Post-weld Atmospheric Contamination of Gas Tungsten Arc Deposited Welds in Commercially Pure and Ti-6Al-4V Titanium Alloys

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Titanium alloys are known to exhibit unique weldability issues, particularly atmospheric contamination from interstitial species such as oxygen. The prevention of such impurities from entering the weld region and surrounding heat affected zones is critical for engineering applications as these species are seen to dramatically alter the microstructure and so mechanical properties of the material. Of greatest concern is embrittlement of the weld region. During this study, the influence of inert shielding gas on atmospheric contamination by interstitial species, namely hydrogen, carbon, nitrogen and oxygen, was investigated as a function of post-weld gas shielding temperature. Gas tungsten arc welding (GTAW) was used to compare samples of commercially pure (CP) titanium and Ti-6Al-4V alloy formed by conventional manufacturing methods. The influence of post-weld gas shielding on mechanical properties was quantified *ex-situ* through microhardness testing with observations of microstructure also made. It is shown that mechanical hardness levels are inversely proportional to the temperature to which continuous post-weld inert gas shielding is maintained. Hence interstitial impurity levels within the weld and heat affected zones are seen to increase with increasing post-weld shielding temperature. This effect was more pronounced in the Ti-6Al-4V material, and may be attributed to the comparatively low thermal conductivity.

Keywords: *Titanium (Ti) alloys, Ti-6Al-4V, oxidation, welding, hardness, weld quality*

1. Introduction

It is widely acknowledged that titanium based alloys offer a unique combination of mechanical and physical properties, making them highly attractive engineering materials. Widespread use of these materials, however, is limited by their relatively high cost due to difficulties in primary and secondary processing. Recent years have seen a putsch towards cost reduction of components made from titanium alloys by development of new technologies such as additive manufacture through fusion welding processes[1-3]. In addition to these developing technologies, gas tungsten arc welding (GTAW) is currently the most widely used joining process for titanium[4,5].

The welding of titanium poses a number of unique issues, the most prevalent of which is contamination by interstitial species such as oxygen, nitrogen and hydrogen due to inadequate atmospheric shielding. It is clearly understood that the presence of such interstitial species in titanium alloys significantly affects the mechanical properties of the material giving an increase in strength and hardness while reducing ductility and toughness[6]. Given the reactive nature of titanium and its alloys, it can be appreciated that such contamination is highly temperature dependant with both pick-up and diffusion of interstitial species increasing with temperature.

It follows then that the reduction or elimination of such contamination is key in the execution of high quality welds as required for typical titanium applications. To ensure satisfactory welds are achieved, titanium welding guidelines, published predominantly by titanium and welding manufacturers, state that the weld and all adjacent regions must be shielded from atmosphere while above 800°F (427℃)[5,7-10], however there appears to be little quantitative justification for this threshold. Further, the presence, and degree, of surface colouration due to weld contamination is commonly considered a measure of weld quality[4-8]. Despite this method of visual assessment being surface based and highly subjective in nature, it is still recommended by a number of technical guidelines[10,11].

Harwig et. al. [12] propose another method of weld quality assessment where mechanical hardness of the weld region is measured by an ultrasonic contact impedance method. This hardness value may then be related to an oxygen equivalence (OE) which reflects the material composition[6,13] and so may be used to give an indication of the weld contamination relative to the base parent metal. This OE is seen to be analogous to the carbon equivalence used in ferrous materials[14]. Yulan et. al. [15] have shown the use of similar equivalencies, based on the common alloying elements aluminium and molybdenum, in titanium alloys for evaluation of tensile strength and fracture toughness.

The aim of this study was to quantitatively assess the post-weld atmospheric contamination of titanium welds made by the gas tungsten arc (GTA) process. This was done by observing the variation of mechanical hardness with the temperature to which post-weld inert gas shielding is maintained. It is hoped that such a study will provide qualitative justification for post-weld inert gas shielding of titanium welds to a given temperature, and so help to improve the productivity and quality of titanium welding.

2. Experimental Procedures

Samples of grade 2 commercially pure (CP) titanium, approximately 10mm x 10mm square, were prepared from commercially sourced sheet 2mm in thickness while samples of Ti-6Al-4V (grade 5) titanium alloy, 11.5mm in diameter and 2.5mm in thickness, were prepared from solid round bar.

Samples were then held in a water cooled copper support stand and welded according to the procedure detailed in Table 1. This support stand was mounted to the carriage of a modified centre lathe with the welding torch held fixed above. This arrangement allowed the rapid post-weld exposure of the sample to atmosphere through a traversing motion provided by the lathe feed, simulating the torch removal from the weld area as would occur during manual GTAW. Current and voltage during welding of each sample was recorded using an AMV4000 weld monitor produced by Triton Electronics Ltd. with this data used to determine the average heat input. Both the welding power supply and lathe feed were controlled through NI LabVIEW software with temperature, measured by an R-type thermocouple on the upper surface of the sample, used to trigger the lathe feed at the desired post-weld value. These values ranged from 900℃ to ambient temperature.

Table 1. Summary of GTA weld parameters

Polarity	DCEN
Electrode	2% Ceriated, 2.4mmø
Shielding gas	Welding Grade Argon
Flow rate	15L/min
Pre-flow duration	10 seconds
Up slope duration	5 seconds
Peak current	40 amps
Peak duration	5 seconds
Down slope duration	1 second
Average arc energy	13.52kJ
Average heat input	8.11kJ

Following welding, samples were sectioned along the weld pool centreline, with one of the resulting halves hot compression mounted using phenolic powder. Sectioned faces were then prepared by plane grinding and chemical-mechanical polishing as per Struers application notes for titanium[16]. Hardness profiles across these surfaces were then generated through Vickers micro-hardness testing(200g load) using an array of indentations originating at the solidified weld pool centre and covering some 4.5mm × 1.5mm in 500μm intervals.

This procedure was undertaken as a means of preliminary examination to validate the experimental concept and so warrant a further, more detailed investigation using both nano-indentation (UMIS) and secondary ion mass spectrometry (SIMS) techniques.

3. Results and Discussion

Initial visual inspection showed surface colouration of the welded samples increased with shielding gas cut-off temperature, ranging from silver when shielded to ambient conditions through straw at intermediate temperatures to light blue at 900℃. This trend, shown in Figure 1, was consistent with literature, where it is understood greater colouration indication increased contamination levels. These observations may be readily explained by considering that those samples exposed to atmosphere at elevated post-weld temperatures are more reactive to atmospheric contaminants and also have a greater ability to react as cooling times are comparatively longer.

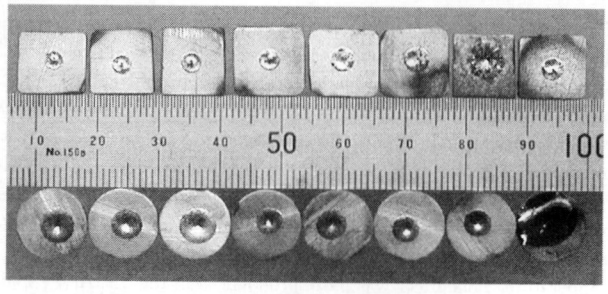

Figure 1. Macro photograph showing surface colouration due to atmospheric contamination in welded samples of CP G2 Ti (top) and Ti-6Al-4V (bottom). Post-weld shielding gas cut-off temperatures are (L to R) ambient conditions, 200, 300, 400, 500, 600, 700 and 900℃. Scale provided for reference shows units of millimetres

Moreover, colouration was seen to be more pronounced in samples of CP G2 Ti compared to Ti-6Al-4V. This may allude to reduced levels of atmospheric contamination in Ti-6Al-4V, however such a qualitative visual examination of surface conditions cannot be taken as representative of the bulk. These observations were somewhat expected given that inclusion of aluminium as a substitutional alloying element in Ti-6Al-4V allows the formation of a passivating Al_2O_3 structure which acts to reduce oxygen diffusion[17]. It is considered that the reduced colouration identified in Ti-6Al-4V samples may be attributed to alloy composition with the formation of surface oxides and nitrides other than TiO_2 including, but not limited to, aluminium and vanadium oxides altering the surface appearance.

Considering the results of microhardness testing illustrated in Figures 2 and 3 it can be seen that, in general, welding causes a distinct increase in overall sample hardness with respect to the un-welded reference. In the case of CP G2, this appears to be relatively independent of shielding gas cut-off temperature with a general increase of approximately 6%. In comparison, samples of Ti-6Al-4V showed increasing levels of hardness with increased shielding gas cut-off temperatures, from some 4% when shielded to ambient conditions up to 7.5% with shieling cut at 900℃.

During the welding process, it is considered that samples undergo an annealing type process where residual stresses from manufacture are relieved through thermally activated recrystallization and grain growth. These are evident through the significant coarsening of grains such that the final grain structure across each sample could be observed unaided. Additionally, the weld pool can be understood to represent a cast microstructure

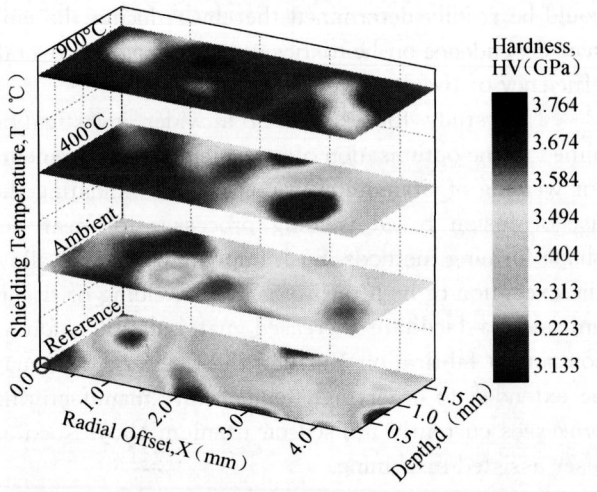

Figure 2. Two dimensional contour plots showing hardness profiles across sectioned surfaces for samples of Ti-6Al-4V with shielding gas removed at various post-weld temperatures. Note: weld pools are centred about the origin (0,0), highlighted above

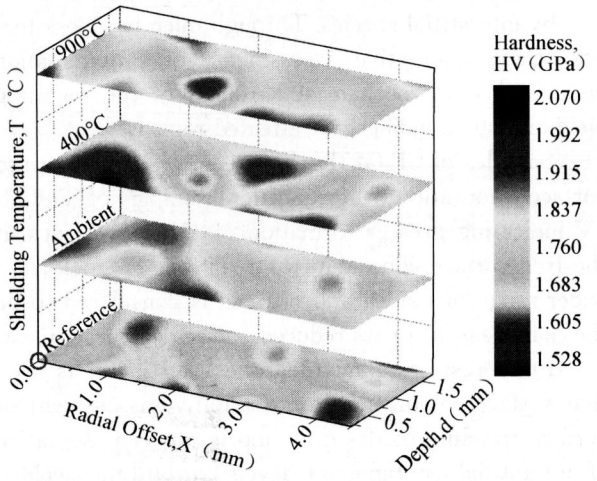

Figure 3. Two dimensional contour plots showing hardness profiles across sectioned surfaces for samples of CP G2 Ti with shielding gas removed at various post-weld temperatures. Note: weld pools are centred about the origin (0,0), highlighted above

with a further increase in grain size relative to the heat affected zone noted. These factors of increased grain size and reduced residual stress would then suggest a decrease in mechanical hardness may be expected in the welded sample. It follows then that the general increase in hardness observed is best attributed to contamination by interstitial species such as oxygen, nitrogen, carbon and hydrogen resulting in solid solution strengthening or formation of oxides, nitrides, carbides and hydrides that interact with dislocations and so increase resistance to plastic deformation. As this increase in hardness was observed in all welded samples it is thought that such contamination has occurred during the welding process and may be credited to residual or entrapped air surrounding the sample in the support stand and low levels of oxygen and moisture in the shielding gas. Effects of turbulent shielding gas flow drawing atmospheric gases into the weld area are believed to have been minimised by use of a gas lens and large diameter nozzle. It is also worth noting that the contribution of these species to strengthening may be greater than the above results suggest when the anticipated mechanical softening phenomena are considered.

The results above also show that the increase in hardness in Ti-6Al-4V tends to be more prevalent in the regions directly adjacent to the weld pool and decrease with radial offset from the weld pool centre. This is illustrated in Figure 4 which shows a three dimensional hardness profile for the Ti-6Al-4V sample shielded to 400℃. The zone of increased hardness is also seen to broaden with increasing shielding gas cut-off temperature. This trend is significantly less pronounced in samples of CP G2 Ti particularly when considering that sample which was removed from post-weld inert gas shielding at 900℃.

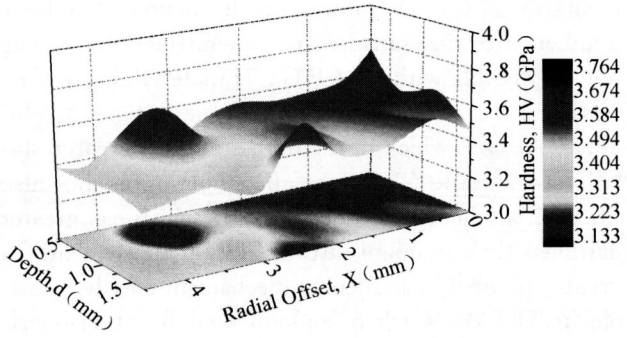

Figure 4. Three dimensional contour plot of hardness profile across sectioned surfaces of Ti-6Al-4V sample with shielding gas removed at 400℃ upon cooling. Weld pool is centred about the origin (0,0)

The increase in hardness, and so post-weld interstitial pick-up, with increased shielding gas cut-off temperatures observed in Ti-6Al-4V is consistent with theoretical predictions based on the knowledge that the reactivity of titanium increases dramatically at elevated temperatures. In addition, samples exposed to atmosphere at higher temperatures are subjected to these oxidising conditions for a greater period of time as they cool to ambient conditions. This increased cooling time also allows for increased diffusion facilitating the pick-up of more interstitial contaminants as well as deeper penetration of these impurities into the bulk material. Further, the cooling of the sample is clearly dependant on the thermal conductivity of the material and so how readily heat may be dissipated. From RMI[5], the thermal conductivity of Ti-6Al-4V is 6.6W/m. K while that of CP G2 Ti is some three times greater at 20.8W/m. K and so the cooling time of Ti-6Al-4V would be expected to be several times greater than that of CP G2 Ti cooling from the same post-weld temperature. Hence thermal conductivity, and so cooling time, is considered to be the defining difference between Ti-6Al-4V and CP G2 Ti in terms of increasing hardness

with increased shielding gas cut-off temperature.

The relatively low thermal conductivity of Ti-6Al-4V also reduces the ability for thermal energy to be dissipated throughout the bulk material and so would be expected to give rise to a more severe thermal gradient across the weld region both during and after welding when compared to CP G2 Ti. Such a thermal gradient would cause the central regions of the sample to cool more slowly and, as previously described, ultimately give increased atmospheric contamination in these regions with an accompanying increase in mechanical hardness as shown for Ti-6Al-4V in Figure 2. This variation of hardness with radial offset from the weld pool centre may also be due to differing oxidation and diffusion properties between the weld metal and heat affected zone, however, as such a trend was not apparent in samples of CP G2 Ti this explanation is considered to be unlikely.

Finally, the addition of substitutional alloying elements in Ti-6Al-4V allows the formation of a large number of oxides, nitrides and oxy-nitrides that would not be possible with the CP G2 Ti material. Particularly, the inclusion of aluminium gives rise not only to alumina (Al_2O_3), which in the pure state has greater stability than rutile (TiO_2) at all temperatures, but also titanium aluminium nitride (TiAlN) which has greater hardness than titanium nitride (TiN). Subsequently, a greater number of hardening mechanism may be possible in Ti-6Al-4V when contaminated by atmospheric gases such as oxygen and nitrogen. It must be noted that a detailed thermodynamic study is required in order to determine which oxides and nitrides are favoured and formed under the post-weld cooling conditions. Additionally, the hardness of each sample may be influenced by microstructure, in particular crystallographic orientation, grain boundaries and morphology resulting from the weld process thermal cycle and so the influence of such variations would be required in later investigations.

Overall it can be seen that the post-weld inert gas shielding cut-off temperature has a recognisable influence on mechanical hardness of the resulting weld and surrounding heat affected regions in titanium alloys. As such a more comprehensive study is being undertaken using both UMIS and SIMS techniques to relate the observed changes in hardness to actual interstitial contaminant levels. Such a study may then be used to develop or verify diffusion models for interstitial pick-up in titanium alloys. This data may then be related to changes in microstructure and mechanical properties, and ultimately lead to a more thorough understanding of inert gas shielding requirements during the fusion welding of titanium alloys. Through combination with suitable weld thermal models, physical shielding requirements in terms of trailing and backing shielding could be readily determined thereby reducing the current dependence on heuristics so improving the overall efficiency of titanium welding.

This study forms part of a wider investigation aimed at the optimisation of gas shielding arrangements for welding of titanium alloys as well as validating the use of fusion based welding processes for near net shape forming methods. Such improvements will allow the execution of high quality general welding of titanium and so facilitate increased material utilisation in component fabrication. Further, these observations may be extended to other high temperature manufacturing processes currently utilised on titanium alloys such as laser assisted machining.

4. Conclusions

The results of this preliminary study have shown that the post-weld inert gas shielding cut-off temperature during gas tungsten arc welding of titanium alloys has a significant influence on atmospheric contamination by interstitial species. Through microhardness testing, these qualitative assessments of contamination were related to mechanical hardness of the resulting weld and surrounding heat affected regions.

Samples of CP G2 Ti were seen to show increased surface colouration over equivalent samples of Ti-6Al-4V indicating greater formation of titanium oxides at the free surface. The ability for Ti-6Al-4V to form a wider range of oxides and nitrides is considered to be the main reason for its reduced surface colouration.

From results of microhardness testing it is seen that surface colouration is a qualitative assessment of surface titanium oxides only and is not representative of interstitial contaminant levels within the welded bulk material.

Microhardness measurements clearly showed a general increase in mechanical hardness due to welding which may be attributed to residual or entrapped air surrounding the sample in the support stand and impurities within the argon shielding gas.

Mechanical hardness increased with increasing post-weld gas shielding cut-off temperatures in Ti-6Al-4V alloys while such trends were not apparent in CP G2 Ti. This is believed to be primarily due to the relatively low thermal conductivity of Ti-6Al-4V giving comparatively longer cooling times.

The low thermal conductivity of Ti-6Al-4V is also believed to give rise to a more severe thermal gradient across the weld zone, and so contribute to the observed decrease in hardness with radial offset from the weld pool. Similarly, the apparent lack of such variations in samples of CP G2 Ti may be explained by the increase thermal conductivity establishing a less severe thermal gradient.

Finally, more in depth studies using both UMIS

and SIMS techniques are being conducted to better understand the post-weld atmospheric contamination behaviour of titanium alloys. In conjunction with weld thermal modelling and thermodynamic details of oxide and nitride formation, such information may lead to improved efficiency of titanium welding by fusion methods.

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