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Processing of Titanium Powder Made by the Armstrong Process

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During the past five years, the US Army and Navy have been exploring ways of reducing the cost of titanium products for their weapon systems. Single melt, cold-hearth melting and the development of non-aerospace specifications have received most of the funding. In parallel to these efforts, the Defense Advanced Research Projects Agency (DARPA) has funded a multi-task project exploring alternatives to the Kroll process. One of these processes is the Armstrong/International Titanium Powder (ITP) process. This process uses a liquid sodium reduction of $TiCl_4$ vapor to produce titanium powder. Since neither of the services uses titanium powder as a final product, the powder must be introduced into the manufacturing environment either as a replacement for sponge or by direct rolling of the powder into plate. This paper provides a summary of the process and results conducted at RTI International Metals and Concurrent Technologies Corporation *(CTC)* and funded by the US Army in using ITP powder in manufacturing plate from cast slabs produced from plasma melting of the ITP powder.

Keywords: *titanium (Ti). Powder Metallurgy (PM), mechanical properties, welding, Plasma Arc melting (PAM), Armstrong Process,*

1. Introduction

During the past five years, the US Army and Navy have been exploring ways of reducing the cost of titanium products for their weapon systems. Two of the most promising methods are single melt processing using Plasma Arc melting (PAM) and the Armstrong process as developed by International Titanium Powders (ITP). Though PAM has been used for a number of decades, it relies on bulk solids for melting either from sponge or scrap rather than powder which is produced by the Armstrong process. In addition, neither the Army nor Navy uses titanium powder. Since the titanium powder produced by the Armstrong process must be consolidated into a plate or bar, a project was started to investigate the properties of plate made from the plasma arc melting of 100% titanium powder to determine if the ITP powder can he used as a substitute for sponge.

2. Production of Titanium Powder

ITP supplied RTI International Metals, Inc. (RTI) 135 Kg of commercial pure titanium powder made using the Armstrong process. Figure 1 shows a representation of the process and Figure 2 shows the apparatus where the reaction occurs.

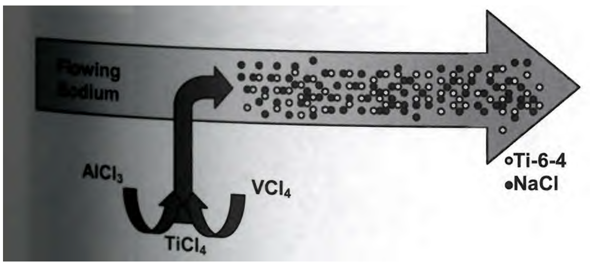

Figure 1. Schematic of the Armstrong process. For CP Ti only $TiCl_4$ is injected into the reaction apparatus

Figure 2. Reaction apparatus for the Armstrong process

3. PAM Processing

135 Kg of CP Ti powder was sent to RTI in Niles, Ohio for processing into slabs using their laboratory PAM furnace. First, aluminum and vanadium master alloys were blended with the CP Ti powder to form a master blend. The powder was then pressed into 75mm diameter by 25 mm high "pucks" for melting. 45 Kg of powder was melted in each heat producing 70 mm by 200 mm by 750 mm slabs. Next, the slabs were sectioned into thirds each 250 mm long and crossed rolled into 12.5 mm thick plate, 450 mm by 450 mm. Figure 3 shows a photo of one of the as-rolled plates.

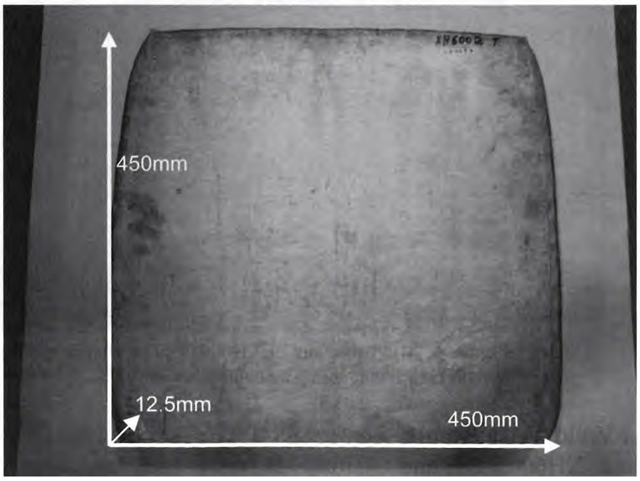

Figure 3. Photo of rolled plate

Table 1. Summary of the seven plates produced by PAM melting using ITP powder

Plate ID	Al wt.%	V wt. %	O, wt. %	Rolling Condition	Location in Ingot
XH6002-T	5.77	3.90	0.184	A (β + α/β)	top
XH6004-B1	6.39	4.42	0.183	A	middle
XH6004-B	6.39	4.42	0.183	A	bottom
XH6004-T	5.53	3.78	0.173	A	top
XH6005-B1	6.77	4.48	0.208	A	middle
XH6005-B	6.77	4.48	0.208	A	bottom
XH6005-T	6.00	4.03	0.183	A	top

4. Tests

Tensile, fracture toughness, and ballistic tests were conducted on both as-rolled and welded plates as listed in Table 1. The three plates produced from heat XH6005 were used for determining properties in the as-rolled condition and plate H6004-B and H6005-B1 were welded and tested.

4.1 Tensile Results

6.35 mm diameter tensile bars were sectioned from plate XH6005-T and tested to ASTM E8 in the as-rolled condition. The results of these tests are shown in Table 2. The results are better than listed in AMS 4911. This is probably the result of the cross rolling of the plates and the amount of therrnomechanical processing of the plates. Figure 4 shows a micrograph of plate XH6005-T. The microstructure shows flow lines, elongated prior β grains, transformed β containing acicular α, typical of Ti-6Al-4V plate made from sponge. Because the plates were cross rolled, tensile properties were only measured in one direction.

Table 2. Tension Test Results of Non-Weld Plate HX6005-T

Specimen Identification	Ult. Ten. Strength (MPa)	0.2% Offset Yield Strength (MPa)	Elongation (%)	Reduction of Area (%)
XH 6005T_Tensile 1	969.4	920.0	12.0	30.8
XH 6005T_Tensile 2	986.4	937.2	13.0	36.6
XH 6005T_Tensile 3	975.5	917.5	13.0	39.7
XH 6005T_Tensile 4	984.6	936.8	13.0	30.1
XH 6005T_Tensile 5	980.4	921.4	13.0	43.9
Average	**979.2**	**926.6**	**12.8**	**36.2**
Standard Deviation	**6.92**	**9.64**	**0.45**	**5.88**
AMS 4911$^{1)}$	897	828	10	30

ASTM-E8 round tension test. Specimens gauge diameter 6.35mm.

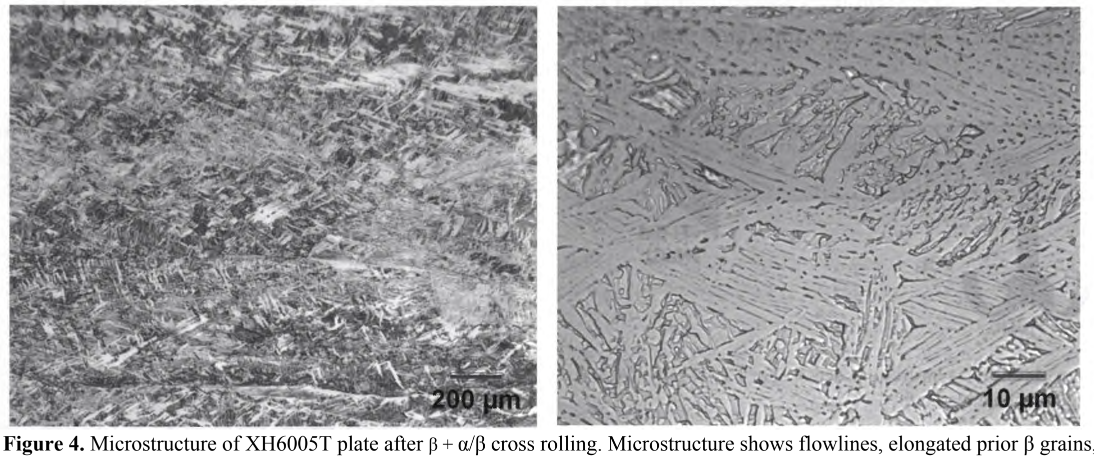

Figure 4. Microstructure of XH6005T plate after β + α/β cross rolling. Microstructure shows flowlines, elongated prior β grains, transformed β containing acicular α.

4.2 Weld Tests Results

Plate XH6005-B1 and XH6004-B were sectioned into quarters, welded and inspected in accordance with NAVSEA Technical Publications S9074-AR-GIB-010/278, and S9074-AQ-GIB-010/248. Plate XH6005-B1 was sectioned for tensile tests and plate XH6004-B was sent to the U.S. Army Research Laboratory for ballistic testing, which will is still in progress. Figure 5 shows the plates prior to sectioning the tensile specimens. The results of the tensile tests are listed in Table 3.

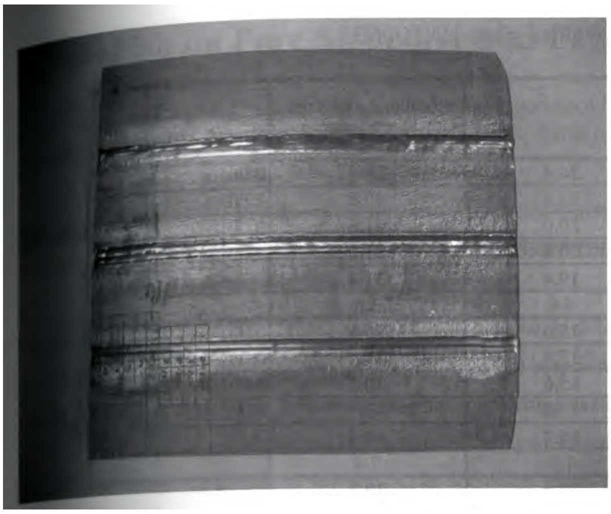

Figure 5. Plate XH6005-B1 after welding showing locations of tensile specimens

The results of the tensile tests exceed AMS4911 for both the Heat Affected Zone (HAZ) and the weld metal. Figure 6 shows a cross section of the weld and Figure 7 shows microstructures of the HAZ and Figure 8 shows the microstructures of the weld metal. Both are as expected.

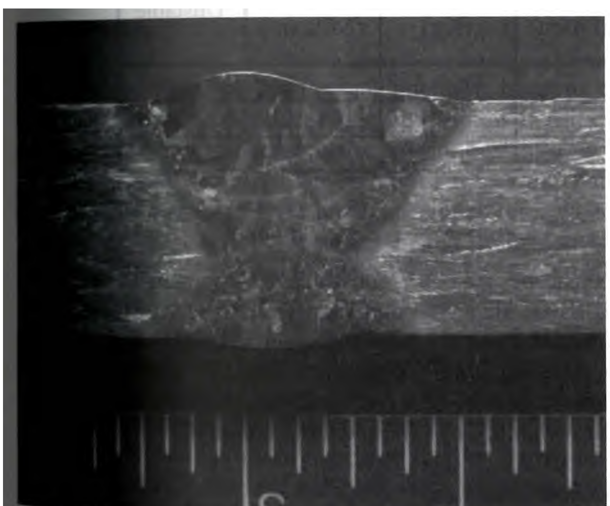

Figure 6. Cross section of weld.

Figure 7A. HAZ of welded plate

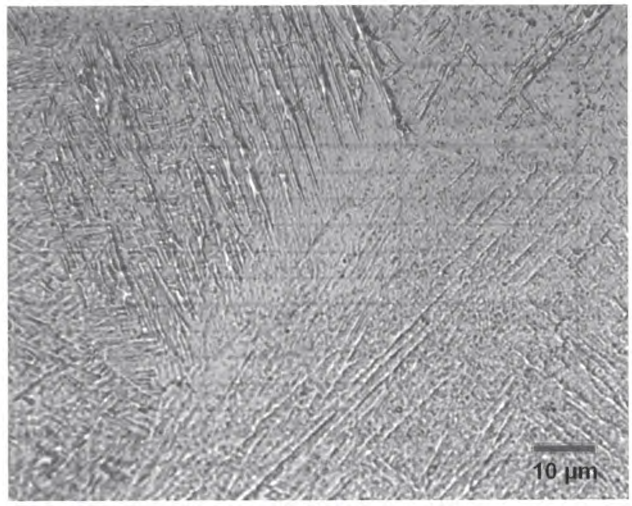

Figure 7B. Microstructures of HAZ

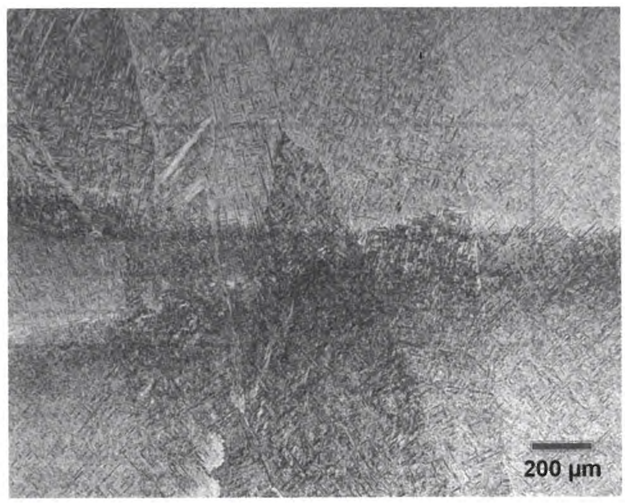

Figure 8A. Microstructure of weld metal, center area of XH6005-B Plate

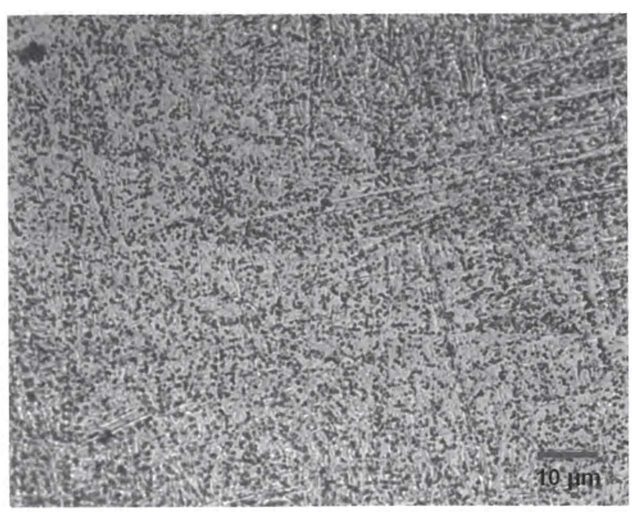

Figure 8B. Microstructure of weld metal from center of weld

Table 3. Tension Test Results of welded plate HX6005B1

Specimen Identification	Ultimate Tensile Strength (MPa)	0.2% Offset Yield Strength (MPa)	Elongation (%)	Reduction of Area (%)	Strain Rate until 2.0% Strain
Tensile-HAZ-1	948.7	837.0	24.4	36.1	0.001/sec
Tensile-HAZ-2	931.7	823.8	13.3	39.0	0.001/sec
Tensile-HAZ-3	991.1	836.4	20.0	41.8	0.001/sec
Tensile-HAZ-4	999.9	843.8	20.0	33.0	0.001/sec
Average	**967.9**	**835.3**	**19.4**	**37.4**	
St. Dev.	32.9	8.4	4.6	3.8	
Tensile-Weld-1	1033.2	892.0	15.6	26.5	0.001/sec
Tensile-Weld-2	1045.4	830.9	17.8	37.4	0.001/sec
Tensile-Weld-3	931.5	838.2	15.6	30.5	0.001/sec
Tensile-Weld-4	950.2	891.7	17.8	43.1	0.001/sec
Average	**990.1**	**863.2**	**16.7**	**34.4**	
St. Dev.	57.5	33.2	1.3	7.4	
AMS4911	**897.0**	**828.0**	**10.0**	**30.0**	

ASTM-E8 Round Tension Test. Specimen gauge diameter 2.87mm.

Table 4. J-Integral Test Results

Results of J-Integral Test [2)]

Specimen	J_U (N/m x 10^3)	J_Q (N/m x 10^3)	K_{JU} (MPa√m)	K_{JQ} (MPa√m)	P_Q (Kg)	K_{IC} (MPa√m)	Unstable
J_{IC}-A	20.1		50.9		468	47.0	Yes
J_{IC}-B	17.5		47.5		786	43.8	Yes
J_{IC}-C		16.4		46.0	856	47.9	Yes

4.3 Fracture Toughness (J-Integral) Testing Results

J-Integral testing was performed per ASTM E1820-01 on plate XH6005T. Nominal size of CT specimen used was total thickness of 12.5 mm, width (W) of 25 mm, fatigue pre-crack length to final a/W measuring approximately 0.50, side groove depth equal to 20% of the nominal thickness. The following data were used in the calculations:

Material: Ti-6Al-4V
Modulus: 117 GPa
Ultimate tensile strength: 980 MPa
0.2% off-set yield strength: 953 MPa

Table 4 shows the J-Integral test results. All measurements of J_U and K_{IC} are valid data.

5. Conclusion

The test results conducted in this study demonstrated that powder made using the Armstrong process and supplied by ITP can be used as a substitute for sponge and scrap. The results of all tests conducted (except HAZ-2) matched or exceeded those of standard specifications. If during scale up, International Titanium Powder can manufacture titanium powder at a cost less than that of sponge, then the future viability of ITP powder is favorable.

Acknowledgement

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REFERENCES

1) MIL-Handbook-5, TABLE 5.4.1.0(b), pp5-53

2) Metals Handbook, Vol. 2, 10th Edition, Table 22, pp622