Causal Factors of Weld Porosity in Gas Tungsten Arc Welding of Powder-Metallurgy-Produced Titanium Alloys

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An investigation was undertaken using gas tungsten arc (GTA) welding on consolidated powder metallurgy (PM) titanium (Ti) plate to identify the causal factors behind observed porosity in fusion welding. Tramp element compounds of sodium and magnesium, residual from the metallothermic reduction of titanium chloride used to produce the titanium, were remnant in the starting powder and were identified as gas-forming species. PM-titanium made from revert scrap, where sodium and magnesium were absent, showed fusion weld porosity, although to a lesser degree. We show that porosity was attributable to hydrogen from adsorbed water on the surface of the powders prior to consolidation. The removal and minimization of both adsorbed water on the surface of titanium powder and the residues from the reduction process prior to consolidation of titanium powders are critical for achieving equivalent fusion welding success similar to that seen in wrought titanium produced via the Kroll process.

BACKGROUND

Titanium and titanium alloys produced via the Kroll reduction process, which are subsequently melt refined and wrought processed into mill forms such as bar and plate in modern titanium plants, have excellent quality, high integrity, and they are metallurgically uniform. (The aforementioned production process will hereafter be designated as the Kroll route for producing titanium.) Fusion welding is commonly used to fabricate large or complex geometry structures from titanium mill forms. Extensive studies have been conducted by previous researchers in the joining of Kroll route alloys by conventional fusion welding processes, including gas metal arc welding,¹ gas tungsten arc (GTA) welding,² laser beam welding,³ and electron beam welding.^{4,5}

For Kroll route titanium, controls to ensure welding success revolve around the cleanliness of cover gas, prevention of atmospheric contamination during the weld thermal cycle, and cleanliness of

the surfaces of both the feed wire and the base metal. In addition to cleanliness control, control of heat input is also required to avoid vaporization of alloying elements that may cause porosity and deleterious microstructural features. Fusion welding, while avoiding environmental contaminants, with a controlled heat input, reliably results in a porosity-free weld with an acceptable microstructure.

Significant efforts have taken place over the last decade to establish powder metallurgy titanium from a number of reduction technologies that yield a particulate, as an alternative to the Kroll route.⁶ The impetus has been to lower the energy input for producing titanium components by eliminating melting and improving yield. The expected results of the powder metallurgy (PM) efforts were to broaden the use of titanium, while making it affordable for industrial use. There have been modest breakthroughs in niche areas where titanium produced via powder metallurgy has found acceptance⁷; however, the comparison between titanium mill forms produced via the Kroll route

Table II. Chemical reactions of titanium with water, oxygen, and hydrogen¹⁰

$\text{Ti} + 2\text{H}_2\text{O}_{(\text{g})} = \text{TiO}_2 + 2\text{H}_{2(\text{g})}$		$3\text{Ti} + 2\text{H}_2\text{O}_{(\text{g})} = 2\text{TiO}_2 + 2\text{TiH}_2$		$\text{Ti} + \text{O}_{2(\text{g})} = \text{TiO}_2$		$\text{Ti} + \text{H}_{2(\text{g})} = \text{TiH}_2$	
$T(^{\circ}\text{C})$	Free energy, ΔG (kcal)	$T(^{\circ}\text{C})$	Free energy, ΔG (kcal)	$T(^{\circ}\text{C})$	Free energy, ΔG (kcal)	$T(^{\circ}\text{C})$	Free energy, ΔG (kcal)
0	-103	0	-155	0	-214	0	-25.9
100	-102	100	-147	100	-209	100	-22.7
200	-100	200	-138	200	-205	200	-19.4
300	-98	300	-130	300	-201	300	-16
400	-96	400	-121	400	-196	400	-12.6
500	-94	500	-112	500	-192	700	-2.5
600	-92	600	-104	600	-188	750	-0.85
700	-91	700	-96	700	-183	775	0
800	-89	800	-87	800	-179	780	0.2
900	-87	900	-79	900	-175	800	0.8

Fig. 1. Solubility of hydrogen in titanium (data from Ref. 11).

in the formation of oxides and hydrides. Four chemical reactions that are thermodynamically favorable that bear examination during heating are presented in Table II¹⁰: the oxidation reactions; $\text{Ti} + \text{O}_{2(\text{g})} = \text{TiO}_2$ and $\text{Ti} + 2\text{H}_2\text{O}_{(\text{g})} = \text{TiO}_2 + 2\text{H}_{2(\text{g})}$; the hydride reaction $\text{Ti} + \text{H}_{2(\text{g})} = \text{TiH}_2$; and the combination $3\text{Ti} + 2\text{H}_2\text{O}_{(\text{g})} = 2\text{TiO}_2 + 2\text{TiH}_2$. How these reactions manifest themselves on titanium powders can be observed by using temperature-programmed desorption coupled with mass spectrometry (TPD-MS). TPD-MS was performed on Armstrong process powders in this study.

Because hydrogen is the reaction by-product of the water oxidation reaction on titanium, it is important to examine its effects in titanium fusion welding. Lakomskii and Kalinyuk in 1963, showed the solubility of hydrogen in liquid titanium follows the curve in Fig. 1.¹¹ The liquid metal has 1.7 times the solubility for hydrogen compared to the solid. When hydrogen dissolved in solid titanium is present and titanium is melted, hydrogen moves from the solid base metal into the liquid to satisfy equilibrium. In the case of a fusion weld, two conditions can happen to form porosity upon weld solidification; hydrogen that is moving from the base metal into the liquid gets trapped at the fusion line behind the solidification front, leaving porosity at the fusion line, or if the hydrogen in the weld is above 215 mL/100 g (183 wppm) as solidification proceeds, hydrogen is rejected from the liquid and trapped in the solidifying metal.

In addition to the adsorbed water, titanium powders produced by solid-state metallothermic reduction of TiCl_4 , using either sodium (Na) or magnesium (Mg) as reductant metals, contain residual reaction by-products that, if present in the consolidated metal, generate gasses in fusion welds.

When titanium powder contains residues of either Mg or Na, and the titanium powder is exposed to atmospheric air during handling, the role of water vapor and oxygen must again be considered. Some of the common compounds expected from Mg and Na upon atmospheric exposure are shown in Table III, along with some physical properties germane to fusion welding and arc melting. (Note that the chlorides NaCl and MgCl_2 are not included in

Table III. Common compounds of suspected tramp species in PM-Ti

Species	Molecular weight	Melting point (°C)	Boiling point (°C)	Oxygen g of O ₂ /g of species	Hydrogen g of H ₂ /g of species
Ti	47.86	1,668	3,287	0	0
TiO ₂	79.86	1,843	2,972	0.4	0
Mg	24.3	714	1,091	0	0
MgO	40.3	2,852	3,600	0.79	0
Mg(OH) ₂	58.3	dis 350	—	0.55	0.03
Na	23	98	1,413	0	0
Na(OH)	40	318	1,388	0.4	0.01
Na ₂ O	62	1,132	1,950	0.26	0

Table IV. Reactions of Na compounds with Ti to produce Na metal¹⁰

2NaOH + Ti = TiO ₂ + H ₂ (g) + 2Na.		2Na ₂ O + Ti = TiO ₂ + 4Na	
T(°C)	Free energy ΔG (kcal)	T(°C)	Free energy ΔG (kcal)
0	-30.4	0	-32.3
100	-33.3	100	-34.1
200	-36.6	200	-36.6
300	-39.8	300	-39.2
400	-42.4	400	-41.7
500	-44.8	500	-44.2
600	-47.0	600	-46.6
700	-49.1	700	-48.9
800	-51.2	800	-51.1
900	-53.1	900	-53.2
1000	-54.9	1000	-55.0
1100	-56.6	1100	-56.4
1200	-58.3	1200	-56.6
1300	-59.9	1300	-56.3

the list. An analysis on consolidated PM titanium in this study showed the absence of chlorides.)

Magnesium as a tramp metal in elemental form has a boiling point of 1,091°C. This is well below the melting point of titanium and could cause gas evolution in a weld, where temperatures exceed 1,800°C. (Kroll route processing eliminates Mg and Mg compounds in the multiple consumable vacuum arc melting processes.) If Mg were present as magnesium oxide (MgO) in the starting powder, then upon exposure to normal atmospheric air, MgO would convert to Mg(OH)₂, the stable room-temperature species. Upon heating, Mg(OH)₂ decomposes to MgO and H₂(g) at 350°C.¹² The speed of the decomposition is well within the time/temperature cycle used to consolidate powders to a fully dense plate. The expected result is for MgO solid to be remnant in a matrix of titanium alloy that contains dissolved hydrogen or the compound TiH₂. Hydrogen therefore should be considered a source of

porosity in fusion welds of PM-Ti containing residual magnesium. The MgO by-product of the dissociation should remain as slag or as a nonmetallic inclusion for the short-time weld thermal cycle.

When the TiCl₄ reduction process uses sodium, consideration is given to elemental sodium. Sodium is not stable as a metal under normal atmospheric conditions; NaOH and Na₂O are deemed the likely species at room temperature. However, during consolidation of the titanium powders in an inert environment, at elevated temperature, with NaOH and Na₂O present, some reduction reactions are expected to convert the sodium compounds back to elemental sodium. Those considered reactions are listed in Table IV¹⁰ and show a negative Gibbs free energy (ΔG), indicating the reaction is thermodynamically favorable in the range of temperatures where powder consolidation occurs. Recognizing that the reactions are solid-state reactions, requiring intimacy of reacting species for the reactions to proceed, it is reasonable to consider that all three Na, NaOH, and Na₂O are present in consolidated powders, where the powders are produced via sodium reduction. Na and NaOH are both gasses below the liquidus of titanium. Na₂O has a higher boiling point, 1,950°C, and if trapped in the liquid of a fusion weld, it can either decompose or evaporate if the weld is superheated. All three sodium species are candidates likely to cause gas evolution during fusion welding.

It is suspected that these internal contaminants are the underlying reason why the welding protocols used to eliminate external contaminants for Kroll route produced metal do not result in similar weld quality in PM-Ti. Experiments to confirm the role of these contaminants are the subject of this study.

EXPERIMENTAL WORK

Reactivity of powder titanium below 1,000°C was studied using a TPD-MS technique to understand the role of adsorbed water on titanium prior to and during consolidation. The objective was to see if hydrogen is a contributing species to porosity in fusion welds on

Fig. 2. TPD-MS curves generated during the heating of Armstrong process powders at a rate of 10°C per min.

PM-Ti. In addition to the TPD-MS work, the poor fusion welding malaise observed in PM-Ti was highlighted using GTA welding techniques on consolidated powders. To augment the GTA welding trials, arc melting was performed on several PM-Ti alloys to allow longer observation of the molten metal. The longer observation times and larger sample sizes associated with arc melting allowed some conclusions to be drawn about the sources of gas-induced porosity in PM-Ti fusion welds.

Desorption Analysis of Titanium Powder

A sample of Armstrong process, commercially pure (CP) titanium, with a composition of 2,350 weight parts per million (wppm) O_2 and 246 wppm N_2 was placed in a Quantachrome 1C (Quantachrome Instruments, Boynton Beach, FL) TPD-MS machine under flowing helium. Sampling of the off-gas through the mass spectrometer during the heating cycle resulted in the diagrams shown in Fig. 2. The top left diagram is the examined spectrum as a function of time. The Y-axis scale is ion current, ranging from 1×10^{-10} amperes to 1×10^{-13} amperes. The bottom left diagram is the corresponding time/temperature cycle used to heat the sample. The time portions of the two left-side diagrams are aligned so that time/temperature and gas species are synchronized. The two right-hand diagrams are similar to the left-hand diagrams except the scale for ion current is magnified to the range of 2×10^{-11} to 2×10^{-12} , to allow detailed observation of the hydrogen curve.

The heating cycle began with a room-temperature hold for 50 min in flowing helium, followed by a

10°C per minute heating rate to 950°C. The analysis showed that during the 50-min room-temperature cycle, $H_2O_{(g)}$, $H_{2(g)}$, $OH_{(g)}$, and $O_{(g)}$ diminished with time by an exponential decay curve. (OH with $m/z = 17$ and O with $m/z = 16$ were tracked in parallel with water to confirm the signal $m/z = 18$ was from $H_2O_{(g)}$. Both $OH_{(g)}$ and $O_{(g)}$ are fragments of ionized $H_2O_{(g)}$ induced by the magnetic field and accelerating voltage in the detector inside the mass spectrometer.) Once heating commenced, an increase in $H_2O_{(g)}$, $OH_{(g)}$ and $O_{(g)}$ was registered in the mass spectrometer with a peak occurring at 300°C. Beyond 300°C, $H_2O_{(g)}$ diminished while $H_{2(g)}$ showed an increase. Hydrogen evolution diminished to the normal decay curve above 450°C, where it once again followed the expected decay curve. At 775°C, hydrogen was detected and increased up to 885°C where again it was seen to diminish.

An explanation of the TDP-MS data is proposed. During the 50-min room-temperature hold, free water from humidity exposure is evolving from the powder surface, indicated by the diminishing concentration of all species in this range. Between room temperature and 300°C, the outermost layers of adsorbed H_2O are desorbing, indicated by the ascending curve for water in this range. At 300°C, H_2O desorption is diminishing, and the oxidation reaction $Ti + 2H_2O_{(g)} = TiO_2 + 2H_{2(g)}$ begins with $H_{2(g)}$ evolving as evidenced by the ascending H_2 curve at 300°C. Between 300°C and 450°C, the evolving hydrogen has two reactionary paths: $H_{2(g)}$ can form TiH_2 according to the reaction $Ti + H_{2(g)} = TiH_2$ or $H_{2(g)}$ can dissolve into the alpha titanium as interstitial hydrogen according to equilibrium.¹³ Evidence that TiH_2 forms explains

the second evolution of hydrogen seen to begin at 775°C. At 775°C, the hydrogen concentration curve reaches a minimum at the temperature where delta G turns positive for the reaction $\text{Ti} + \text{H}_{2(g)} = \text{TiH}_2$ (Table II). From 775°C to 885°C, TiH_2 continues to dissociate as indicated by the ascending curve, until 885°C is reached. At 885°C, the beta transus is reached where hexagonal closed-packed alpha titanium transforms to body-centered cubic beta titanium. (Beta titanium at 885°C can dissolve $\text{H}_{2(g)}$ to 10,500 wppm as an interstitial species compared to a solubility of less than 30 wppm for alpha titanium at 880°C.¹³) Hence $\text{H}_{2(g)}$ dissolves into beta titanium at 885°C, resulting in a diminished detection of hydrogen in the mass spectrometer. The second reactionary path for hydrogen at 300°C is the dissolution of hydrogen into alpha titanium. That path cannot be validated in this analysis.

Because the sample form in the TPD-MS is loose powder, under flowing helium, evolving hydrogen can be detected. If the powder were consolidated to 50% to 80% as is typical for PM consolidation, and subsequently thermally treated in a vacuum or inert furnace, as is the typical practice for PM-Ti, then it is likely the majority of the evolving hydrogen would be consumed by the aforementioned reactions prior to escaping into the free space of a furnace. The result is an increase in both oxygen content via oxidation and hydrogen content via solid-state dissolution. In general, the higher the surface area of the starting titanium powder, the higher the increase in hydrogen and oxygen upon consolidation. Armstrong process powders show higher increases in oxygen upon consolidation than do HDH powders, due to the surface area difference.

Plate Sources for GTA Welding and Arc Melting

Four sources of plate material made from powdered titanium, 6 wt.% aluminum, 4 wt.% vanadium

(Ti-64), and two sources of plate made from CP powders, are shown in Table V. Table V also shows the composition of two commercial wrought alloys incorporated in the study for comparison, KW-Ti-64 and KW-CP. The Ti-64 plates were produced from Armstrong process powder (X1-ITP-Ti-64, and X2-ITP-Ti-64) (Cristal Metals, Lockport, IL) and hydride dehydride powder (HDH-Ti-64) (Reading Alloys, Robeson, PA). The HDH-Ti-64 powder was manufactured from revert scrap from Kroll route source material at Reading Alloys. Oak Ridge National Laboratory (ORNL) also purchased Ti-64 plate for this work from ADMA Products (ADMA-Ti-64; Hudson, OH), a commercial, PM-Ti plate producer. The two sources of commercially pure titanium powders were consolidated into plate via vacuum hot pressing. The HDH-CP powder source was from Global Titanium, Inc. (Detroit, MI). The X3-ITP-CP powder was from Cristal Metals.

Since the study was limited to plates previously consolidated, there was a variation in methods of consolidation. In the case of the Ti-64 alloy X1-ITP-Ti-64, consolidation was by vacuum hot pressing Armstrong process powders at 1,300°C into a 150-mm diameter disk. The plate was cut from the pressed disk via electrode discharge machining. Upon cross-sectional examination of the machined plate, porosity was observed and the plate was subsequently hot rolled at 950°C, taking a 20% reduction to achieve full consolidation at a 6-mm thickness. X2-ITP-Ti-64 was vacuum hot pressed to full density and hot forged in air at a forging temperature of 950°C. Porosity was observed in the ADMA-Ti-64 plate prior to welding and it was hot rolled at 950°C with a 20% reduction to achieve full density at a 6-mm thickness. The HDH-Ti-64 was consolidated by HIP at 925°C in a steel can, followed by machining to produce a rectangular weld coupon. The HIP'ed, HDH-Ti-64 appeared fully dense and no further processing was required. The CP titanium plates were both produced by vacuum hot pressing at

Table V. Compositions of PM-Ti consolidated plate

Species	Source plate Ti-64					Source plate CP-Ti		
	KW-Ti-64	ADMA Ti-64	X1-ITP Ti-64	X2-ITP Ti-64	HDH Ti-64	KW-CP	HDH CP	X3-ITP CP
Al (wt.%)	—	5.97	5.85	6.68	6.28	—	—	—
V (wt.%)	—	4.08	5.76	—	—	—	—	—
Fe (wt.%)	—	0.046	0.022	—	—	—	—	—
Cl (wppm)	<10	<10	<10	—	<10	<10	<10	<10
Na (wppm)	—	720	26	48	—	—	—	240
Mg (wppm)	<5	10	<5	<5	<5	<5	92	—
N ₂ (wppm)	90	210	6230	325	250	120	80	290
O ₂ (wppm)	1590	2480	3720	4235	1390	144	2280	3135
H ₂ (wppm)	18	48	160	17	150	15	120	44
	M	W	W	M	W & M	M	M	M

W Welded via GTA, M Melted via nonconsumable electrode vacuum arc

1,100°C. Full density in both plates was observed after hot pressing.

Noteworthy in the compositions of Table V are that X1-ITP-Ti-64 has high nitrogen, oxygen, hydrogen, and vanadium compared to ASTM B265-Gr5 specifications. The tramp element sodium, residual from the reduction process, is present in X1-ITP-Ti-64,

X2-ITP-Ti-64, and X3-ITP-CP. The HDH-Ti-64 material shows a hydrogen level equal to the maximum of the ASTM B265-Gr5 specification (150 wppm); all other elements fall within the desired range. ADMA-Ti-64 shows higher oxygen, 2,480 wppm, compared to the 2,000 wppm limits in the ASTM B265-Gr5 specification. All other species

Fig. 3. Plan view of autogenous GTA welds on PM-Ti alloy plates from three different sources. The white boxes denote the zones where cross sections were taken for the images in Fig. 4.

Fig. 4. Cross sectional view of the GTA welds showing the significant porosity in the ADMA-Ti-64, lesser but still present in X1-ITP-Ti-64, and minor in HDH-Ti-64.

in ADMA-Ti-64 fall within the specification limits, although detectable levels of both magnesium and sodium are present.

Fusion Welding

Autogenous GTA welding was performed on 6-mm-thick plate from ADMA-Ti-64, X1-Ti-64, and HDH-Ti-64 material sources. The cover gas was high-purity argon. The calculated heat input for the welds, using Eq. 1, was 93.6 kJ/m. Q is the heat input in megajoules per meter, η is arc efficiency (0.48 for GTA welding),¹⁴ E is electrode voltage (11 V), I is electrode current (120 A), and v is travel speed in meters per second (6.77×10^{-3} m/s).

$$Q = \eta \frac{EI}{v} \quad (1)$$

A plan view of the fusion welds is shown in Fig. 3 with the metallographic cross sections of each shown in Fig. 4 at the places indicated.

Significant porosity was visible on the surface and in the cross-sectional images of X1-ITP-Ti-64 and ADMA-Ti-64 as shown in Figs. 3 and 4. The HDH-Ti-64 had a smooth surface appearance with minor porosity identified in the cross section.

From the compositions shown in Table V the tramp elements sodium and magnesium in the case of ADMA-Ti-64 and sodium alone in the case of X1-ITP-Ti-64, stand out as likely causes for the porosity.

In the case of the HDH-Ti-64 plate, the porosity seen at the fusion line in Fig. 4 is likely due to hydrogen evolution.

To provide further evidence that the residual tramp element compounds of sodium and magnesium

were the cause of the gross porosity in ADMA-Ti-64 and X1-ITP-Ti-64, and that hydrogen was the likely source in HDH-Ti-64, arc melting was performed on plates of X2-ITP-Ti-64 and HDH-Ti-64.

Arc Melting

A nonconsumable tungsten electrode arc melter, running in 0.5 atmospheres of high-purity argon at 450 amperes, was used to melt 9 to 13 g cuboid coupons of the consolidated PM-Ti alloys whose compositions are depicted in Table VI. Figure 5 is a photograph of a coupon in the water-cooled copper crucible prior to melting. A molten pool was sustained for 30 s for each alloy source material while visual observations were made. Following cool down, the solidified masses were sectioned for

Fig. 5. Photograph of arc-melting coupon in the water-cooled copper crucible prior to melting.

Table VI. Compositions of PM-Ti consolidated plate before and after arc melting

Species	Melt condition	Source plate-Ti-64			Source plate Ti-Cp		
		X2-ITP-Ti-64	HDH-Ti-64	KW-Ti-64	X3-ITP-Cp	HDH-Cp	KW-Cp-Ti
Al (wt.%)	Pre	6.68	6.28	6.26	—	—	
	Post	7.12	—	6.32	—	—	
V (wt.%)	Pre	—	—	—	—	—	
	Post	—	—	—	—	—	
Fe (wt.%)	Pre	—	—	—	—	—	
	Post	—	—	—	—	—	
Na (wppm)	Pre	48	—	—	240	—	
	Post	<5	—	—	<5	—	
Mg (wppm)	Pre	—	<5	<5	<5	92	<5
	Post	—	<5	<5	<5	<5	<5
N ₂ (wppm)	Pre	310	250	9	290	80	120
	Post	340	260	10	310	90	120
O ₂ (wppm)	Pre	4235	1390	1590	3135	2280	1440
	Post	3940	1430	1780	3055	2345	1340
H ₂ (wppm)	Pre	17	150	18	44	120	15
	Post	10	51	16	19	54	18

compositional analysis using direct current plasma emission spectroscopy for alloying elements and LECO interstitial analysis for oxygen, nitrogen, and hydrogen (LECO Corporation, St. Joseph, MI).

The arc melting observations, where the molten pool was held for a minimum of 30 s, showed disturbances caused by evolving gas in all the PM-Ti melts. Aggressive disturbance was observed in the X2-ITP-Ti-64: vigorous in the initial 10 s and less so but still active at termination (30 s). Moderate molten pool disturbance was observed in the HDH-Ti-64 but ceased after 10 s and remained quiet for the duration of the 30-s hold. The KW-Ti-64 showed no disturbances. Examining the premelt and postmelt compositional values, a reduction in sodium from 48 wppm to nondetectable levels was shown in the X2-ITP-Ti-64 sample. A reduction in oxygen from 4,235 wppm to 3,190 wppm is unexplained in the X2-ITP-Ti-64 sample and requires further investigation. A reduction in hydrogen is also observed from 17 to 10 wppm.

The analytical results and the visual observations allow some speculation to be considered. If sodium were present in the starting material as NaOH or Na₂O, in the case of X2-ITP-Ti-64, upon heating to liquid, NaOH would likely either boil (1,388°C) or convert to Na₂O evolving hydrogen. The Na₂O would either reduce to Na and boil (1,413°C) or remain as solid Na₂O, until some superheat in the molten pool forced the Na₂O to boil (1,950°C). Na boiling may account for the early vigor. A time-temperature-dependent sustained release where Na₂O boils or slowly dissociates in the presence of molten titanium reasonably explains the sustained disturbance observed in X2-ITP-Ti-64.

The postmelt analysis where bulk hydrogen dropped from 17 wppm to 10 wppm indicates hydrogen evolution during melting. The sodium level went to nondetectable levels indicating complete release of sodium as a gas. If Na₂O was the sodium-containing species and Na₂O boiled, then a drop in oxygen level could be explained as seen in the analysis; however, if all the sodium (48 wppm) were Na₂O, that would equate to less than 20 wppm oxygen reduction, in contrast to the measured 245 wppm reduction. The reduced oxygen remains unexplained. It would have been beneficial to have arc melted ADMA-Ti-64 to further examine the apparent deoxidizing effect of sodium. The study did not allow that to occur.

In the case of HDH-Ti-64, early moderate disturbance could be attributable to hydrogen. A reduction in hydrogen from 150 wppm to 51 wppm occurred. Recall that the HDH-Ti-64 plate was produced from revert scrap, meaning that Kroll route material was reduced to a metal hydride powder by the hydride dehydride process and then consolidated. The triple-melt purification of the titanium alloy in the Kroll route material, prior to hydride/dehydride

processing, eliminated the residual magnesium as indicated by the premelt composition.

The KW-Ti-64 had little or no change in hydrogen and was calm throughout the 30-s melt, indicating no gas species were evolved during arc melts.

CONCLUSIONS

Powder-metallurgy-produced titanium cannot yet be reliably fusion welded due to weld porosity. The role of water vapor on the surface of titanium powder is one causal factor of the porosity. Water vapor has two effects; it increases the oxygen content of the consolidated powder via an oxidation reaction, and it increases the hydrogen content of the consolidated powder through a reaction dynamic that eventually ends up with hydrogen dissolved as an interstitial element in the consolidated base metal.

The porosity is also caused by internal contaminants: magnesium compounds in the case of Mg reduced TiCl₄, and sodium compounds in the case of Na-reduced TiCl₄. The contaminants are remnants of the reduction process, and if not removed prior to fusion welding, they become significant gas-forming species.

The challenge of removing the tramp compounds of sodium and magnesium without melting remains. Efforts to remove those tramp compounds by thermal distillation in the case of Mg compounds and aqueous removal in the case of sodium compounds is ongoing. To economically remove absorbed water or render its effects negligible is a significant challenge for PM-Ti. Work is underway at ORNL to find a remedy.

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