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EVALUATION OF ARCAM DEPOSITED TI-6AL-4V

Kevin Slattery[1], Blake Slaughter[2], Emily Speorl[3], James Good[4], Scott Gilley[5]and Carole McLemore[6]
[1] Boeing – Phantom Works
Saint Louis, MO, USA
kevin.t.slattery@boeing.com
[2] Boeing – Phantom Works
Saint Louis, MO, USAz
blake.slaughter@boeing.com
[3] Boeing – Phantom Works
Saint Louis, MO, USA
emily.j.speorl@boeing.com
[4] Teledyne Brown Engineering - Marshall Space Flight Center
Huntsville, AL, USA
Jim.Good@tbe.com
[5] Tecmasters - Marshall Space Flight Center
Huntsville, AL, USA
sgilley@techmasters.com
[6] NASA - Marshall Space Flight Center
Huntsville, AL, USA
Carole.A.McLemore@nasa.gov

ABSTRACT

A wide range of Metal Additive Manufacturing (MAM) technologies are becoming available. One of the challenges in using new technologies for aerospace systems is demonstrating that the process and system has the ability to manufacture components that meet the high quality requirements on a statistically significant basis.

The widest-used system for small to medium sized components is the ARCAM system manufactured in Gothenburg, Sweden. This system features a 4kW electron-beam gun, and has a chamber volume of 250mm long x 250mm wide x 250mm to 400mm tall.

This paper will describe the basis for the quality and consistency requirements, the experimental and evaluation procedures used for the evaluation, and an analysis of the results for Ti-6Al-4V.

1 INTRODUCTION AND BACKGROUND

While its high strength, low density, and outstanding corrosion resistance make titanium is the material of choice for a wide variety of applications, especially in aerospace; the high cost of mill products and machining are obstacles in providing lower-cost aircraft. While many parts are machined from solid mill products, others are made from closed die forgings. The long lead times needed for die design and fabrication makes it difficult to optimize design and build the components on time.

Metal Additive Manufacturing processes have the potential to reduce both the material usage, cost, and lead time needed to make metallic components. These processes consists of using software to guide an energy beam to build a net or near-net component in a layerwise fashion, as shown in Figure 1. Over 20 of these processes have been developed or proposed throughout the world. Some processes inject powder into a molten puddle, others use a powder bed, and still others feed a wire into the molten puddle. The majority of the work performed to date has been on Ti-6Al-4V because of its high cost, and wide application in aerospace.

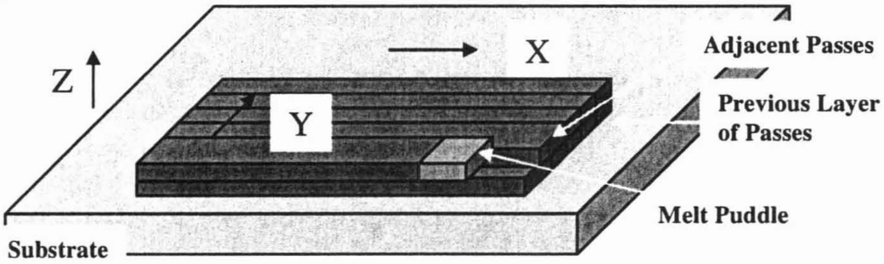

Figure 1: Metal Additive Manufacturing

While the Laser Additive Manufacturing (LAM) process was successfully implemented by Boeing on several aircraft, the company commercializing it in the United States, AeroMet, was shut down by its parent company. One thing that was gained out of the development and implementation of the LAM process, however, was an extensive material property database and product quality standards. The result is that a material specification with chemistry, heat treat, and quality assurance provisions has been drafted. This draft specification, known as AMS 4999A, not only contains the usual part minimum tensile property requirements, but also the mechanical property requirements for process and supplier qualification, and process parameter qualification. This enables use of multiple processes and feedstocks, and enables suppliers to perform one set of tests to be approved by multiple Original Equipment Manufacturers.

One of the best selling Metal Additive Manufacturing machines is made by Arcam in Sweden. In excess of 20 of these machines have been sold worldwide. The purpose of this work was to see if the ARCAM system was capable of making parts that meet the requirements for qualification to the draft revision to AMS 4999. This work was performed jointly by Boeing and NASA-Huntsville.

2 DESCRIPTION OF ARCAM SYSTEM

The Arcam process is a powder-bed based layered - or additive - manufacturing process. The process uniquely utilizes an electron beam as an energy source. A wide variety of materials have been processed on the Arcam system. The nature and efficiency of the electron beam's interaction enables the processing of many difficult materials from aluminum to tungsten. Vaporization of lower melt point alloying elements is often more of a concern than the ability to melt the base material, due to the vacuum environment. The environment also provides some advantages in eliminating residual stress, because of the temperature and dwell time of builds.

Arcam's first offering, the S12, featured basic functions, and is a good representation of the technology. Recently, the company has begun offering the A2. The A2 offers a taller build chamber, improved process monitoring, and process stabilization techniques. The A2 process improvements - available to some extent as an upgrade for the S12 - should be a welcome improvement for those focusing on production applications.

3 TEST PROCEDURE AND MATRIX

The test program involved fabrication of eight bulk specimens on each of two separate but identical design EBM systems per Table 1. One system was located at the NASA Marshall Space Flight Center in Huntsville, AL and the other at Boeing Phantom Works in St. Louis, MO. Specimens in the as-built condition directly from the systems were compared to those post-treated by the Hot Isostatic Press (HIP) process as shown in the first two rows of Table 1. The lower part of the table shows that the test plan included four different powder feedstock lots to investigate multiple lot effects. The powder lots were first utilized in the Boeing sample builds and then transferred to the NASA system for fabrication of the same geometries with identical process settings.

Table I – Bulk Specimen Test Matrix

System, Powder, Lot ID1	**Bulk Specimen Treatment Condition A – As-Built, H – HIP Post-Processed**							
	S1	**S2**	**S3[2]**	**S4**	**S4I[3]**	**S5**	**S6**	**S7**
NASA Build	A	A	A/H	H	A	A	A	H
Boeing Build	A	H	A	H	A	H	H	A
NASA Powder	87	89	89	87	87	84	89	87
Boeing Powder	88	89	89	87	87	88	89	87

1. All powder lots were Plasma Rotating Electrode Processed (PREP) per AMS 4999.
2. S3 comprised two mirrored features in the same build. Prior to NASA S3 coupon extractions, one half was HIPed and the other was as-built.
3. Specimen S4I was a grouping of individual coupons arranged in the same build orientation as that for the S4 bulk specimen.

HIP treatment was performed on the indicated bulk specimens in Table 1 prior to coupon extraction. This was carried out under pressure greater than 100 MPa at a temperature range of 899°C to 954°C for 2 to 4 hours, and cooled under inert atmosphere to below 427°C. Subsequent stress relief was not performed for the test results presented herein.

The test plan involved extraction of over 300 individual test coupons out of the bulk specimens via machining in the three main axis directions X, Y and Z. The test coupons included tensile, strain-life, fatigue crack growth, and short bar fracture toughness as shown in Table 2. Note that two sets of all the tests shown were performed since each fabrication system produced one set. Chemical analyses were performed on the coupons as well as pre-build and post-build powder feedstock samples to assess compositions relative to specification limits. These also assessed oxygen build-up or loss of alloy elements during any single build and after multiple fabrication runs.

Table II – Sample Coupon Test Matrix

Test Type	Bulk Specimen Identification							
	S1	S2[1]	S3	S4	S4I	S5	S6	S7
Tensile	24	30	12	21	21	24	15	36
Strain-Life	9	12	0	0	0	3	0	0
da/dN	0	1	1	0	0	0	0	0
Toughness	0	0	3	0	0	0	3	0
Chemical[2]	3	3	4	3	4	3	4	5

1. Boeing S2 bulk specimen was not completed in time for testing.
2. Boeing powder feedstock was not tested.

Tensile testing was performed per ASTM E8 with strain rate maintained within 0.003 to 0.007 mm/mm/minute through the yield strength and then increased so as to produce failure in approximately one additional minute. Strain-life fatigue testing was in accordance with ASTM E606 with $R = -1$ and $R_{max} = 0.005$. Fatigue coupons were tested per ASTM E606-04 using a triangular waveform at a frequency of 30 cycles per minute with an R ratio of –1.0 and a maximum strain of 0.5%. Failure was defined as the point where the maximum stress decreased to 50% of the maximum stress at the 100th cycle. Fracture toughness was assessed per ASTM E1304 for short fracture bars. Chemical composition analyses were performed on extracted coupons and powder feedstock in accordance with AMS 4911L.

4 MICROGRAPHIC TEST RESULTS

The thirteen (13) parts were successfully fabricated, with some of the larger parts taking up to 40 hours to build. One of these parts is shown in Figure 2. Figure 3 shows the columnar microstructure typical of deposits in the ARCAM system, and many other MAM processes. Figure 4 shows the fine Widmanstatten structure also typical of these processes, where the material cools rapidly across the β-transus. Nothing atypical was observed in the microstructures.

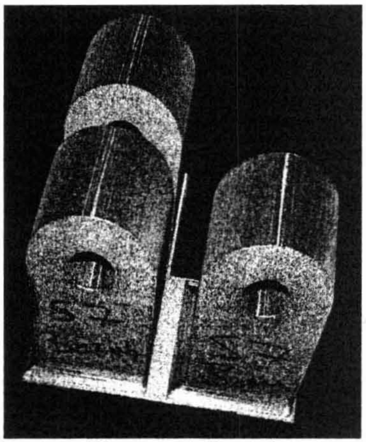

Figure 2: Part S7 (Hole Diameter is 25mm)

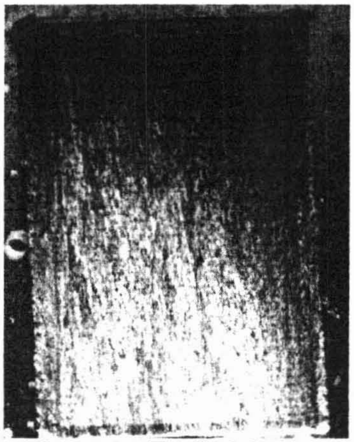

Figure 3 – Typical Cross-Section – 13mm Wide

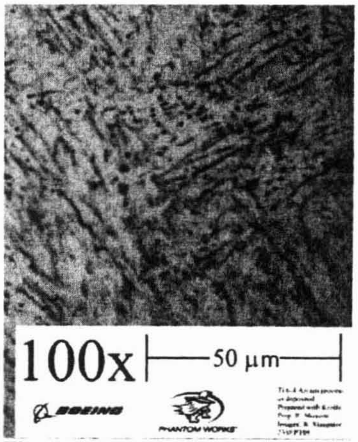

Figure 4: Typ Microstructure

5 MECHANICAL TEST RESULTS AND ANALYSIS

The mixture of powder heats, heat treatments, and machines used enabled analysis of the variables in a variety of ways

In this study 335 tensile coupons were harvested from 13 components produced on two separate Arcam S12 machines. Some of the produced coupons come from hot isostatically pressed (HIP'ed) material, and the remainder were produced from material in the "as-deposited" condition. Of the coupons produced, roughly 9% of the coupons were suspected - and verified - to have lack of fusion conditions. Of these coupons, only one coupon came from HIP'ed material. These coupons have been excluded from the data analysis, and the parts will be replaced at a later date for evaluation per AMS 4999.

Table III: Test Result Summary

Criteria	Direction	Hot Isostatically Pressed - All Specimens	As Deposited Specimens - Excluding Those with Detectable Lack of Fusion	Draft AMS 4999A
Minimum UTS (MPa)	X	1031	1032	130
	Y	931	917	130
	Z	928	968	125
Coefficient of Variation for UTS (%)	X	0.55	0.85	3.3
	Y	0.91	[redacted]	3.3
	Z	2.96	1.94	3.3
Minimum YS (MPa)	X	927	951	116
	Y	820	825	116
	Z	836	892	110
Coefficient of Variation for YS (%)	X	1.48	0.86	3.1
	Y	1.06	[redacted]	3.1
	Z	2.76	2.23	3.1
Minimum Elongation (%)	X	14	10	6
	Y	13	10	6
	Z	16	6	6

With respect to Boeing deposited material which received HIP treatment, the material meets the requirements of AMS 4999 with the exception of a Coefficient of Variation (CV) for the Z direction of 3.4% YTS (3.1% is allowed) and 3.5% UTS (3.3% is allowed). The CV values of coupons taken from the same component are less than 1%. However, the mean values of YS and UTS are significantly different for the two components. When the populations are combined the collective CV grows out of spec. Boeing material which was not HIP processed, meets the requirements of AMS 4999 in the Y and Z directions for minimum tensile values. However, the Y oriented coupons have a CV higher than is allowed by the specification. As with the HIP treated material, CV within components is very minimal, but the difference in mean values across the components causes the failure. Z orientation coupons meet requirements of AMS 4999.

NASA material in the HIP'ed condition met all requirements of AMS 4999 in the Y and Z directions. Because of the selection of components, no X orientation components were HIP'ed in this study. These coupons met the requirements of AMS 4999 before any lack of fusion coupons where removed. NASA "as-deposited" material met the requirements of AMS 4999 in the X, Y, Z directions once coupons with detectable lack-of-fusion were removed from the population.

Low Cycle Fatigue (LCF) results for the material confirm an expected increase in sensitive to lack-of-fusion conditions. All coupons which failed to meet AMS 4999 where from material in the as-deposited condition. If the coupons with detectable levels of lack-of-fusion are removed from the population, the remaining material meets AMS 4999 with a mean value of 35,653 cycles at failure, well above the criteria lf 15,000 cycles.

All Boeing and NASA fracture toughness samples met the requirements of AMS 4999. As a result no coupons were removed from the population or examined for lack-of-fusion conditions.

Additional coupon testing is needed to increase statistical significance. However, based on current available data, material which is HIP processed will meet requirements of AMS 4999. Material in the as-deposited state - while comfortably above minimum values - suffers from scatter in some cases. This scatter may be addressable or acceptable. Until process maturity improves, the use of as-deposited material may be practically and economically infeasible in most aerospace applications. The presence of lack-of-fusion in as-deposited material places a great deal of pressure on NDT evaluation to detect unacceptable flaws. The presence of these defects would also cause high scrap rates for components. It should be pointed out that processing parameters for individual components can be customized to improve the quality of as-deposited material on a case-by-case basis.

6 FRACTOGRAPHY

Fractographic methods are often used to determine crack growth behavior and locations of premature fracture. Using destructive and non destructive testing methods enables the identification of lack of fusion in the tensile and fatigue coupons. Regions that contain lack of fusion exhibit gaps of air between the particle spheres, which facilitate crack growth and are the location of failure during tensile and fatigue testing in the X, Y, and Z coordinates. Testing of the coupons involved over 300 specimens from Boeing and NASA, with less than 40 containing noticeable lack of fusion that likely led to premature failure. In the majority of specimens viewed, lack of fusion is very apparent and characterized by the spherical dimples left in the metallic surface. Lack of fusion would have been determined via x-ray metallographic techniques for lack of fusion greater than 2% of total thickness or via dye penetrant testing up to 0.050 mm deep.

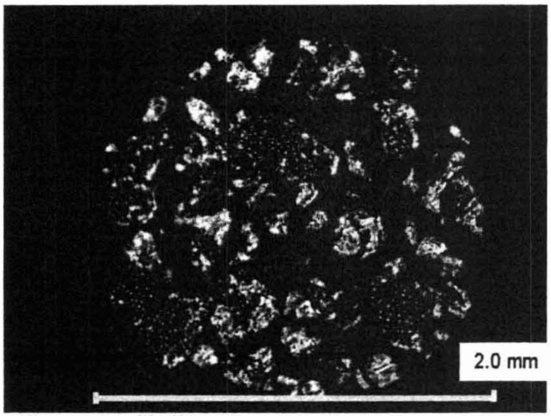

Figure 5: Y-direction tensile coupon containing significant lack of fusion

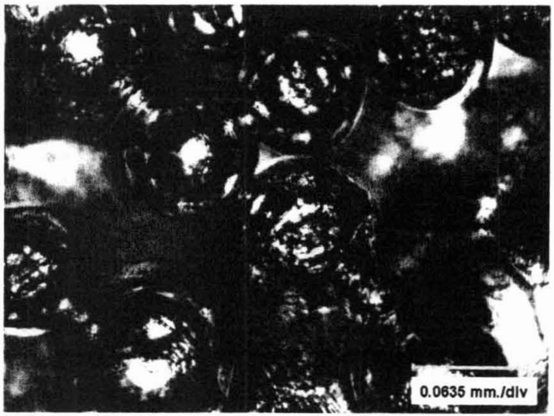

Figure 6: Close up of lack of fusion in fatigue coupon in the X-direction

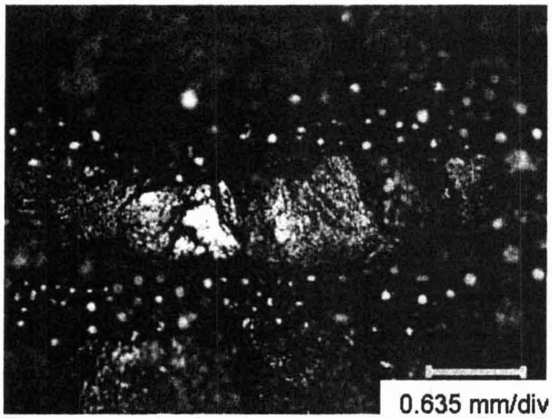

Figure 7: Spherical lack of fusion in Y-direction

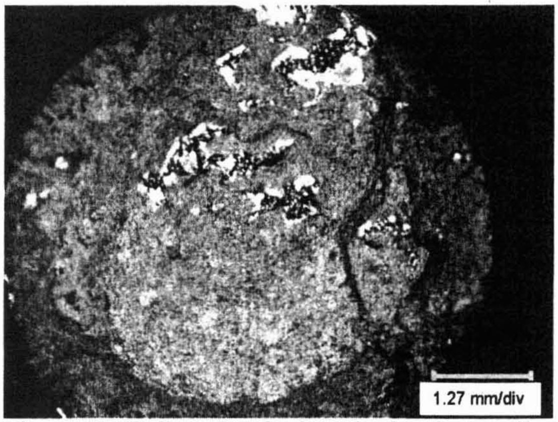

Figure 8: Z-direction lack of fusion in tensile coupon

7 CONCLUSIONS

Ti-6Al-4V components produced on the Arcam system are capable of meeting the requirements of the proposed Revision A to AMS 4999, when the part receives Hot Isostatic Pressing.

The lack of fusion that does occur in the Arcam system is of a size that can be detected with standard aerospace inspection methods.

8 RECOMMENDATIONS

The root cause of the lack of fusion should be investigated and corrected.

Additional parts should be made and tested to replace those containing lack of fusion, and the results re-compiled.