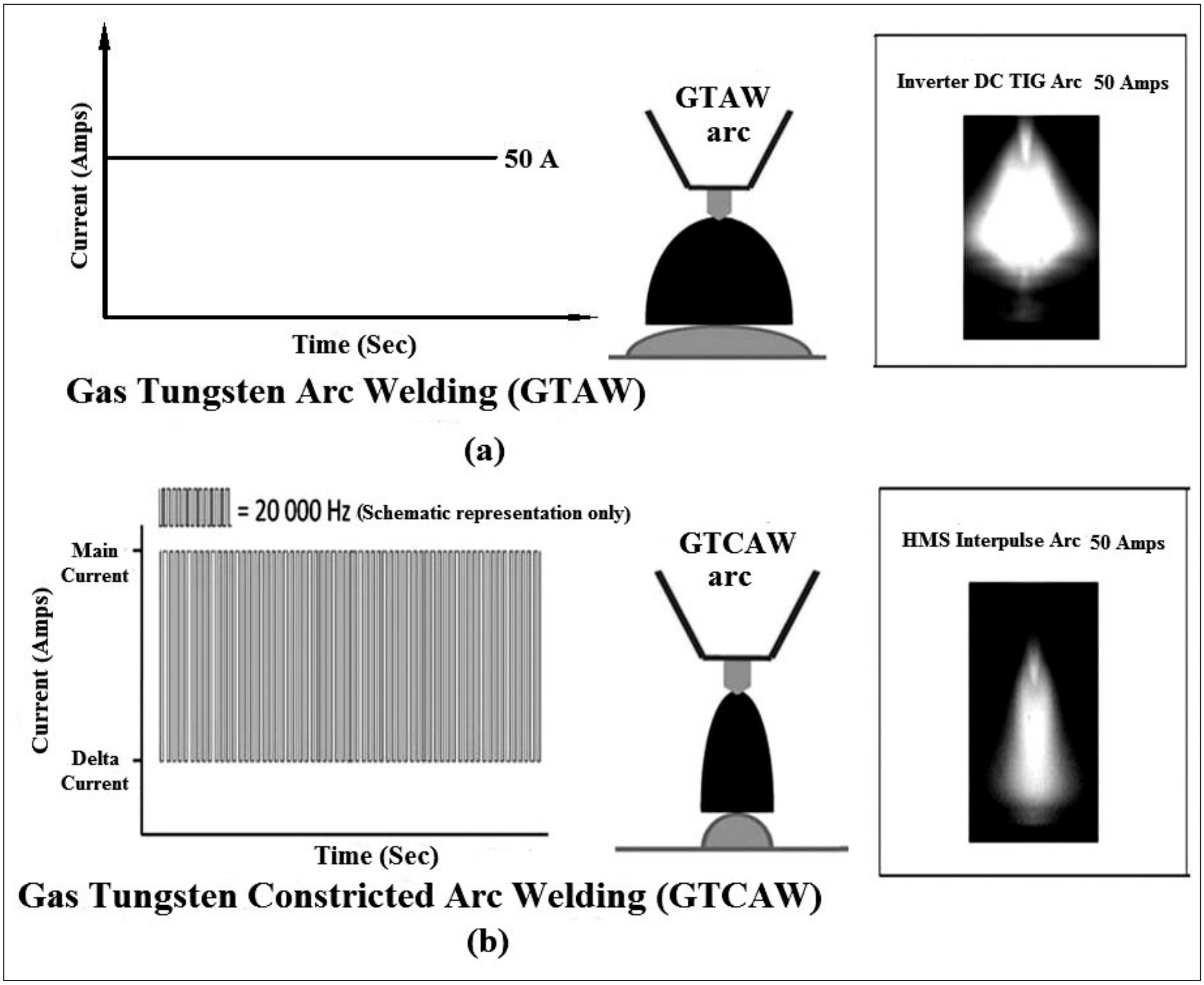


Fig 1. Schematic diagram showing the difference between GTAW and GTCAW

zone. The higher pulse frequency provides better effect on grains refinement [10-13]. Several results indicated that reduction in the beta grain size improved the strength, hardness and ductility in the weld condition by pulsed GTAW. Acceptable level of ductility cannot be improved under the usual welding conditions [14-15].

The process chosen for this investigation is the gas tungsten constricted arc welding (GTCAW) developed by Vaccum Brazing Company (VBC), UK. The GTCAW operates at 20 kHz and produces a magnetically constricted columnar profile arc, like that of a plasma arc. The arc is constricted by the magnetic field around the arc. The GTCAW machine generates high frequency pulse, the relationships of which are programmable to alter the magnetic field of the arc, thus enabling the control of the constriction of the arc as shown in Fig 1. The constriction of the arc produces narrow but deeper weld beads along with narrow heat affected zone [16-19].

There are many reports available on tensile properties of constant current and pulsed current GTA welded Titanium alloys. However, a detailed comparison has not yet been reported on tensile properties of GTAW and GTCAW joints of titanium alloy. Hence, this article is aimed to reveal the influence of constricted arc welding on tensile, hardness and microstructure of thin sheets of titanium alloy used in aero-engine applications.

2. EXPERIMENTAL

The as-received base material (BM) used in this investigation was 1.2 mm thin Ti-6Al-4V alloy sheets. The chemical composition of base metal is presented in Table 1. Square butt joint configuration, as shown in Fig. 2 (a), was prepared to fabricate the joints. The sheets to be joined were mechanically and chemically cleaned by acetone before welding to eliminate surface contamination. The direction of welding was normal to the rolling direction. Necessary care was taken to avoid joint distortion and the joints were made by securing the base metal. Single pass welding procedure was applied to fabricate the joints. The joints were fabricated by Interpulse TIG (IE175i) Welding machine (Make: VBC, UK). High-purity (99.99%) argon gas was used as shielding gas. The welding conditions and the optimized process parameters used to fabricate the joints are presented in Table 2. The welded joints were sliced (as shown in Fig. 2b) in transverse direction using wire cut EDM process to the required dimensions as shown in Fig. 3(a) and (b). American Society for Testing and Materials (ASTM E8M-05) standard for sheet type material (i.e., 25 mm gauge length and 6 mm gauge width) was followed to prepare tensile specimens.

Two different tensile specimens were prepared to evaluate the transverse tensile properties.

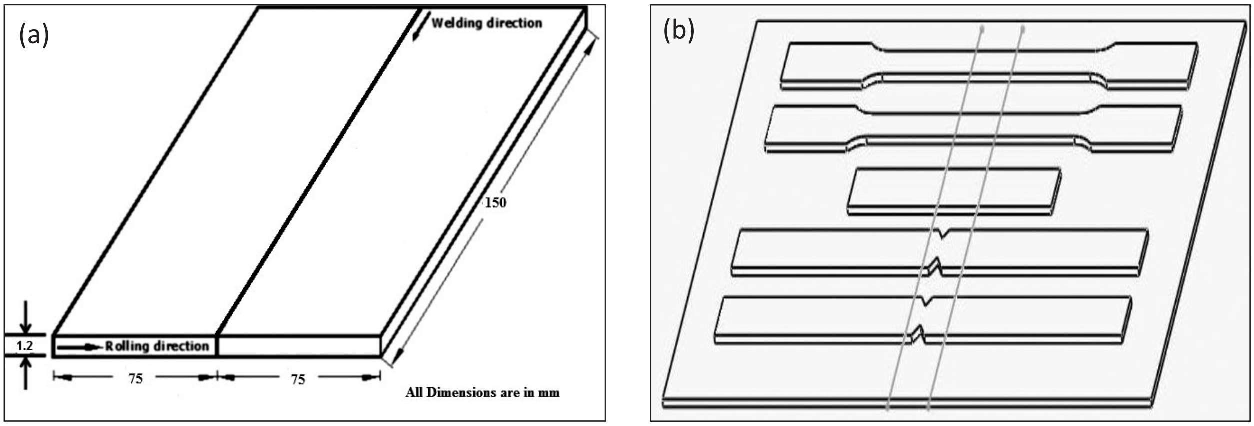


Fig 2. (a) Joint configuration (b) Scheme of specimen extraction

Table 1: Chemical composition (wt%) of base material

Al	V	Fe	C	Si	Ti
6.181	3.745	0.266	0.029	0.025	Bal

Table 2: Optimized welding parameters used to fabricate the joints

Process	GTAW	GTCAW
Electrode Material	**Tungsten (Lanthanated)**	**Tungsten (Lanthanated)**
Tungsten electrode diameter (mm)	**1.6**	**1.6**
Polarity	**DCEN**	**DCEN**
Voltage (volts)	**9**	**9**
Main Current (amps)	**50**	**50**
Delta Current (amps)	**-**	**30**
Delta Frequency (kHz)	**-**	**20**
Welding Speed (mm/min)	**60**	**60**
Shielding Gas	**Argon**	**Argon**
Back Purging Gas	**Argon**	**Argon**
Gas Flow Rate (lpm)	**15**	**15**
Heat Input (J/mm)	**270**	**216**

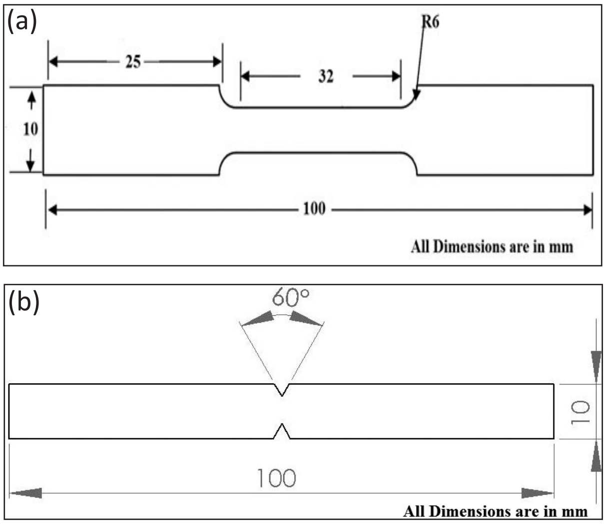
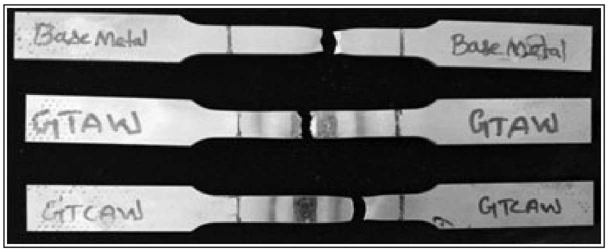
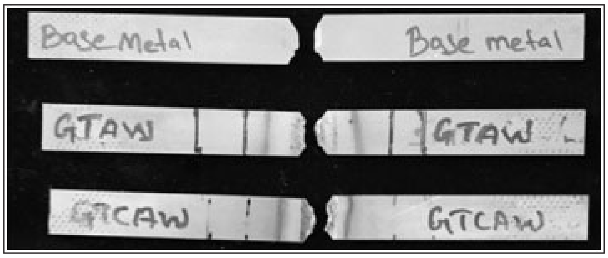


Fig 3. Dimensions of tensile specimen: (a) Un-notched tensile specimen (b) Notched tensile specimen



(a) Unnotched



(b) Notched

Fig 4. Photographs of tensile specimens (after testing)

The smooth (unnotched) tensile specimens were prepared to evaluate yield strength, tensile strength, and elongation. Notched tensile specimens were prepared to evaluate notch tensile strength (NTS) and notch strength ratio (NSR) of the joints. Tensile test was carried out using 50 kN universal testing machine (UTM) with the strain rate of 1 mm/min (Make: Tinius Olsen; Model: 50 ST). The 0.2% offset yield strength was derived from the load-displacement diagram. Vicker's microhardness tester (Make: Shimadzu, Japan and Model: HMV-2T) was used to measure the hardness across the joints with a 0.2 kg load. Microstructural examination was carried out using a light optical microscope (Make: Huvitz, Korea; Model: MIL-7100) incorporated with an image analyzing software. The specimens for metallographic examination were sectioned to the required dimensions from the joint comprising weld metal, HAZ and base metal regions and polished using different grades of emery papers. Final polishing was done using the diamond compound (1 µm particle size) in the disc polishing machine. Specimens were etched with a standard reagent made of 2% HF and 3% HNO_3 in 95% distilled water to reveal the micro and macrostructure.

3. RESULTS

3. 1 Tensile Properties

The transverse tensile properties such as yield strength, tensile strength, percentage of elongation, notch tensile strength, and notch strength ratio of Ti-6Al-4V alloy joints were evaluated. In each condition, three specimens were tested and the average of three results is presented in Table 3. Photographs of tensile specimens are displayed in Fig. 4. The stress-strain graphs of unwelded parent metal and welded joints are

Table 3: Transverse tensile properties base metal and welded joints

Material	0.2 % Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation (25 mm gauge length) (%)	Notch Tensile Strength (MPa)	Notch Strength Ratio (NSR)	Joint Efficiency (%)	Fracture Location
Base Metal	977	1010	15	1230	1.21	-	-
GTAW	956	985	7	1100	1.08	97	FZ-HAZ Interface
GTCAW	981	1030	11	1140	1.12	102	BM

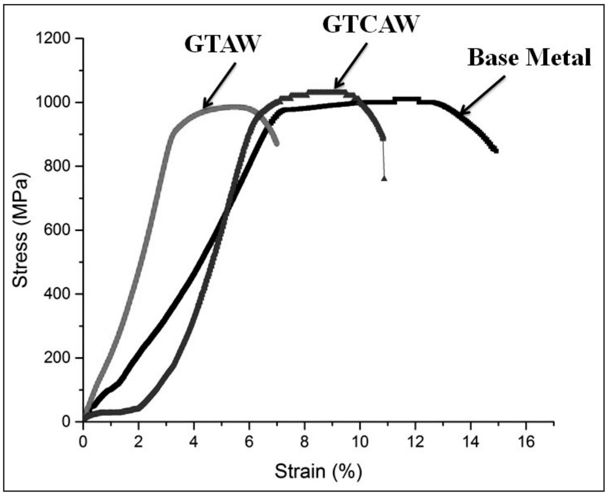


Fig 5. Engineering stress-strain curves

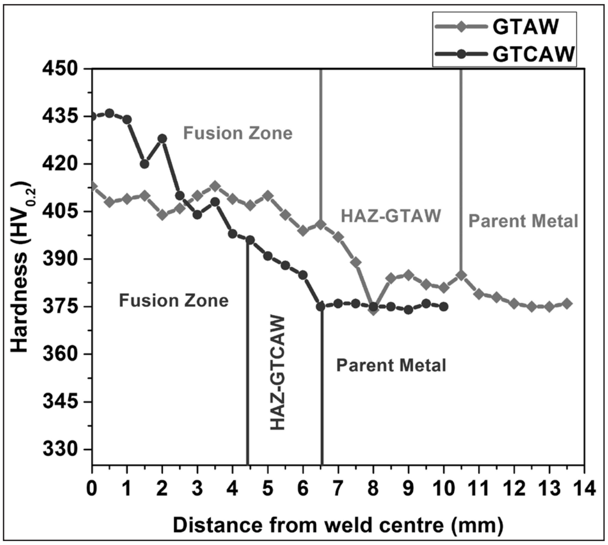


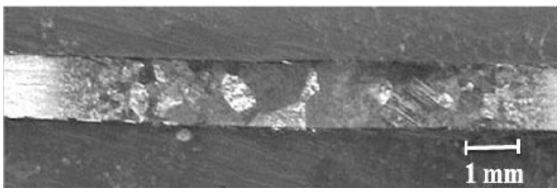
Fig 6. Hardness profile at mid cross section

displayed in Fig. 5. The yield strength and tensile strength of unwelded parent metal are 977 and 1010 MPa, respectively. But the yield strength and tensile strength of GTAW joints are 956 and 985 MPa, respectively. This indicates that there is a 3 % reduction in strength values due to GTA welding. Similarly, the yield strength and tensile strength of GTCAW joints are 981 and 1030 MPa, respectively, which are 2 % higher compared to unwelded parent metal. Of the two joints, the joints fabricated by GTCAW process exhibited higher strength values and the difference is approximately 5 % higher compared to GTAW joints.

Elongation of unwelded parent metal is 15 %. But the elongation of GTAW joints is 7 %. This suggests that there is a 53 % reduction in ductility due to GTA welding. Similarly, the elongation of GTCAW joints is 11 %, which is 26 % lower compared to the parent metal. Of the two joints, the joints fabricated by GTCAW exhibited higher ductility values and the difference is approximately 36 % higher compared to GTAW joints.

Notch tensile strength (NTS) of unwelded parent metal is 1230 MPa, but the notch tensile strength of GTAW joint is 1100 MPa. This reveals that the reduction in NTS is approximately 11 % due to GTA welding. Of the two joints, the joints fabricated by GTCAW process exhibited higher NTS values and the difference is 4 % higher compared to GTAW process. Another notch tensile parameter, NSR, is found to be greater than unity for all the joints. This suggests that the Ti-6Al-4V alloy is sensitive

Table 4: Macrostructure and bead geometry of GTAW and GTCAW

Joint type	Cross section	DOP (mm)	WOB (mm)	FZA (mm^2)	Width of HAZ (mm)
GTAW		1.2	12.82	15.93	1.46
GTCAW		1.2	7.90	9.59	0.94

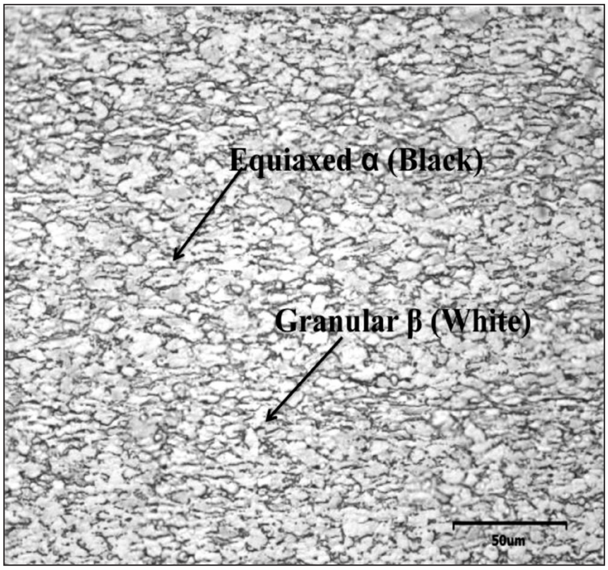


Fig 7. Optical microscope of base metal

to notches and they fall into the 'notch ductile materials' category. The NSR is 1.21 for unwelded parent metal but it is 1.08 and 1.12 for GTAW and GTCAW joints, respectively. Of the two joints, the joints fabricated by GTCAW process exhibited a relatively higher NSR.

Joint efficiency is the ratio between tensile strength of welded joint and tensile strength of unwelded parent metal. The joint efficiency of conventional GTAW joints is approximately 97 % (under matching). The joint efficiency of GTCAW joints is 102 % (over matching) which is 5 % higher than GTAW joints.

3. 2 Macrostructure

Macrostructure of cross-section of the joints and bead profile are presented in table 4. There is no evidence of macro level defects in all the joints. Due to the variations in heat input of welding processes, an appreciable variation in the fusion zone characteristics is evident from the macrostructure of the joints. GTAW joint exhibits wider Fusion Zone (FZ) and heat affected zone (HAZ) compared to the GTCAW process. Width of bead (WOB), fusion zone area (FZA) and HAZ of GTAW are 12.82 mm, 15.93 mm2 and 1.46 mm respectively. Similarly WOB, FZA, HAZ of GTCAW are 7.90 mm, 9.59 mm2 and 0.94mm. Of the two process, the joint fabricated by GTCAW process exhibited 40 % reduction in FZA and 36 % reduction in HAZ compared to conventional GTAW process.

3.3 Micro Hardness

The hardness across the weld cross section was measured and presented in Fig 6. The hardness of base metal (unwelded parent metal) is 375 Hv. However, the fusion zone hardness of the GTAW and GTCAW joints are 407 Hv and 435 Hv. This suggests that the hardness is increased in the fusion zone due to welding heat input. The fusion zone hardness of GTCAW joint is 7 % higher compared to GTAW joint and 14 % higher compared with the base metal. This may be one of the reasons for higher tensile strength of GTCAW joints. From the hardness profile, it is evident that the fusion zone (FZ) and heat affected zone (HAZ) of GTCAW joints are narrow than GTAW joints.

3. 4 Microstructure

Optical micrograph of base metal is shown Fig 7. It consists of equiaxed alpha (dark) and granular beta phase (white) and the average grain size is approximately 6 µm. The fusion zone of GTAW (Fig 8(c).) consists of massive α, widmanstatten α+β and HAZ (Fig 8(e)) consists of intermediate α+β. Similarly the fusion zone of GTCAW (fig 8(d)) consists of short acicular alpha martensitic structure with α platelets at grain boundary and HAZ region (Fig 8(f)) consists of intermediate α+β with some acicular alpha martensite.

3.5 Fractographs

Fig. 9 displays the fractographs of tensile tested specimens of base metal, GTAW and GTCAW joint. The displayed fractographs invariably consist of dimples, which are an indication that most of the tensile specimens failed in a ductile manner under the action of tensile loading. An appreciable difference exists in the size of the dimples with respect to the welding processes. Coarse dimples are seen in GTAW joints (Figs. 9(b)) and fine dimples are seen in GTCAW joints (Figs. 9(c)). Since fine dimples are a characteristic feature of ductile fracture, the GTCAW joints have shown higher ductility compared to all other joints (Table 4). The dimple size exhibits a directly proportional relationship with strength and ductility, i.e., if the dimple size is finer, then the strength and ductility of the respective joint is higher and vice versa.

4. DISCUSSION

In GTCAW joint, the formation of narrow fusion

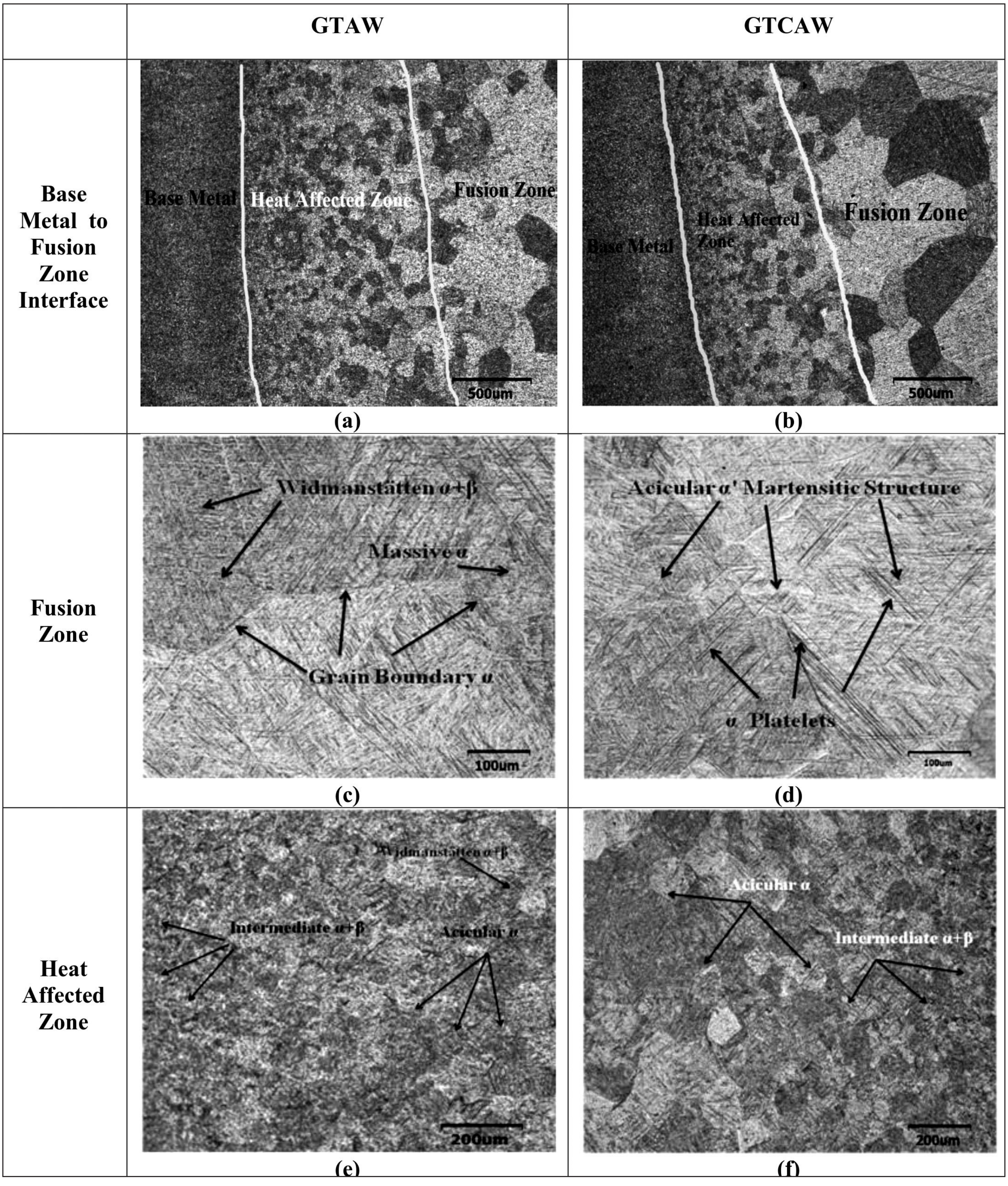


Fig 8. Optical micrographs of various regions

zone and narrow heat-affected zone (HAZ) is due to low heat input (216 J/mm) involved in the process. Delta current plays a major role in restricting fusion zone area because the weld arc is constricted by the magnetic field around the arc by delta current. This delta current generates high frequency pulse, to alter the magnetic field of the arc, thus enabling the constriction of the arc and leads to deeper penetration as well as minimum fusion zone area [17-18]. Transverse tensile properties of the base metal and welded joints are presented in Table 3. The GTCAW joint exhibits higher tensile strength and lower elongation (ductility) than the unwelded base alloy. The transverse tensile specimen of the joint fractured away from the fusion zone

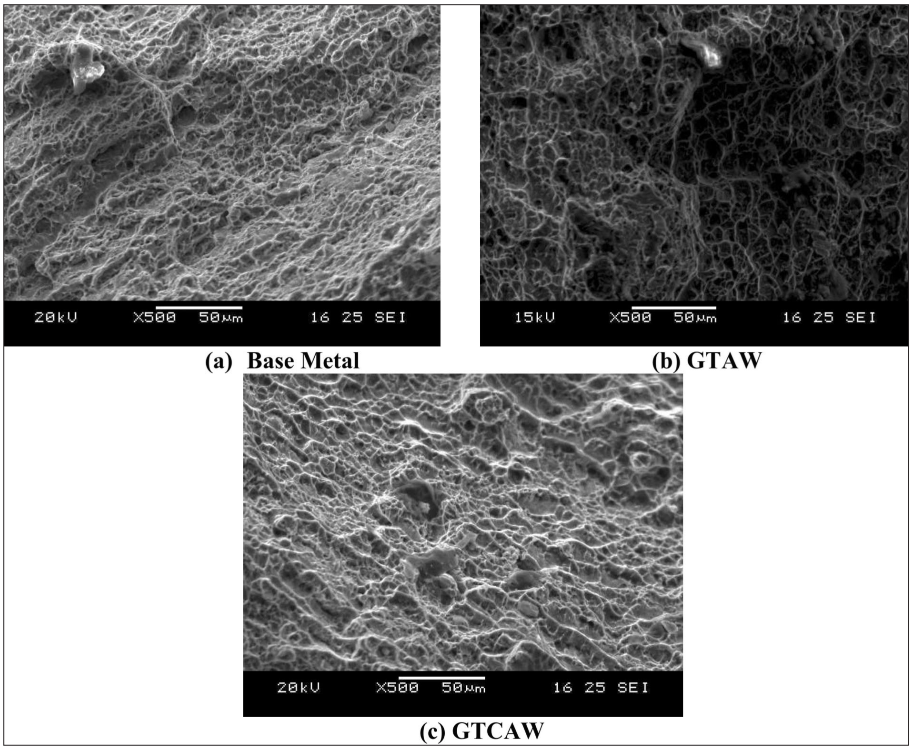


Fig 9. SEM fractographs of tensile tested specimens

(at BM), because the BM is softer i.e., recorded lowest hardness, (Fig. 8). The strength is roughly proportional to hardness, so that the BM region would preferentially yield and then fail during transverse tensile test. The overall mechanical properties of a joint are determined by the characteristic features of the individual microstructures present in the fusion zone and the heat-affected zone of GTAW and GTCAW joints.

The weld FZ in titanium alloys is characterised by coarse, columnar prior-β grains that originate during weld solidification. The size and morphology of these grains depend on the nature of the heat flow that occurs during weld solidification. The FZ β grain size depends primarily on the weld energy input, with a higher energy input promoting a larger grain size [10-11]. The microstructural analysis of GTAW consists of Widmanstätten α+β where GTCAW joints revealed fully acicular alpha and martensitic structure [6]. Periodic pulsing of welding current (delta frequency) in GTCAW, impose thermal variation in the weld pool to enhance the flow of molten metal in the weld pool and help to reduce the prior β within the weld metal compared to GTAW. Current pulsing resulted in grain refinement (Figures 5c and 5e) [15].

The higher strength of the GTCAW joint is attributed to the presence of acicular alpha martensitic in the weld metal, and finer grain size which offers greater resistance to dislocation motion [17]. The HAZ of both GTAW and GTCAW high hardness value compare with parent metal, due to the intermediate α+β structure [10]. However, they exhibited lower ductility compared to the parent metal. This could be caused by the presence of α′ martensite in the fusion zone. The high strength of the martensite in the welds is attributed to a very high defect density and the fine size of the martensite plates [5]. In GTCAW exhibited a slightly higher hardness (435 HV) compared with GTAW (407 HV) due to a refinement in prior β grain size [3].

5. CONCLUSIONS

1. Gas Tungsten Constricted Arc Welding (GTCAW) joint exhibited higher tensile strength and the enhancement in strength is approximately 5 % compared to conventional GTAW joint. Similarly, ductility (elongation) of GTCAW joint is found to be 36 % higher compared to the GTAW joint.
2. Hardness was found to be higher in the fusion zone compared to the HAZ and base metal regions, irrespective of welding processes. Very low hardness was recorded in the GTAW joints (407 Hv) and maximum hardness

was recorded in the GTCAW joints (435 Hv). This is mainly due to the presence of acicular alpha martensitic structure in the fusion zone.

3. GTCAW process resulted in smaller fusion zone area (40 %) and narrow heat affected zone (36 %) compared to conventional GTAW process. This is mainly due to arc constriction involved in GTCAW process.
4. The equiaxed alpha and intergranular beta in the base material are changed in to acicular alpha martensitic structure with prior beta grain boundary in the fusion zone are the main reasons for superior tensile properties of GTCAW joints compared to GTAW joints.

Acknowledgements

The authors wish to thank Gas Turbine Research and Establishment (GTRE), Bangalore, for the financial support to carry out this investigation through a R&D project no. GTRE/GATET/ CS20/1415 /071/15/001 under Gas Turbine Enabling Technology (GATET) Initiative. The authors also wish to record their sincere thanks to The Director, GTRE, Bangalore for providing base metal to carry out this investigation.

REFERENCES

1. G. Lutjering and J. C. Williams: ‘Titanium’, 177–232; 2003, Berlin, Springer-Verlag.
2. R.R. Boyer An overview on the use of titanium in the aerospace industry: ’Material Science and Engineering A’ Vol.213, 1996, 103–114
3. Wang, RR, Welsch, GE: Joining titanium materials with tungsten inert gas welding, laser welding and infrared brazing, ‘J Prosthet Dent’, Vol - 74(5), 1995, 521–530
4. Malinov S, Sha W Application of artificial neural networks for modeling correlations in titanium alloy, ’Material Science and Engineering A’ Vol-365, 2004, 202–211
5. Yunlian Qi, Deng Ju, Quan Hong, Liying Zeng: Electron beam welding, laser beam welding and gas tungsten arc welding of titanium sheet, ‘Materials Science and Engineering A’, Vol-280, 2000, 177–181
6. S.H. Wang, M.S. Wei: Tensile properties of gas tungsten arc weldments in CP, Ti-6Al-4V and Ti-15V-3Al-3Sn-3Cr alloys at different strain rates, ‘Science and Technology of Welding and Joining’, Vol- 9, 2004, 415-422
7. Becker DW, Adams CM Jr: The role of pulsed GTA welding variables in solidification and grain refinement, ‘Weld research supplement’, 1979, 143–152
8. Ram, G.D.J., Mitra, T.K., Shankar, V., Sundaresan, S: Microstructural refinement through inoculation of type 7020 Al–Zn–Mg alloy welds and its effect on hot cracking and tensile properties, ‘Journal of materials processing technology’, Vol- 142, 2003, 174–181
9. Rao, K.P., Angamuthu, K., Bala Srinivasan: Fracture toughness of electron beam welded Ti-6Al-4V, ‘Journal of materials processing technology’, Vol-199, 2008, 185–192
10. Sundaresan S, Janaki Ram GD, Madhusudhan Reddy ,G: Microstructural refinement of weld fusion zones in alpha–beta titanium alloy using pulsed current welding, ’Material Science and Engineering A’, Vol-262, 1999, 88–100
11. Prasad Rao ,K: Fusion zone grain refinement in GTA welds using magnetic arc oscillation and current pulsing. RAMP; 2001, 176–196
12. Shinoda T, Ueno Y, Masumoto I: Effect of pulsed welding current on solidification cracking in austenitic stainless steel weldsjournal of the japan welding society’, vol-7, 1989, 245-249
13. Madhusudhan Reddy G, Gokhale AA, Prasad Rao K: Optimization of pulse frequency in pulsed current gas tungsten arc welding of Al–lithium alloysteels, ‘material science and technology’, Vol- 14, 1998, 61–66
14. Simpson, RP: Refinement of weld fusion zones in alpha-beta titanium alloys, ‘Weld Journal’ 1977, 56–67
15. Kishore BN, Ganesh SRS, Mythili R: Correlation of microstructure with mechanical properties of TIG weldments of Ti-6Al-4V made with and without current pulsing, ‘Materials Characterization’, Vol- 58, 2007, 581–587
16. Naveen Kumar P, Bhaskar Y, Mastanaiah P: Study on dissimilar metals welding of 15CDV6 and SAE 4130 steels by Inter pulse gas tungsten arc welding, ‘Procedia materials Science’ Vol-5, 2014, 2382-2391
17. Leary R, Merson E, Birmingham,K: Microstructural and microtextural analysis of InterPulse GTCAW welds in Cp-Ti and Ti–6Al–4V, ‘Materials Science Engineering A’, Vol- 527, 2010, 7694-7705.
18. V. Vaithiyanathan, V. Balasubramanian, S. Malarvizhi: Identification of Optimized Gas Tungsten Constricted Arc Welding Parameters to attain Minimum Fusion Zone Area in Ti-6Al-4V alloy sheets used in Aero Engine Components, ‘Journal of Advanced Microscopy Research’, Vol-13, 2018, 354-362 ◘

V Vaithiyanathan is working as Research Scholar, Centre for Materials Joining & Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Chidambaram, Tamilnadu. He obtained B.E Manufacturing Engineering from Annamalai University, M.E Manufacturing Engineering from Anna University, Chennai. He has published papers in Journals and Conference Proceedings. He has 5 years of teaching experience & 3 years Research experience. His area of interest is Welding of similar and dissimilar materials, and Mechanical Metallurgy.
(E-mail: vaithimfg@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, India. 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 Associate Professor, Centre for Materials Joining & Research (CEMAJOR), Department of Manufacturing Engineering, Annamalai University, Annamalai Nagar India. 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. Vijay Petley (Scientist-E-GTRE, Bangalore) obtained Ph.D in Indian Institute of Science (IISc), Bangalore in the year 2018. He joined Gas Turbine Research Establishment DRDO in the year 2001. He executed the Aero Engine Weld Qualification program wherein all the weld joints on the engine are qualified by certifying authorities. His areas of interest are in the field of composites, brazing, repair and refurbishment, thin films for aero engine application. He has published approximately eighty internal technical reports, six specifications, 18 national and international journal publications and eleven conference papers.
(E-mail: petleyvijay@gmail.com)

Ms. Shweta Verma (Scientist-D-GTRE, Bangalore) has obtained M.Tech. Degree in Metallurgical Engineering from IIT-BHU in the year 2006. She worked as Lecturer in Metallurgy Department of NIT Raipur (Chhattisgarh) for two years. She joined Gas Turbine Research Establishment DRDO in the year 2008. Since then she is working towards metallurgical qualification of protective coatings, welded & brazed joints of aero engine components for various engine development programs of GTRE. She is also working towards repair of engine component through additive manufacturing, laser cladding and brazing techniques. Her area of interest is microstructural characterization of metals, composites in welded, brazed and parent condition and performing microstructural analysis of metals, composites manufactured through various techniques. (E-mail: shweta@gtre.drdo.in)