A Review of Layer Based Manufacturing Processes for Metals

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Abstract

The metal layered manufacturing processes have provided industries with a fast method to build functional parts directly from CAD models. This paper compares current metal layered manufacturing technologies from including powder based metal deposition, selective laser sinstering (SLS), wire feed deposition etc. The characteristics of each process, including its industrial applications, advantages/disadvantages, costs etc are discussed. In addition, the comparison between each process in terms of build rate, suitable metal etc. is presented in this paper.

1. Introduction

For more than two decades, Layered Manufacturing (LM) technology, also known as Rapid Prototyping (RP) has given industry an approach to achieve the goal of providing products with a shorter development time and at a lower cost. Instead of removing material as in the traditional subtractive manufacturing processes such as machining, LM processes fabricate a physical part in an additive fashion, layer by layer. It involves successively adding raw material, in layers, to create a solid part directly from a CAD model. A host of layered manufacturing technologies are available commercially, including Stereolithography (SLA) by 3-D systems, Selective Laser Sintering (SLS) by DTM Corp., Fused Deposition Modeling (FDM) by Stratasys Corp., Solid Ground Curing (SGC) byIt Cubital and Laminated Object Manufacturing (LOM) by Helisys etc [Dutta01].

Recently, one of focuses of research and applications has been shifted to metal rapid prototyping for the manufacturing industry. This technology is of interest since it can provide a means to directly produce net-shape part from a CAD model without intermediate steps. Most of the metal rapid systems involve the continuous supply of metallic materials and localized energy source where the material is melted and forms a melt pool which quickly solidifies into metal layers. Parts are built to completion layer by layer from bottom to top. Systems built on this principle include LENS, DMD, E-Beam, wire-feed based deposition and SLS etc. Another system like ultrasonic consolidation builds part by welding metal foil sheets together to form the geometry.

This paper aims to address the rapid metal forming related processes by surveying existing metal rapid technology including the processes discussed above. The paper will summarize the characteristics of each process, including its industrial applications, advantages/disadvantages, costs etc. In addition, the discussion on build rate, suitable metal etc. is presented in this paper. All the information and discussion presented in this paper are based on published data.

The paper is organized as follows: In section 2, each metal rapid forming process is briefly described. The material that has been applied on each process is summarized in section 3. Then, section 4 discusses the capabilities of each process, including the major characters. Sections 5 and 6 discuss the application areas and costs associated with each process respectively. The discussion and conclusion are presented in section 7.

2. Description of the Systems

This section discusses the basic features and operating principles of the different systems included in this paper. Sections 2.1 through 2.3 discuss the laser based processes: LENS, DMD, SLS, and Wire Feed systems. Section 2.4 talks about the Ultrasonic Consolidation Process. Finally, section 2.5 discusses the Electron Beam Melting process.

2.1 Laser Engineered Net Shaping™ and Direct Metal Deposition™

Laser Engineered Net Shaping (LENS™), originally developed at the Sandia National Laboratories, is a solid freeform fabrication process that has the capability of direct fabrication of metal parts. The process uses a focused laser beam as a heat source to create a molten pool on an underlying substrate. Powder material is then injected into the molten pool through nozzles. The incoming powder is metallurgically bonded with the substrate upon solidification. The part is fabricated in a layer by layer manner in a shape that is dictated by the CAD solid model, which is sliced into thin layers orthogonal to the z-axis. After the slice data is then translated into laser scanning paths, an outline of each feature of the layer is generated and then the cross section is filled using a rastering technique to fabricate a single layer. After the deposition of a single layer, the subsequent layers are deposited by incrementing the nozzles and the focusing lens of the laser in z-direction, until the three-dimensional part is completed. The LENS system consists of a Nd:YAG laser, a controlled atmosphere glove box, a 3-axis computer-controlled positioning system, and a powder feed unit. A schematic of the process is shown in Figure 1.

2.2 Selective Laser Sintering (SLS)

Selective Laser Sintering is a form of rapid prototyping developed by Carl Deckard for DTM Corporation in 1986 [Hale02]. A laser beam is traced over the surface of a tightly compacted powder. The powder is spread by a roller over the surface of a build cylinder. A piston moves down one object layer thickness to accommodate the layer of powder. The powder supply system is similar in function to the build cylinder. It also comprises a cylinder and piston. The piston moves upward incrementally to supply powder for the process, shown in Figure 2. Heat from the laser melts the powder where it strikes under guidance of the scanner system. The

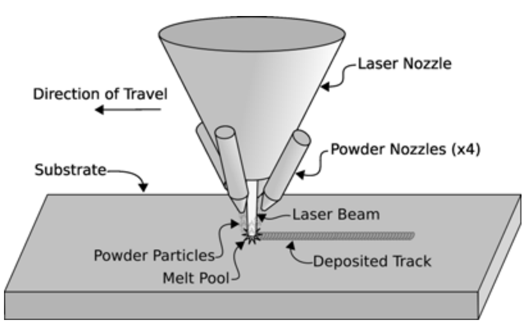

Figure 1 LENS/DMD Process

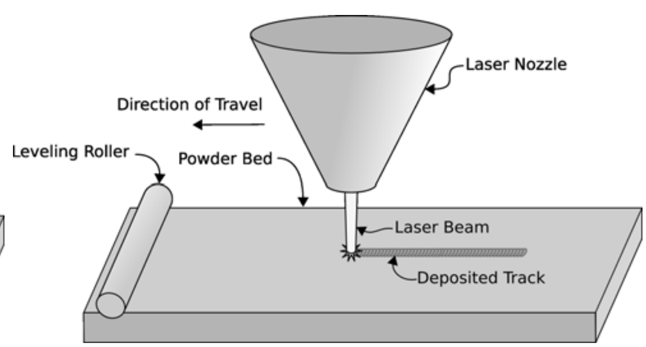

Figure 2 SLS Process

entire fabrication chamber is sealed and maintained at a temperature just below the melting point of the plastic powder. Thus, heat from the laser need only elevate the temperature slightly to cause sintering, greatly speeding the process. After the object is fully formed, the piston is raised to elevate the object. Excess powder is simply brushed away and final manual finishing may be

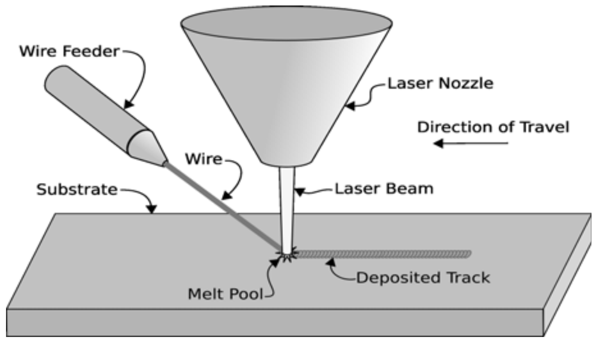

Figure 3 Wire Feed Process

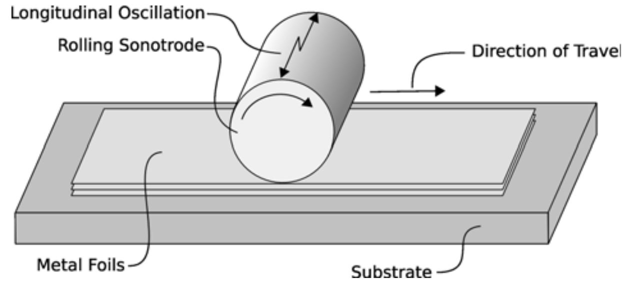

Figure 4 Ultrasonic Consolidation Process

carried out. It may take considerable time before the part cools down enough to be removed from the machine.

2.3 Wire Feed

Wired feed deposition system is developed based on wire feed welding technology. Similar to other RP processes, this technology builds part by layer by layer. The wire is aimed and delivered into the melt pool at where the energy is pointed. Figure 3 shows the basic setup of a wire feed deposition system. This technology creates a relatively clean working environment due the fully usage of the material, which is a big advantage in a strict environment controlled area.

However, some drawbacks limit the usage of the application. This technology requires a precise location of the wire for the production of smooth material transfer. The shadowing effect of the wire prevents the fully coupling between the melting heat and substrate; therefore the dilution during the cladding/deposition is very difficult to control [Salehi05]. Furthermore, the accuracy of this process is limited to the size of the wire; so far, the process can not produce/build part with high accuracy.

2.4 Ultrasonic Consolidation

Ultrasonic Consolidation (UC) is a layer based manufacturing process using ultrasonic welding for material addition and conventional NC machining for material removal. UC uses a rolling sonotrode to weld strips of metal foils, shown in Figure 4. This method of welding has a very low heat input and very little mechanical deformation, allowing for inter-lamellar additions to the metal part. Fiber composites can be assembled by placing the fibers between layers of metal foils. Sensors such as thermocouples or strain gages can also be inserted.

2.5 Electron Beam Melting

Electron beam melting (EBM), a direct-metal freeform fabrication process used to build functional parts and tooling, was developed by Arcam of Sweden. A layer of metal powder is distributed over a platform in a vacuum chamber. To reduce the concentration of residual stresses that cause distortion in a fabricated part, an electron beam gun preheats the powder layer.

After the preheating is finished the layer is selectively melted by increasing the beam power or decreasing the speed. The platform is then lowered, a new layer of powder is distributed and the process is repeated until the part is complete [Cormier04], as shown in Figure 5. Finish heat treatment or machining, depending on the type of metal powder or wire deposited, is used to improve the surface finish. Complex shapes with overhangs and undercuts can be built with this technique. Support structures are not required because the loose powder serves as support for the next layers. Parts come into existence within the vacuum chamber's main area, the build tank. A platform or base plate holds the part being created and moves only in the vertical direction inside the build tank. Also, within the vacuum chamber are the powder dosing feeder and the metal powder carriage. The environment of the vacuum chamber is typically 10-5 Torr for Ti deposition, but can vary down to 10-2 for other types of metals. Finally, the EBM process requires an electron beam gun to direct the beam for the selective melting of the powder. [Wallace02][Villalon05]

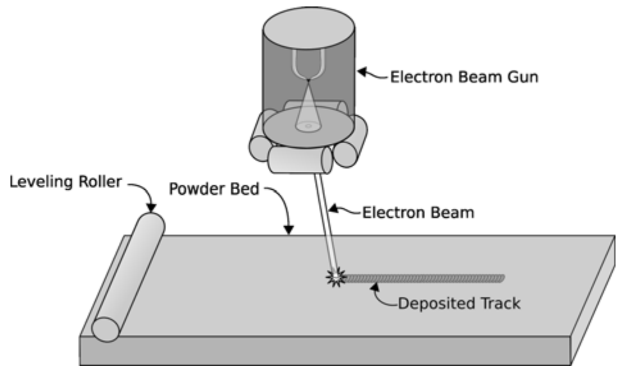

Figure 5 E-Beam Process

The electron beam is generated when a filament current passes through a wolfram or tantalum filament. Electrons are emitted after current is applied and the filament heats up. Regulating the current of the beam is a control electrode and the beam is focused by a focusing coil. When the electrons hit the powder surface, their kinetic energy is transformed into thermal energy; thereby reaching the metal's melting temperature. Deflection coils using a magnetic field are employed to steer the electron beam to the desired position to scan the metal powder. [Villalon05]

3. Material

Most of the processes reviewed here work with a variety of materials. LENS and DMD supported all materials included in this study. UC has the least material compatibly, with only Aluminum and Copper parts reported. All of the laser based processes work with steel, Titanium, and Nickel based alloys. The LENS process works with a variety of materials, such as steel, tool steel, stainless steel, Aluminum, Copper, Nickel based alloys, Titanium alloys, Inconel, Cobalt, Tungsten, composite, and [Erzincanli2002,[functionally graded material deposition George2003, Sandia's website]. The DMD process uses a variety of materials, including tool steel alloy, stainless steel, Copper, Stellite alloys, Inconel, Tungsten Carbide, Titanium Diboride, Beryllium-Copper alloy and metal matrix composite materials [Krar 2002, Knights01]. Researchers have reported that Al 2219 [Taminger03] and Ti64 [Wallace04] have been tested on their EBF^3 Wire feed system. Ni-based Inconel 625 [AMPTIA04] has been used as repairing material to restore the components of Navy ships. Different kinds of steel wire have also been adopted into this process.Ultrasonic Consolidation has been shown to be capable of producing Aluminum [Solidica's website] and Copper parts [Soar05] from foils. Solidica's Formation machine has also been shown to be capable of producing metal matrix composite structures from Aluminum Silicon Carbide [Solidica's website].

A variety of materials is available for the electron beam melting process such as: Titanium, steel, Tantalum [Villalon04]; Titanium alloy and a wide variety of metal and metal composite materials [Williams05]; commercially pure Titanium, Ti-6Al-4V, Ti Alloy, low alloy steel, H13 tool steel, and nickel alloy [Beaman04]; 2219 Aluminum and Titanium wire alloys and Nickel ferrous based alloys [Taminger03]. This information is based upon published results. Other materials may be technically feasible, but have not been tested/reported. Material availability is summarized below in Table 1.

4. Process Capabilities

In this section, the processes capabilities of each process include the build rate, geometry accuracy etc are discussed. For laser based processes, the build rate is related to laser energy per unit time. As such, the surveyed literature quoted build rates that varied from 1-6 in^3/hr, depending on the power output of the laser in the system. The LENS build rate is reported in the range of 3.5-4 in^3/hr [Knights 2001, Ensz 1999, Aston2005]. According to MCP Realizer SLM Technology, SLM is a high speed building process with a building rate of 5 cm^3/hr (~2 in^3/hr) for dense steel [MCP Realizer05]. The Advanced Materials and Processes Technology Information Analysis Center (AMPTIAC) reports a deposition rate of 0.79 kg/hr (~6.14 in^3/hr) has been achieved by feeding wire with a high power direct diode laser (HPDDL). [AMPTIA04]. The non-laser based processes are equally difficult to compare via their build rates. Solidica claims that their formation machine can build a 6"x8"x4" mold in 36 hours or less, which equates to a volumetric build rate of 5.33in^3/hr. Electron Beam Freeform Fabrication (EBF^3), developed at NASA Langley research center [Watson02], feeds material by the a wire feeder to eliminate the issues in powder feeding system in microgravity. The material is 2219 Al and the build rate ranges from 10in^3/hr~80in^3/hr with a change in deposition width from 0.25cm-1.25cm (0.1in~0.5in) [Taminger03]. An investigation done by Williams, et al. 2005 has shown powder-based EBM to have a build rate of 23.6 in^3/hr or 60 cm^3/hr. Where as, wire EBM can perform up to 150 in/hr depending on the thickness of wire used as seen by the NASA Langley Research Center. [Taminger03].

All of the commercialized systems discussed in this review (i.e. all save wire feed) have addressed the issues of control. Both LENS and DMD process has closed loop control for accurate part fabrication [Sandia's website, McPhail00]. The DMD process has the closed loop optical feedback system on each side, allows the DMD machines to be [McPhail00].[run unattended Solidica has custom CAD/CAM software, rpCAM, for process planning for their Formation machine [Solidica's website]. Arcam also custom software to help drive their closed loop control system, Arcam EBM Studio Software [Arcam05].

Geometric accuracy is an important consideration in metal RP processes. LENS and DMD have a reported accuracy of ±.015in in the Z direction, but only ±0.020in in the direction of travel. Using SLM it is possible to build fine details like thin vertical walls of less than 100 micrometer thickness [MCP Realizer05]. Inserts for injection mold tools manufactured using SLM has a precision better than 0.1mm [Fraunhofer ILT]. Due to the physical limitations of wire-feed technology, the resolution a system based on wire feed can not be finer than the wire diameter. UC is capable of producing a part with feature-to-feature accuracy of 0.002in. to +/-0.005in. depending on geometry [White02]. The EBM process is a very accurate system when used with powder. The beam has a spot size, i.e. diameter, of approximately 100µm or 0.1mm, which can create a part feature of 1.2 mm at minimum. [Beaman 2004, Williams 2004,05]. Furthermore, the EBM system has high beam scan speeds of 400 or 800 mm/sec for the Arcam machine [Berman 2004, Villalon03] Within the vacuum chamber build tank of the Arcam EBM system, the maximum build size available is 200x200x260 mm and has a reported accuracy of ±0.3 mm [Beaman04]. However, when using a wire feed system, EBM is subject to the same physical limitations as the alser abased wire feed system. Finally, the Z-axis resolution on the build platform was recently found to be 0.1 mm by an investigation lead by Williams in 2005.

For metal based RP systems, the resultant part's interior structure is as important as the external geometry. The LENS process produces fully dense parts with high power YAG laser. The obtained fine grained microstructure shows the feature of rapid solidification. The as-formed mechanical properties are similar to, or even better than those of the intrinsic materials and those for conventionally processed [Atwood98, Zhang03, Erzincanli02]. The typical microstructural defects for the LENS process are pores between deposition layers, resulting from not well fused layers during fabrication, which can make the parts have poor mechanical properties [Griffith00, Williams05]. The DMD process has the similar microstructure and microstructural defects to the LENS process since the working principles of them are similar. The etched, microstructure of Inconel 625 processed by SLS reveals an equiaxed microstructure, which compares well with that obtained by hot-rolled annealed material [Das1998]. The surface finish of the part made by SLS tends to be rough, the part itself can be porous and the density may can vary [Hale02]. The EBM process produces a grain size of 10-30µm for powder EBM [Beaman04]. UC is capable of producing parts that are 98.6% dense [Kong02]. Surface finish of a part created by the powder EBM process has found to be consistently grainy and looks like a sand casting. This type of surface needs to be machined or blasted with glass beads to remove the excess powder. When Ti powder is used, an extra heat treatment is required during post processing to increase the structure of the structure. However, as reported by Villalon 2003, pre and post heating is necessary with the EBM process to produce parts with structural integrity.

Both LENS and DMD need post processing achieve the desired net shape and surface finish since a material envelope remains after the deposition. According to MCP SLM Technology, no post processing is required for their process. [MCP Realizer05]. For selective laser sintering of Alloy 625 and Ti6Al4V, post processing using hot isostatic pressing was required [Das1998]. UC requires no post-processing, as CNC machining is part of the part production process. Inserts for injection molds made out of stainless steel 1.4404 required post processing using EDM, grinding and polishing [Fraunhofer ILT].
Build rate, resolution, surface finish, typical microstructure, defects observed in the processed parts, geometry limitation, post processing, and ease of control for each process are all summarized in Table 2.

5. Application Area

All metal RP processes are suitable to manufacture products of low volume and high value, therefore, their applications include rapid tooling, repair, rapid manufacturing etc.

<u>Rapid tooling</u>

LENS has been reported to be used to build plastic injection mold tooling made from high quality hardened tool steel [Atwood 1998, George2003]. The DMD process is mainly used in tooling and prototyping areas, including fabrication of new tooling, die repair and refurbishment, rapid metal prototypes, surface modification and coatings [Krar2002, Martin2001]. Solidica also reports that their process can be used to build mold/die.

Rapid manufacturing

Almost all the metal RP processes can be used in this area. However, the products from these processes require the post-process like machining to improve the condition of surface finishing. For example, parts from aerospace industry which are difficult to produce via traditional machining processes can be manufactured using metal RP processes.

Repair

LENS, DMD and wire-feed base processes have been applied in repair practice to restore the damaged part to original condition. High power direct diode laser (HPDDL) is developed at The Advanced Materials and Processes Technology Information Analysis Center (AMPTIAC) has helped NAVY to refurbish the damaged part by using wire-feed cladding technology. Coaxial material feeding is adopted in both LENS and DMD. The working distance of these two types of systems is limited by laser focus and material focus and difficult to adjust. Therefore some deep damaged locations are very difficult to repair using LENS and DMD. On the other hand, the working distance of wire-feed is only dependent on laser focus which can be changed by using different focusing lens. It is reported that a deposition rate of 0.79 kg/hr has been achieved by feeding wire [AMPTIA04]. The powder EBM process has been found to be useful for many applications and researchers are further developing a wire EBM process for specific NASA applications. Repairing worn or damaged parts, creating tool parts, and fabricating complex structures are the typical uses for powder EBM [Villalon 2003, Beaman03]. NASA Langley researchers are perfecting the wire EBM process for the use of in-space repairs. Metallic powder in a microgravity environment imposes many safety and operational risks, thereby making metallic wire preferable [Watson 2002, Taminger 2003, Wallace02]. Table 3 summarizes applications of discussed metal RP processes

6. Costs and Commercialization

Table 4 summarizes the available commercial systems of metal RP processes.

7. Conclusions

Since the wire is used as deposition material, the relatively low material efficiency encountered for powder deposition is not an issue. Usually 100% material is used. On the other hand, the shadow of wire will prevent building complicated geometry due to the collision. LENS cannot produce complex geometries featuring overhangs since it cannot generate support structures. The maximum angle achieved in a single width deposition is 30°. Due to wire-feed mechanism, the quality of the deposition is affected significantly by the wire feeding direction (angle between wire and laser as well as the angle between wire and traveling direction). It is found that the leading wire resulted in the best deposition/cladding rate [Zheng99]. However, due to the nature of manufacturing, the traveling direction can not be always kept the same, which leads to inconsistent deposition.

Acknowledgments

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Table 1 – Material Availability by Process

Material availability	LENS	DMD	SLS	Wire Feed	UC	E-beam
Steel	stainless steel, maraging steel, tool steel	D-2, F-7, 420 and 316 stainless, H-13, H-19, H-21, and P-20	Stainless steel, Tool steel	AISI 309L [Zhang99]		H-13, tool steel, low alloy steel
Al	Y	Y		Al 2219 [Taminger03]	Al foil [Solicida05]	2219, Al alloys
Ti	Y	Y	Y	Ti64 [Wallace02]		commercially pure Titanium, Ti-6Al-4V, Ti Alloy
Cu	Y	Y	Y	70:30 CuNi [AMPTIA04]	Cu foil [Soar05]	
Ni	nickel-based superalloys	Inconel	nickel-based superalloys [Das98]	Inconel 625 [AMPTIA04]		Ni alloy and nickel ferrous based alloys
Cr		Stellite alloys,Inconel				
FGM (No/Z/XYZ)	Y	Not reported	Y			
MMC (Y/N)	Y	Y	Y		Aluminum Silicon Carbide [Solicida05]	

Table 2 – Process Capabilities						
Capacities	LENS	DMD	SLS	Wire Feed	UC	E-beam
Build Rate	3.5~4 in^3/hr [Knights 2001, Ensz 1999, Aston2005]	1-3 in^3/hr [Knights01]	5 cm3 dense steel/hr [MCP Realizer05]	10in^3/hr~80in^3/hr		5 cm^3/hr (2in^3/hr) Powder - 25.622 cu. In^3/hr [Williams05]Wire - 20-150 In^3/hr [Taminger03]
Resolution	Z direction: ±.015 inches Travel direction: ±0.508 mm	Z direction: ±.015 inches	Thin walls less than 100 micrometer thickness. Precision better than 0.1mm	Due to the physical limitation of wire-feed technology, the resolution can not be finer than the wire diameter.	+/- 0.003 [Solidica's website], +/-0.002-in. to +/-0.005-in. depending on geometry [White02]	accuracy of +- 0.3 (mm), Z-resolution (mm) = 0.1, min feature size (mm) = 1.2 , Beam diameter of 0.1 mm [Vallion03, Beaman04, Williams05]
Surface finish	200-300 microinch average roughness (Ra) for optimum size particle	Not reported	Rough Surface finish		CNC Machining	Grainy and resembles a sand casting, rough
Microstructure	Fine grained	fine grained	Equiaxed microstructure			grain size of 10-30µm for powder EBM [Beaman04],
Fully Dense?	yes	yes	Part density may vary [Hale02]	yes	98.6% dense [Kong02]	yes
Geometry limitation	cannot produce complex geometries featuring overhangs			Only 2-1/2 D parts/samples have been built		cannot produce complex internal geometries [Williams04]
Post processing required?	Yes	Yes	Yes	The surface finish is not as good as machining	no [Solidica's website]	Heat treatment for Ti, glass bead blasting, EDM
Ease of Control	closed loop control [Sandia's website]	closed loop control [McPhail2000]			rpCAM software [Solidica's website]	Closed loop, Comercial Arcam EBM Studio Software

Table 3 – Application Areas				
Process	**Repair**	**Rapid tooling**	**Rapid manufacturing**	**Industrial**
LENS	LENS could achieve repairing operations and is especially considered for emergency repairing operation.	A promising application for the LENS process is building production quality plastic injection molds and die cast tooling.		
DMD	Can repair, reconfigure or resurface existing parts.	Fabricate new tooling for molding, casting and stamping applications Reconfigure obsolete tooling into new production tooling	can produce rapid metal prototypes	The DMD process is ideally suited for repair work in the aerospace industry.
SLS		Sheet metal press tools, Pressure die cast tools, injection molds and inserts [MCP Realizer05]		
Wire Feed	Repair/restore the damaged parts from Navy ships			Build parts for aerospace
UC		tooling for injection, blow, and vacuum molding; and investment or sand casting [Solidica's website]	can produce rapid metal prototypes [Solidica's website]	part fabrication, embedded sensors [Solidica's website]
E-Beam	Can repair, reconfigure or resurface existing parts of smaller size that can fit within the build tank	Can fabricate new tooling.		Aerospace

Table 4 – Costs				
Process	**Capital Cost**	**Operating Cost**	**Maintenance Cost**	**Commercially Available?**
LENS	$350,000 to $500,000 [Singer1997]		~$50, [Williams05][000/year	Optomec
DMD	from [Maniscalco00]; from $500,000 to $1[$700,000 to $900,000 million [Martin01]	Costs are based on the magnitude of engineering effort and volume of deposition. For example, to reconfigure an existing tool using DMD, prices range from 20 to 30 percent of the original tool cost [Maniscalco00].		
SLS	$250,000-$497,000 [Wohlers98]			3D Systems[3D Systems] MCP [MCP Realizer05] EOS Electro Optical Systems[EOS] Fockele & Schwarze FS-Realizer[F&S]
Wire-feed				no
UC	$465,000 [Freitag02]	More affordable (up to 80% cheaper than traditional methods) [Solidica's website]		Solidica
E-beam	Reported in Sweden $550,000 in 2003 [Beaman04]	Up to $497,000 a year [Williams05] due to the use of a vacuum chamber and high laser power		Arcam

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