

# COMPARISON OF TWO METALLIC ADDITIVE MANUFACTURING TECHNOLOGIES: SELECTIVE LASER MELTING AND ELECTRON BEAM MELTING

KOK YIHONG, S.B TOR, N.H LOH

*School of Mechanical & Aerospace Engineering, Nanyang Technological University  
50 Nanyang Avenue, Singapore 639798, Singapore*

**ABSTRACT:** This general review paper compares two powder-bed fusion metallic additive manufacturing processes. The method is by reviewing past literature from sources such as scientific databases, journals, conferences and webpages. The scope of this review is on the selective laser melting and electron beam melting additive manufacturing method. The findings have shown large advances in the manufacturing quality of these two methods commercially. This review thus facilitates the choice of using either a laser based or electron based method for a given application.

## INTRODUCTION

The hype and interest in metallic additive manufacturing technology has accelerated in the last year or so, as can be seen from the funding by several governments around the world. Thus it is worthwhile to have a general review of the latest state of the art of the progress of two commonly used powder bed fusion methods namely Selective Laser Melting (SLM) and Electron Beam Melting (EBM), as current research in this field is progressing quickly.

The comparison of the two methods will be done by first describing each method and then by stating relevant material and process considerations unique and common to each method.

Selective Laser Melting (SLM) is a laser-based additive manufacturing method. Any materials that absorb the specific wavelength of photons emitted by the laser can be melted thus SLM is not limited to only metallic materials. The binding mechanism in SLM is by the molten material that binds each powder layer chemically together. The material used in selective laser melting is normally in a powder form.

Electron Beam Melting (EBM) is an electron-based additive manufacturing method. Unlike SLM, only electrically conductive materials are known to be applicable to this method. The melting mechanism is thought to be due to the kinetic energy transfer of the fast moving electron to the powder bed (Zah et al. 2009). The binding mechanism is similar to SLM. However the material used in electron beam melting could be either in powder form or in a solid filament, in this review the material is assumed to be in powder form unless otherwise stated.

### Material Consideration

The different energy source in which the two methods use to melt the material leads to some distinct material considerations.

### **Absorbance**

The definition of absorbance is the ratio of the amount of radiation absorbed by the material over the total amount of radiation transmitted through the material (Gu et al. 2012). This property thus allows the determination of suitable processing windows for different materials to ensure built quality (Nikolay et al. 2000).

### **Reflectivity**

High reflectivity in metal can affect the full densification of parts (Rombouts et al. 2006). This is due to the reflective melt pool affecting the energy density of the laser beam on the powder bed. This can be overcome by adding alloying element to the highly reflective metal to obtain higher build density in the final built parts (Rombouts et al. 2006).

The two considerations Absorbance and Reflectivity mentioned previously is important to Selective Laser Melting due to the nature of using photons to melt the powder material. We will now look at considerations involving the electron beam melting process. Materials with high reflectivity are Aluminum and Copper (Taminger & Hafley 2008)

### **Electrical Conductivity**

Electrical Conductivity of the material is an important parameter due to the use of electron gun in melting the powder material (Petrovic et al. 2011) A phenomenon called powder spreading is associated with the electrical conductivity of the powder interacting with the charge of the beam of electron (Eschey et al. 2009). This phenomenon has been shown to be overcome by the use of spattered shape particles instead of spherical shape particles (Eschey et al. 2009). The flow ability of the powder during each layer could be compromised by the use of spattered shaped particles.

### **Vaporization of Alloying Elements**

The electron beam melting (EBM) process occurs in a vacuum environment, this helps to prevent the dissipation of the electron beam (Hiemenz 2007). Though the vacuum environment and the high temperatures involve causes the vaporization of alloying elements, this phenomenon is well known in the field of vacuum metallurgy (Das 2003). This phenomenon though can possibly be reduced due to the quick solidification nature of the process (Cormier 2004), though a study showing the effects of vaporization of alloying elements of different alloy is still not well established.

### **Recommended Materials**

Due to the different material considerations associated with each method as described above, the range of materials suitable for each method is different. In the case of Selective Laser Melting, SLM Solution GmbH recommends 316L Stainless Steel, as the final built parts show good properties [SLM Solutions 2013]. In the case of Electron Beam Melting, Arcam AB, the manufacturer of the EBM technology recommends Ti-6Al-4V titanium alloy (Arcam 2014).

## **EVALUATION METHODS**

The use of test coupons as a primary experimental method to verify each method has remain unchanged. In this review the author will summarized the evaluation of each method using a common framework of Quality - Time - Cost, to understand the current state of the art for each method. So as to facilitate the choice of method for industrial applications.

## Manufacturing Quality

### Surface & Dimensional Quality

The surface roughness of electron beam melted parts is higher as compared to Selective Laser Melting. This could be due to the powder-spreading phenomenon known in EBM. Process parameters like powder diameter, beam spot size and z layer resolution are also likely to affect the surface roughness of the final built part.

The dimensional accuracies of the two manufacturing methods are shown below. The possible factors affecting the dimensional quality could be the thermal conductivity and process optimization. Such as heat related defects are curling, balling and shrinkage, that can possibly be reduced through process optimization with regards to the specific material.

Table 1. Surface Quality Comparison

	SLM	EBM
Rugosity (um)	Ra 11 (Vayre et al 2012)	Ra 25-35 (Vayre et al 2012)
Powder Diameter (um)	30 (Haijun et al 2013)	60-72.69 (Haijun et al 2013, Khalid et al 2012)
Beam Spot Size (um)	80 (SLM Solutions 2014)	100 (Horn 2013)
Z Layer Resolution (um)	30 (Haijun et al 2013)	50 (Rangers 2012)
Dimensional Accuracy	0.2 mm (Vayre et al 2012)	0.4 mm (Vayre et al 2012)

### Mechanical Properties

The mature material development of certain materials such as 316l Stainless steel for SLM and Ti-6Al-4V titanium alloy for EBM has reached a level of consistency where most of their properties are equivalent to their wrought counterpart. However Fatigue strength and ductility of additive manufactured parts are still generally weaker as compared to wrought material. Fatigue strength can be overcome by the use of heat treatment processes such as hot iso-static pressing (Christensen et al. 2007). Though the reduce fatigue strength of manufactured part is suspected to be due to factors such as microstructure difference, porosity or residual stress in the process (Hrabe et al. 2011). These factors are also likely to cause the reduction in the % elongation properties of additive manufactured parts. A brief comparison of 316L Stainless Steel & Ti-6Al-4V titanium alloy's mechanical properties build using selective laser melting and electron beam melting process will be discuss next.

### Observations on EBM built part by Arcam AB

Arcam AB did a feasibility study in conjunction with NASA for possible space application in 2007 (Good 2007). The result of that study shows that 316L stainless steel can be processed in the Arcam EBM machine, as the mechanical properties compares well against the wrought material properties. The study also claims that no macroscopic porosity was observed, layers are seen the z cross-section and a columnar grain growth microstructure is seen in the z direction (Good 2007).

Though defects were also observed in the study, such as vertical inter granular cracks up to a few millimeters in the Z direction and small particles are seen in some grain boundary (Good 2007).

**Observations on SLM built part by SLM Solution**

SLM Solution did a material study on 316L Stainless Steel and presented its findings in NLR Additive Manufacturing Symposium in 2013. Unlike the defects seen in the Electron Beam Melting feasibility study, this is not seen in SLM. This resulted in higher mechanical properties in terms of yield strength and %elongation as compared to EBM Process. Similar elongated grain structures are also seen in SLM built parts.

Next a comparison of 316L Stainless Steel mechanical properties will be shown in the table 3 (Good 2007).

Table 3. Comparison of 316L Stainless Steel Mechanical Properties

	SLM	EBM	Cast***	Wrought**
Yield Strength (Offset 0.2%) MPa (Vertically Built)	462 (SLM Solutions 2013)	287-304 (Good 2007)	205 (ASTM 2014)	22.8-767 (Good 2007)
Yield Strength (Offset 0.2%) MPa (Horizontally Built)		190-254 (Good 2007)		
Ultimate Tensile Stress (Vertically Built)	565 (SLM Solutions 2013)	539-554 (Good 2007)	485 (ASTM 2014)	341-1000 (Good 2007)
Ultimate Tensile Stress (Horizontally Built)		239-384 (Good 2007)		
% Elongation (Vertically Built)	53.7 (SLM Solutions 2013)	34.5-40.0 (Good 2007)	30 (ASTM 2014)	22.3-57.7 (Good 2007)
% Elongation (Horizontally Built)		14.5-37 (Good 2007)		
Fatigue Strength MPa	266 316* (SLM Solutions 2013)	-	-	256-307 (Good 2007)
*after HIP process **ASM Handbook ***A351/A351M-CF8M				

Next a comparison of Ti-6Al-4V titanium alloy’s mechanical properties build using the two methods (SLM & EBM) will be discussed.

**Observations on EBM built part through literature review**

Ti-6Al-4V titanium alloy built using electron beam melting shows an  $\alpha/\beta$  microstructure [Murr et al 2009, 2012]. In a presentation done by Steve Rengers of ATM, it was stated that EBM processing of Ti-6Al-4V results in a 4% drop in aluminum in the alloy thus advises that when processing with Ti-6Al-4V, the powder used should be on the high side for aluminum content (Rangers 2012).

Similar to the comparison of 316L Stainless Steel it can be seen from the mechanical properties that electron beam melted Ti-6Al-4V is comparable with wrought material with that exception of fatigue strength which requires a post processing heat treatment process (hot iso static pressing).

Porosity defects seen in Ti-6Al-4V EBM built part is mainly attributed to inadequate energy density (Haijun 2013). Porosity is also thought to be a significant factor in the drop of fatigue strength, as after the part undergoes hot iso static pressing the fatigue strength of built part tends to be comparable with wrought material (Arcam 2014).

**Observations on SLM built part through literature review**

Ti-6Al-4V titanium alloys built using SLM shows a  $\alpha/\alpha'$  microstructure (Murr 2009,2012). Unlike the electron beam melted part, which suffers from lower fatigue strength, the selective laser melted part shows a low ductility in the lower % elongation property.

Similar to the EBM built part, porosity defects are only seen (Haijun 2013). The lower % elongation is thought to be due to porosity and the residual stress incur in the selective melting process.

Table 4. Comparison of Ti-6Al-4V Titanium Alloy Mechanical Properties

	SLM	EBM	Cast*	Wrought**
Yield Strength (Offset 0.2%) MPa (Vertically Built)	1143(Khalid et al. 2013)	869 (Khalid et al. 2013)	758 MPa (Arcam 2014)	860 MPa (Arcam 2014)
Yield Strength (Offset 0.2%) MPa (Horizontally Built)	1195(Khalid et al. 2013)	899 (Khalid et al. 2013)		
Ultimate Tensile Stress (Vertically Built)	1219 (Khalid et al. 2013)	928 (Khalid et al. 2013)	860 MPa (Arcam 2014)	930 MPa (Arcam 2014)
Ultimate Tensile Stress (Horizontally Built)	1269 (Khalid et al. 2013)	978 (Khalid et al. 2013)		
% Elongation (Vertically Built)	4.89 (Khalid et al. 2013)	9.9(Khalid et al. 2013)	>8 (Arcam 2014)	>10 (Arcam 2014)
% Elongation (Horizontally Built)	5 (Khalid et al. 2013)	9.5 (Khalid et al. 2013)		
Fatigue Strength MPa	550 (Khalid et al. 2013)	340 (Khalid et al. 2013) 600 MPa *** (Arcam 2014)	430**** (Khalid et al. 2013) 600 MPa *** (Arcam 2014)	600 MPa *** (Arcam 2014)
* ASTM F1108 (cast material) **ASTM F1472 (wrought material) *** after HIP ****MMPDS (Metallic Materials Properties Development and Standardization Hand Book)				

## SUMMARY TABLE OF SPECIFICATION & PERFORMANCE

Table 5 shows the best possible specification for each method and not the specification of specific machines.

Table 5. Summary Table of Specification & Performance

Process	Selective Laser Melting	Electron Beam Melting	Advantage
Environment	Argon/Nitrogen (SLM Solution 2014)	Vacuum/Helium (Koiki et al 2011)	-
Built Area	500x280x325 (SLM Solution 2014)	Ø350×380 mm (Arcam 2014)	-
Built Temperature	700 Deg Celsius (Koiki et al 2011)	700 Deg Celsius (Koiki et al 2011)	-
Power	2 X 400W 2 X 1000W (SLM Solution 2014)	3500 W (Arcam 2014)	EBM
Energy Used (kWh/kg)	31 (316L) (Baumers et al. 2010)	17 (Ti-6Al-4V) (Baumers et al. 2010)	EBM
Powder (Average Size)	30 um(Ti-6Al-4V) (Haijun et al. 2013)	60-72.69 um (Haijun et al. 2013, Khalid et al. 2012) (Ti-6Al-4V)	SLM
Min Wall Thickness	160-180 um (SLM Solution 2014)	-	
Beam Spot Size (um)	80-150 700 (SLM Solution 2014)	100 (Horn 2013)	SLM
Z Layer Resolution (um)	20 -200 (SLM Solution 2014)	50 (Rangers 2012)	SLM
Rugosity (um)	Ra 11 (Vayre 2012)	Ra 25-35 (Vayre 2012)	SLM
Building Speed	70 cm <sup>3</sup> /h (SLM Solution 2014)	55-80 cm <sup>3</sup> /h (Arcam 2014)	EBM

## CONCLUSION

From the summary table, we can see that SLM is advantageous as compared with EBM in terms of powder size, beam spot size, layer thickness and surface roughness which most likely affects the built quality of the final part.

While EBM uses a higher powered energy source and is a more efficient process. This could mean that EBM with its more powerful energy source is possibly capable of melting materials of a higher melting temperature as compared to selective laser melting.

So if we based our conclusion on a Quality-Time-Cost framework and with the information on table 5, the author conclusion of both manufacturing process are as follows. SLM produces a better quality product as compared to EBM. While EBM is a faster and more efficient process thus cost cheaper as compared to SLM. With this in mind it is thus important to understand the application that one hopes to manufacture with such manufacturing process. Whether if quality is the dominant aspect or that cost and time is the dominant aspect.

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