A Comparative Study on Direct and Pulsed Current Gas Tungsten Arc Welding of Alloy 617

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Abstract— **the aim of this article is to evaluate the mechanical and microstructure properties of Inconel 617 weldments produced by direct current electrode negative (DCEN) gas tungsten arc welding (GTAW) and pulse current GTAW. In this regard, the micro structural examinations, impact test and hardness test were performed. The results indicated that the joints produced by direct mode GTAW exhibit poor mechanical properties due to presence of coarse grains and dendrites. Grain refining in pulse current GTAW is reason of higher toughness and impact energy than DCEN GTAW. Further investigations showed that the epitaxial growth is existed in both modes that can strongly affect the mechanical behavior of the joints in heat affected zone (HAZ).**

Index Terms- **Alloy 617, Welding, Pulsed Current, Microstructure, Grain Refining.**

I. Introduction

Super alloys are divided into three groups including iron, nickel and cobalt alloys. Inconel is a registered trademark of Special Metals Corporation that refers to a family of austenitic nickel-chromium based super alloys. Inconels retain their mechanical properties at high temperature applications where many kinds of steels are susceptible to creep as a result of thermally-activated deformation [1-4].

Alloy 617 (UNS N00617- ASTM B 166), a solid solution nickel-based alloy, has a face-centered-cubic (FCC) crystal structure, widely used in the high temperature applications because of its excellent high temperature corrosion resistance, superior mechanical properties, good thermal stability and superior creep resistance [4-6].

The microstructure and phase stability of Inconel 617 alloy were investigated by researchers [7]. They showed that $M_{23}C_6$ carbides can be formed after high temperature exposures (in the range of 649ÚC –1093ÚC). Presence of 1 wt% aluminum also strengthens the matrix by forming Ni_3Al inter metallic compound which slightly improves the mechanical properties at 650ÚC –760ÚC. However, the major role of aluminum and chromium additions is to improve the oxidation and carburization resistance at high temperatures [8]. The corrosion behavior [9, 10] and high temperature properties [8, 11-14] of Inconel 617 have been previously investigated in the literature.

It should be mentioned that welding processes are essential for the development of virtually manufactured Inconel products. However, the papers which deal with the investigation of Inconel 617 weldments are a few. However, the microstructure of dissimilar Inconel 617/ 310 stainless steel produced by gas tungsten arc welding . (GTAW) has beeninvestigated [4]

Pulsed current GTAW (PCGTAW), developed in the 1950s, is a variation of constant current gas tungsten arc-welding (CCGTAW) which involves cycling of the welding current from a high level to a low level at a selected regular frequency. The high level of the pulsed current is selected to give adequate penetration and bead contour, while the low level of the background current is set at a level sufficient to maintain a stable arc. This permits arc energy to be used efficiently to fuse a spot of controlled dimensions in a short time. It decreases the wastage of heat through the conduction into the adjacent parent material [15, 16]. In contrast to CCGTAW, during PCGTA, the heat energy required to melt the base material is supplied only during peak current pulses (for brief intervals of time). It allows the heat to dissipate into the base material leading to a narrower heat affected zone (HAZ). The PCGTAW has many specific advantages compared to CCGTAW, such as enhanced arc stability, increased weld depth to width ratio, refined grain size, reduced porosity, low distortion, reduction in the HAZ and better control of heat input. In general, the PCGTAW process is suitable for joining thin and medium thickness materials, e.g. stainless steel sheets, and for applications where metallurgical control of the weld metal is critical [17].

PCGTAW of super alloys is scanty in the reported literatures, but some researchers have evaluated the effect of pulsed current parameters on corrosion and metallurgical properties of super-duplex stainless steel welds [15]. In addition, PCGTAW of Ti–6Al–4V titanium alloy, AA 6061 aluminum alloy and 304L austenitic stainless steel have been also reported in the previous papers [18-20]. However, PCGTAW of Inconel 617 has not been reported in the literature. The aim of this study is to investigate the micro structural and mechanical properties of Inconel 617 welds produced by GTAW and PCGTAW using Inconel 617 filler metal.

II. Experimental Procedure

A. Materials

Inconel 617 alloys were cut and machined in the form of 11mm × 110mm × 150mm plates. The solution annealing treatment was performed at 1175ÚC for 1 h and then the samples were cooled in turbulent air. The Inconel welds were

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fabricated using CCGTAW and PCGTAW. In this regard, Inconel 617 (UNS N06617, AWS No. ERNiCr22Co12Mo9) filler with diameters of 2.6 mm and 1.4 mm were used in CCGTAW and PCGTAW, respectively. The compositions of base metal and filler metal are given in Table 1.

B. Welding Setup

The multi-pass fusion welds were carried out on 11mm thick plate using the manual GTAW process with Magic Wave 2600- Fornius transformer. The weld joint profile according to DIN EN 29692 standard is shown in Fig.1. The weld is butt type with a v-grooved profile. All butt joints were machined into 37.5Ú for good diffusion and were completed in three passes with shielded argon gas (99.99% purity and 10-15 lit.min-1 flow rates). The welds were completed in four passes with air cooling to at least 200ÚC between passes. Inter pass temperature was measured by a thermocouple attached to the welded plate. The pulsed current mode for root pass uses the optimized frequency 6 Hz with percent peek- time control setting of %70 and the other passes use optimized frequency 8 Hz with peek time of %80. The mean value of current in PCGTAW is calculated with equation (1). Equation (1) is:

$$Im = \frac{(IpTp + IbTb)}{(Tp + Tb)} \qquad (1)$$

Where Im is mean current, Ip and tp are peek current and time respectively, Ib and tb are background current and time respectively. In the pulsed-current mode, the welding current rapidly alternates between two levels. The higher current state is known as the pulsed current, while the lower current level is called the background current. During the period of pulsed current, the weld area is heated and fusion occurs. Upon dropping to the background current, the weld area is allowed to be cooled and solidified. Mean current with this formula can use for calculating the heat input in pulsed current mode. The welding parameters in all 3 passes of GTAW and PCGTAW are shown in Table 2. The efficiency for calculating the heat input is 70% in both modes.

C. Characterizations and Testing

Two ends of weld sample were discarded; remained part was prepared for micro- structural examinations, hardness measurements and notch-toughness test as shown in Fig. 2. These test specimens were prepared according to ASME Sec. IX-QW.462 standard. In addition, the Charpy V-notch test specimens were prepared according to ASTM-A370 sub- size (as ASME Sec. IX referred) with dimensions of 10mm ×7.5mm ×55mm.

Table I. Composition (%Wt) of Filler Metal and Base Metal

Element	Alloy 617	Filler metal
Ni	Balanced	Balanced
Cr	21.84	22
Co	11.87	12
Mo	8.55	9
Fe	1.35	3
Mn	0.06	1
Al	0.68	1
Ti	0.32	0.6
Cu	0.12	0.5
C	0.06	0.1
Si	0.11	1
P	0.002	---

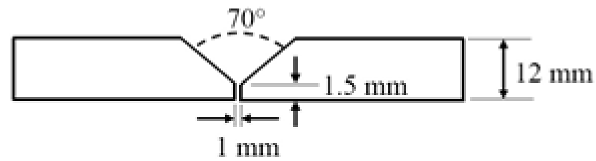

Fig.1. Weld Joint Profile

Table II. Welding Parameters

	Pass No.	Current (A)	Voltage (V)	Welding speed (mms^{-1})	Heat input (KJ mm^{-1})	Total heat input (KJ mm^{-1})
DCEN GTAW	Root	112	22.1	1.28	1.35	5.81
	No.1	123	21	1.32	1.36	
	No.2	124	21.5	1.28	1.45	
	No.3	123	21.1	1.1	1.65	
Pulsed Current GTAW	Root	89.6	19.2	1.06	1.18	4.62
	No.1	108	17.3	1.16	1.12	
	No.2	108	16.7	1.10	1.14	
	No.3	108	16.9	1.08	1.18	

The Charpy V-notch impact tests were performed on weld at room temperature by using Amsler impact test. The samples were machined perpendicular to the weld direction with notch on the center of weld metal. The impact tests were performed on three samples to increase the results of the degree of precision.

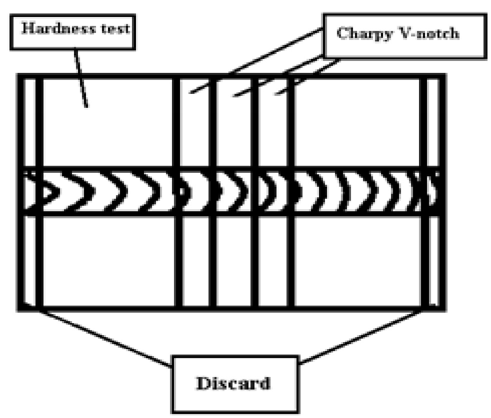

Fig.2. Preparing the Test Samples

Standard metallographic procedures were used to prepare cross sections of the base metals and joints for micro structural characterizations. Sections were etched using aqua regia "Marble etchant solution". Vickers hardness measurements were performed with dwell time of 5 seconds on face of weld metal on three different samples.

III. Results and Discussions

A. Macrostructure

The welded samples were polished and examined using

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optical microscope equipped with camera. The photographs are shown in Fig. 3. The PCGTAW sample exhibit a narrower fusion zone and smaller HAZ as compared to CCGTAW one. This is due to the lower heat input and consequently smaller fusion zone of the pulsed current mode (as shown in Table 2).

A. Annealing Twins

Inconel 617 plates were annealed at 1175 ÚC for 1 h and cooled at turbulent air in order to dissolve the precipitates. Therefore, annealing twins clearly existed in the base metal microstructures of two samples. The boundaries of twins are ordered and have a coherent interface. As twin's boundaries can prevent the dislocations movement during the deformation, they will have good effect on the strength of cubic materials [21]. Fig. 4 shows the microstructure of weld sample and its annealing twins.

The investigation of heat affected zone shows that with moving from base metal toward the weld interface, the grain growth is occurred. It can be due to the increase of heat input and temperature during welding. As γ phase has low heat transfer coefficient and high heat capacity, the cooling rate will be low and consequently the grain growth occurs. The Inconel alloy 617 was supplied in the form of solution treated and water- quenched plate. The typical metallographic feature of alloy consist of an austenitic matrix with some intergranular and transgranular obvious precipitates (Fig.4).

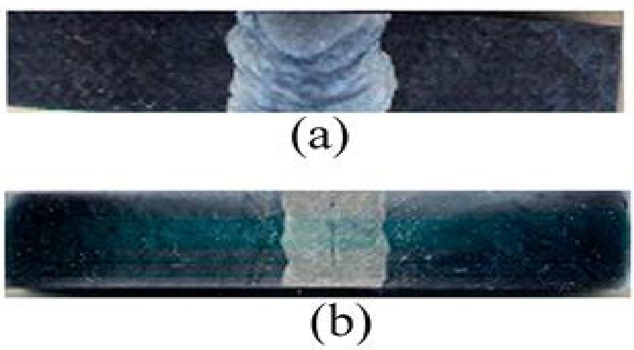

Fig.3. Welded Samples of (a) CCGTAW, (b) PCGTAW

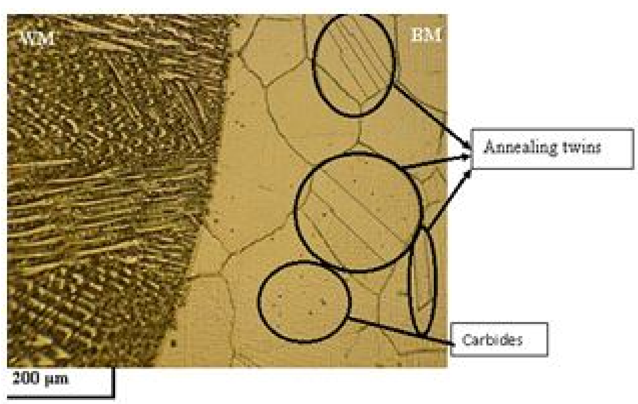

Fig.4. Annealing Twins and Carbides in Base Metal

The EDS results confirmed that these particles are Cr-rich ($M_{23}C_6$), Mo-rich (M_6C) carbides or a combination of both [4].

C. Epitaxial Growth and Competitive Growth

The epitaxial growth in GTAW and PCGTAW process slightly occurs at the weld interface. The epitaxial growth occurs in the weld/base metal systems having the same crystal structures (here FCC). Far from the fusion line, competitive growth is attributed to the growth of grains at different directions. Easy growth direction is <100> in FCC materials, however, the growth can occur at different directions due to presence of different phases [22- 24]. Where metal base is ferritic and weld metal is austenitic, the normal epitaxial growth may occur parallel to the fusion boundary. This kind of micro structural growth was also reported by the others researchers [4, 25].

In fusion welding, the existing base-metal grains at the fusion line act as the substrate for nucleation. Due to complete wet ability ($\theta = 0$) between liquid metal and fusion line, the nucleation from liquid metal occurs easily. Such a growth initiation process is called epitaxial growth or epitaxial nucleation [22]. The structure of grains near the fusion line and during the solidification is different. Grains tend to grow perpendicular to fusion pool boundary due to the more thermal gradient in this direction. But the sub-grains tend to grow in easy-growth direction.

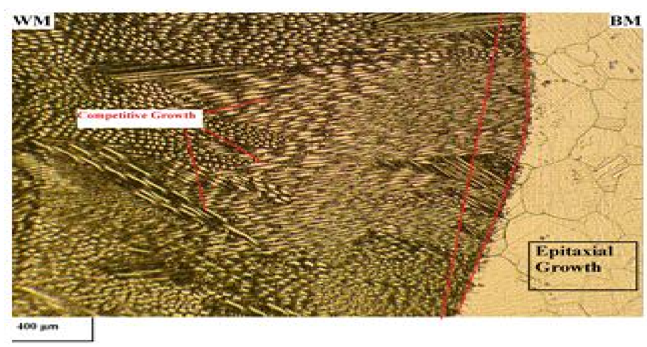

Fig.5. Epitaxial and competitive growth

Therefore, during the solidification, grains will grow faster. This phenomenon is called competitive growth as shown in Fig. 5 [22, 26]. Two types of grain boundaries may present near the weld metal of dissimilar welds: type I (in a direction roughly perpendicular to the fusion boundary caused by epitaxial growth) and type II (in a direction roughly parallel to the fusion boundary). Type I boundary is usually observed in the similar welds (similar bases and filler metals), while type II boundary is a result of allotropic transformation in the base metal that occurs during cooling of weld in dissimilar welds (BCC/FCC). However, in the present study, all the micrographs revealed only type I boundaries. It should be noted that although dissimilar welds are produced, there is no allotropic transformation during the cooling of two base metals [23, 24].

D. Grain Refining in PCGTAW

The optical micrographs from microstructure of welded samples are shown in Fig. 6. Many large columnar grains with dendritic structure existed in CCGTAW specimen. Coarse grains can be observed at HAZ of CCGTAW sample (see Fig. 4). The dendrite spacing of weld metal in the constant current is wider but the pulsed current process reveals narrower

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spacing.

Areas containing fine equiaxed grains were observed, generally located in center of fusion zone. HAZ of the weld was characterized by carbide dissolution and grain growth. n the case of PCGTAW sample, the grain refinement has occurred at fusion zone which can result in better mechanical properties. The Charpy V-notch results (impact test) indicated that absorbed energy during the fracture of PCGTAW sample Iis greater than that for CCGTAW sample (as shown in Table 3). The grain refining in the PCGTAW process can be attributed to lower heat input causing the faster cooling rate which delays the grain growth. The other reason is the effect of pulsed current on dendrites. As shown in Fig. 7, the dendritic structure is observed in CCGTAW specimen. It was found that dendritic structures are associated with greater degree of segregation and are more susceptible to cracking [24]. The room temperature strength of PCGTAW sample with fine grains is greater - than that of GTAW one with coarse grains, as there are no significant chemical difference between two samples [27]. In general, the formation of equiaxed grain

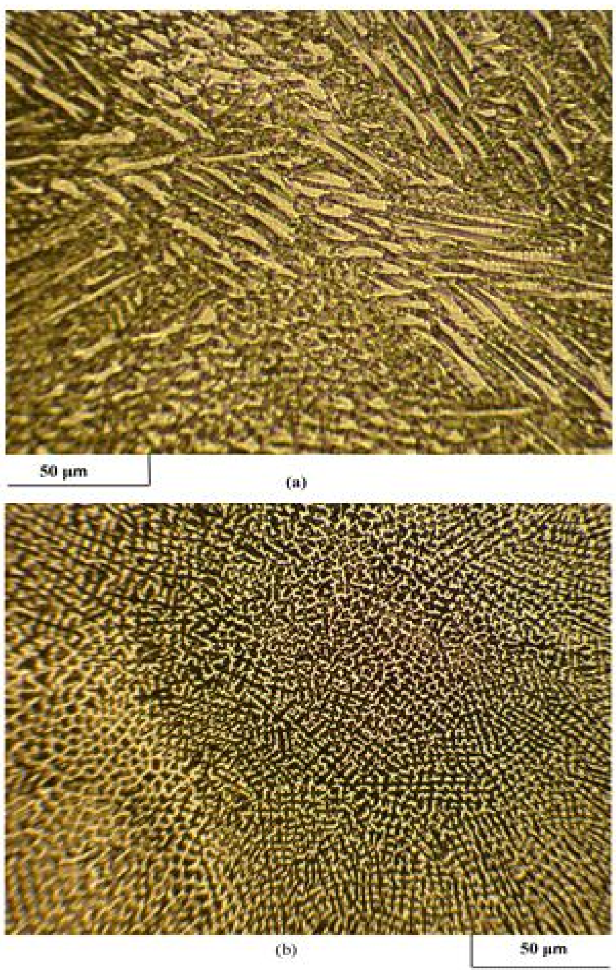

Fig.6. Weld metal microstructure of (a) CCGTAW, (b) PCGTAW samples

structure in CCGTAW weld is known to be difficult because of the remelting of heterogeneous nuclei or growth centers ahead of the solid-liquid interface. This is due to the high temperatures in the liquid, thus making survival nuclei difficult. The evolution of microstructure in weld fusion zone is also influenced in many ways by current pulsing. Principally, the cyclic variations of energy input into the weld pool cause thermal fluctuations, one consequence of which is the periodic interruption in the solidification process. As the pulsed peak current decays the solid-liquid interface advance towards the arc, it increasingly becomes vulnerable to any disturbances in the arc form.

As current increases again in the subsequent pulse, growth is arrested and remelting of the growing dendrites can also occur. Current pulsing also results in periodic variations in the arc forces and hence an additional fluid flows, which lowers temperatures in front of the solidifying interface. Furthermore, the temperature fluctuations inherent in pulsed welding lead to a continual change in the weld pool size and shape favoring the growth of new grains. It is also to be noted that effective heat input for unit volume of the weld pool would be considerably less in pulsed current welds for the average weld pool temperatures are expected to be low. It is important to note that while dendrite fragmentation has frequently been cited as a possible mechanism, and evidence for the same has not been hitherto established or demonstrated. It has been sometimes suggested that the mechanism of dendrite break-up may not be effective in welding because of the small size of the fusion welds and the fine inter-dendrite spacing in the weld microstructure. Thus grain refinement observed in the PCGTAW welds is therefore believed to be due to other effects of pulsing on the weld pool shape, fluid flow and temperatures. The continual change in the weld pool shape is particularly important. As the direction of maximum thermal gradient at the solid-liquid interface changes continuously, newer grains successively become favorably oriented. Thus, the individual grains grow faster in small distance allowing for more grains grow, resulting in a fine grained structure [15-17, 28].

The other declaration of grain refining is that convection through the melting pool may be the reason of dendrite fragmentation. Dendrite's arms may be separated from the main branch during the use of pulsed current. They can act as inoculants in fusion zone of weld. These two theories are the main reasons of grain refining in fusion zone of PCGTAW. Due to the smaller grain size in PCGTAW sample, there are more numerous grains; therefore, more grain boundaries exist. Due to lower free energy of twin boundaries as compared to grain boundaries, the rate of carbide precipitation and corrosion rate is low at these boundaries [26]. It is known that the discrete and discontinuous distribution of the grain-boundary carbides improves the mechanical properties of the material, specifically the creep resistance, because these particles effectively pin the grain boundaries and decrease grain boundary sliding [29].

E. Hardness Examination

The hardness profile versus distance from fusion line is shown in Fig. 8. It can be observed that the hardness of weld metal decreases as compared to the base metal. During fusion

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welding and subsequent fast cooling, the precipitates are dissolved; therefore, the hardness of weld metal decreases. Also, it can be due to grain refinement, precipitation and distribution of carbides, size of carbides and residual stress [27]. Hardness decreases in the HAZ, since there is no allotropic transformation; it is related to grain growth in this area. According to Fig. 8, the weld metal hardness of PCGTAW sample is greater than that of GTAW samples due to grain refining and finer dendrite of PCGTAW mode.

IV. CONCLUSIONS

1. The narrow Inconel 617 welds with smaller HAZ and finer grains were produced using pulsed current as compared to direct current GTAW.

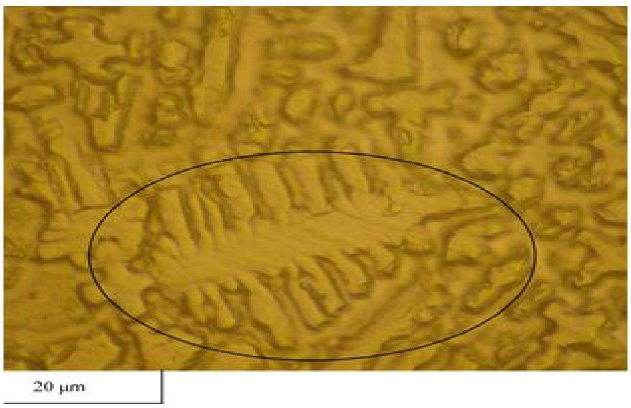

Fig.7. Dendrite structures in CCGTAW weld metal

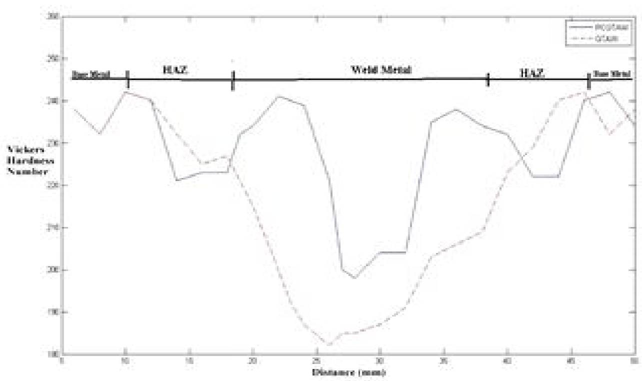

Fig.8. Harness test results

2. In the case of PCGTAW, the mechanical properties improved due to grain refinement. The grain refinement can be rationalized in terms of lower heat input and pulsed current effects. The latter also breaks the arms of dendrites, leading to changes of the solidification mode.

3. The existence of annealing twins and epitaxial growth are clear in the base metal microstructures of two samples, the boundaries of twins are ordered and show coherent interfaces.

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