

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

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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

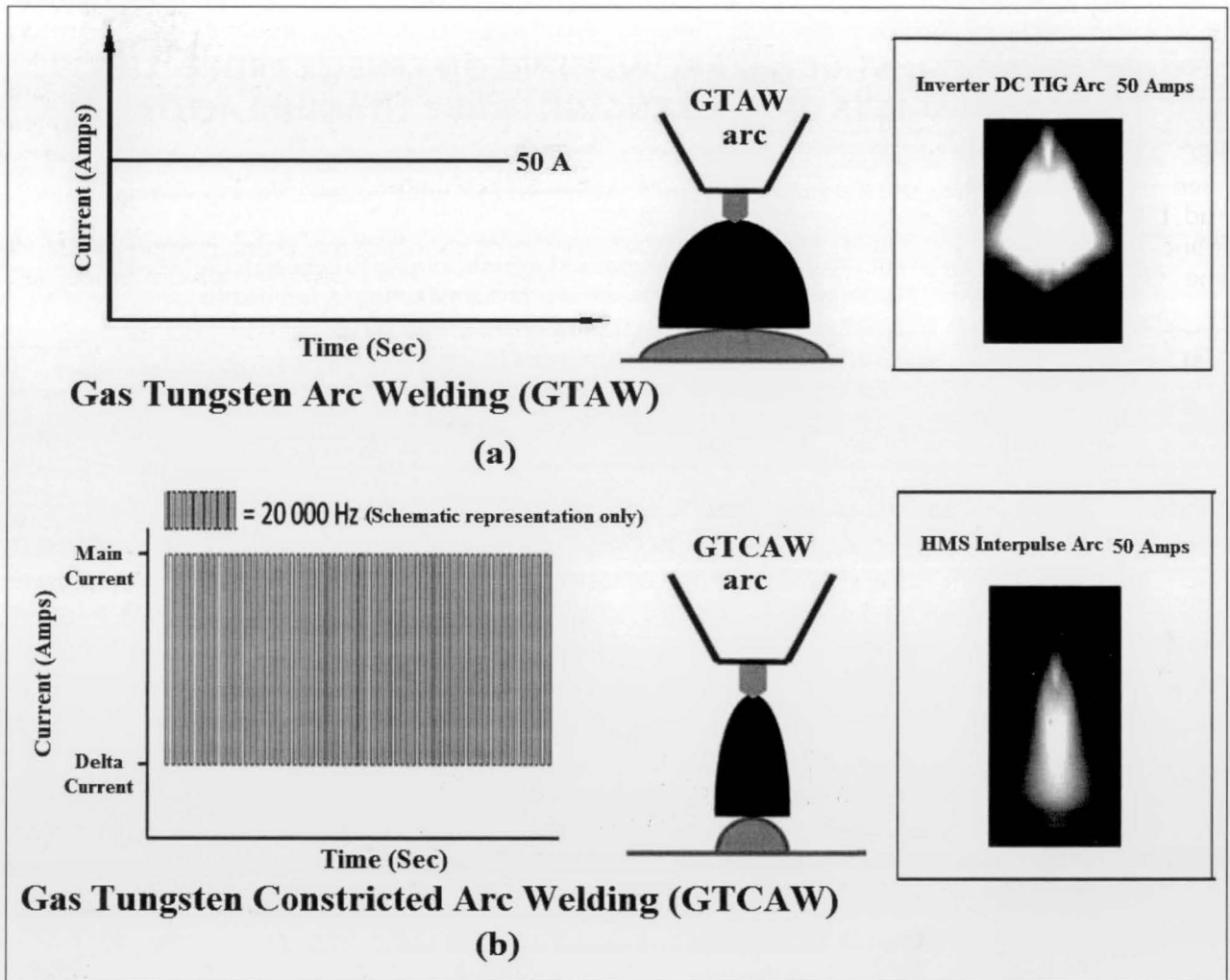


Fig 1. Schematic diagram showing the difference between GTAW and GTCAW

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.

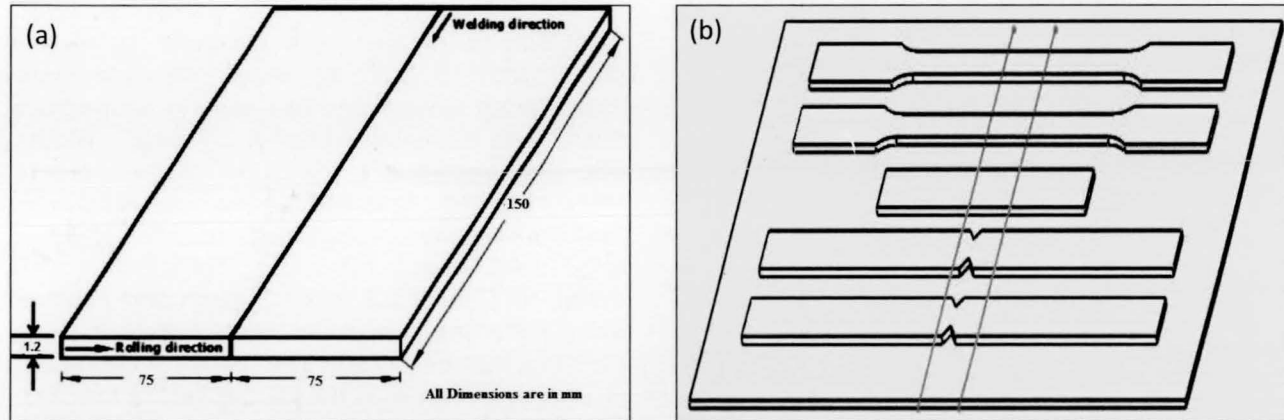


Fig 2. (a) Joint configuration (b) Scheme of specimen extraction

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

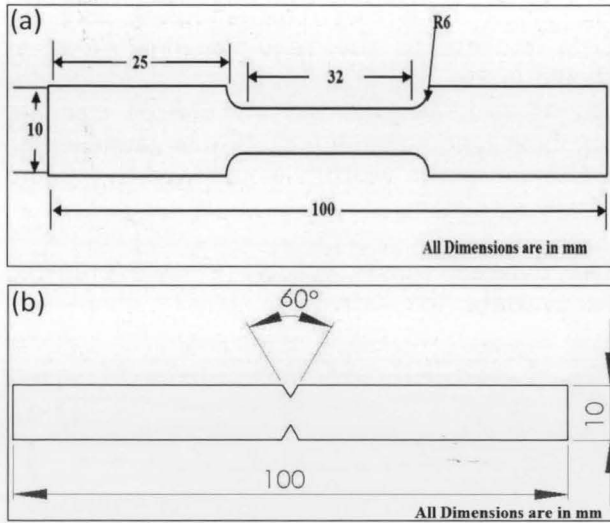
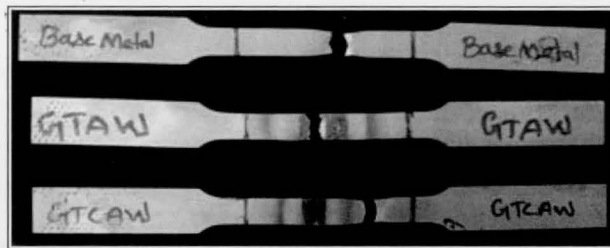


Fig 3. Dimensions of tensile specimen: (a) Un-notched tensile specimen (b) Notched tensile specimen



(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% HNO₃ 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

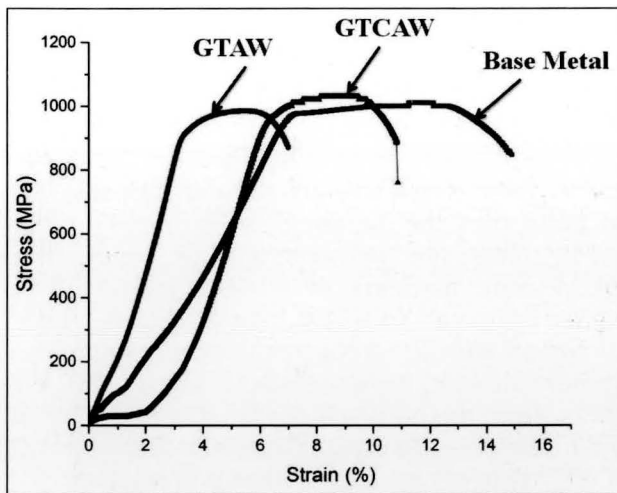


Fig 5. Engineering stress-strain curves

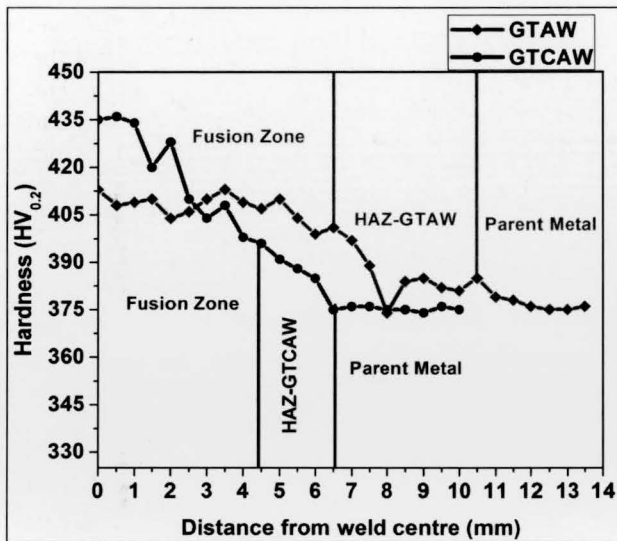



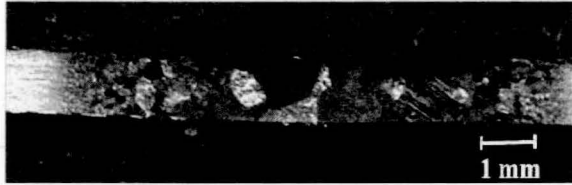
Fig 6. Hardness profile at mid cross section

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

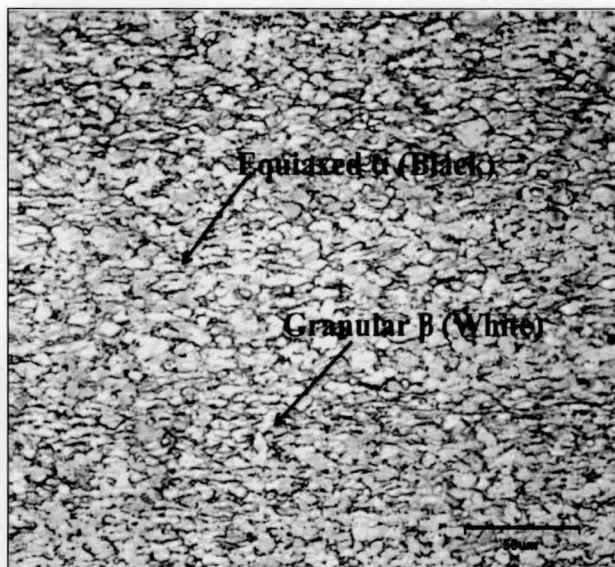


Fig 7. Optical microscope of base metal

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 $\alpha+\beta$ and HAZ (Fig 8(e)) consists of intermediate $\alpha+\beta$. 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 $\alpha+\beta$ 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

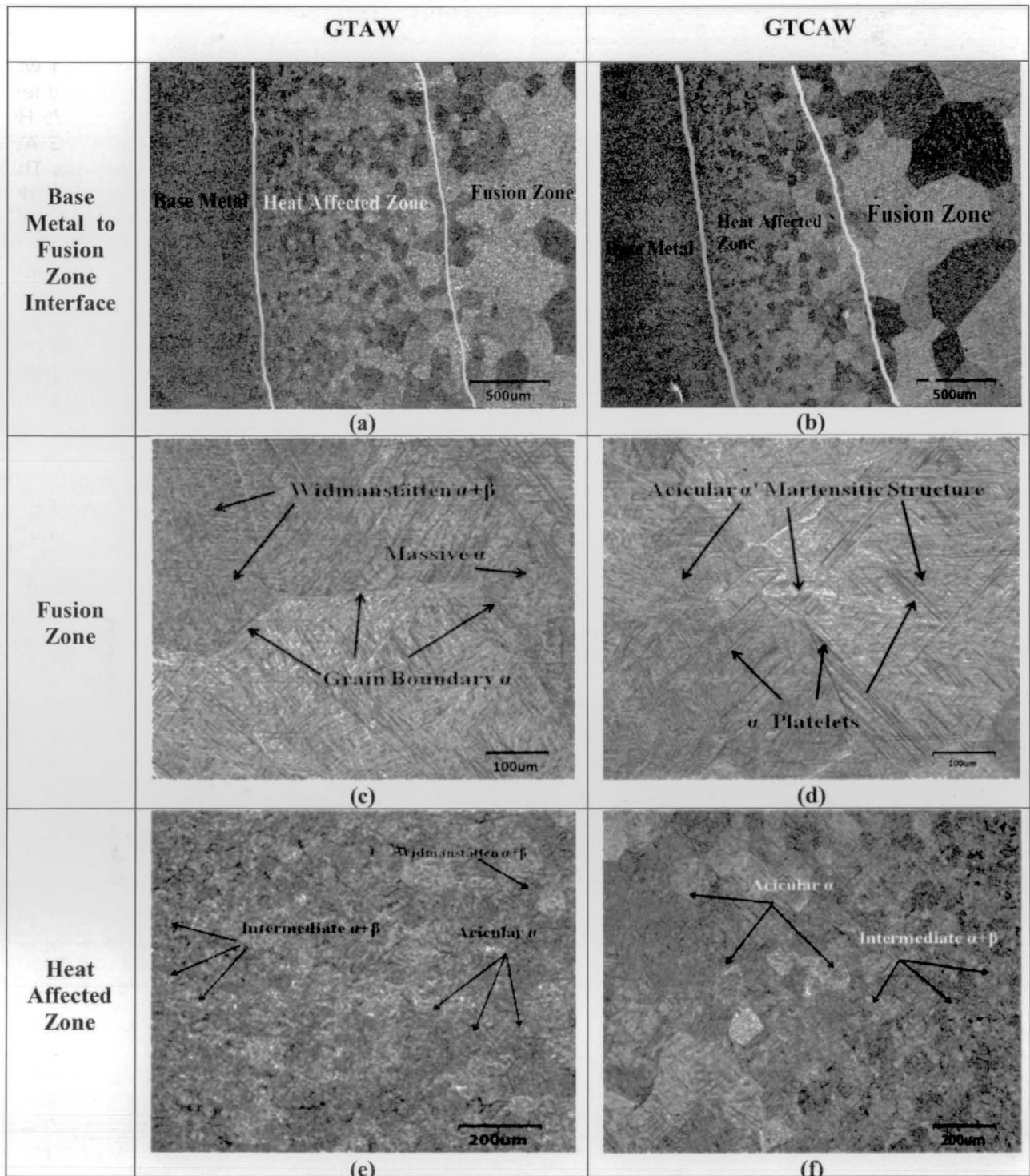


Fig 8. Optical micrographs of various regions

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

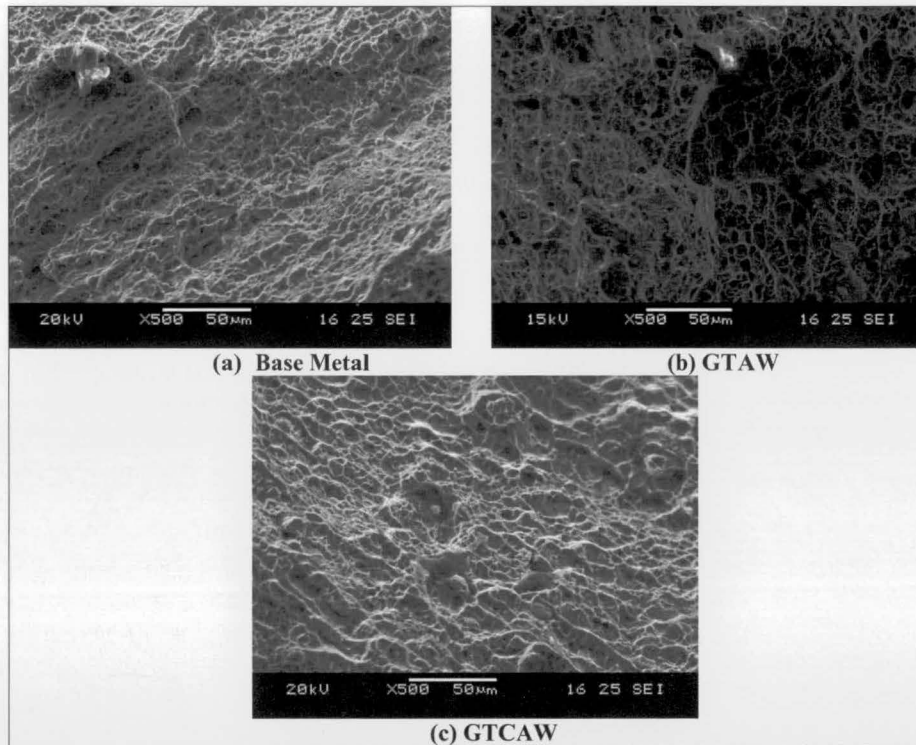


Fig 9. SEM fractographs of tensile tested specimens

(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 $\alpha+\beta$ 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 $\alpha+\beta$ 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.
- 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.
 - 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.

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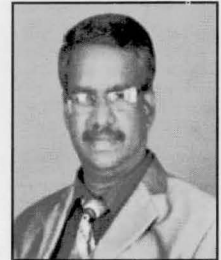
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