COMPARISON OF THE DIRECT METAL LASER FABRICATION TECHNOLOGIES

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ABSTRACT

Rapid Prototyping Technologies have been recognized as a unique technique to achieve the reduction of the product development time and cost for the development of new products for the manufacturing industry for the last decade. Various Rapid Prototyping Systems have been developed to produce prototypes rapidly for model visualization, functional testing, master models or molds for indirect Rapid Tooling (RT) applications. These Solid Free-form Fabrication (SFF) technologies have been developed for the last two decades.

The main goal of these Layered Manufacturing (LM) technologies is to produce fully dense and net shaped metal parts in a single step for next decade. Direct Metal Laser Fabrication (DMLF) processes can generate nearly full density and near net shaped metal parts from CAD data without using any traditional methods or secondary operations. Metal powders are completely melted without retaining much porosity in these processes. In this paper Direct Metal Laser Fabrication applications will be compared and discussed.

1. INTRODUCTION

It is crucial important to reduction of the lead-time and cost for the development of new industrial products for the manufacturing industry since time is one of the most important global manufacturing problems [1]. Tooling process, which requires long lead times with high cost for each iteration, has become significant issue with increasing part complexity and requirements for long production runs to produce a product for the manufacturers [2].

Time-to-market and increased competition are two of the important issues for 21st century businesses to achieve succeed. 21st century manufacturers have to not only produce high quality, low cost and much more functional products, but also respond their customer demands more responsively and quickly speeding up the tooling lead times to put on a product to the market quickly because today's market wants rapid product availability [3,4,5]. Global competition requires manufacturers to fabricate their products in reduced cycle times besides high quality with low costs [6].

This necessity forces the manufacturing sector to take into some technological and strategic considerations. One of these is speeding up the tooling lead times by using non-traditional methods while not sacrificing mechanical properties to create tooling inserts [2, 7].

The Rapid Prototyping (RP) technologies have been recognized as a unique technologic method to achieve this aim. On the other hand, it can be said RP technology is a strategic issue from the point of key benefits in manufacturing industry [8].

2. RAPID PROTOTYPING SURVEY IN TOOLING PROCESS

It is obvious that CAD/RP combination is offering early product entry to the market providing an effective iterative design process giving the design team the opportunity to verify and refine the tool design before produce the model and tool inserts, thereby increasing competitiveness [9,6,10].

Rapid Tooling

The new term Rapid Tooling (RT) has emerged with the development of RP technologies last decade. RT term was referring indirect tooling method using models produced by some RP techniques having good surface properties with good dimensional accuracy from low melting point materials, as master models to make metal tool inserts rapidly[10].

Although this term is not well understood since it is not defined clearly, most would agree that RT is driven from an RP process - the key to making it rapid [8].

Rapid Manufacturing

With the availability of generating prototypes directly from more steady and durable materials, RP term is getting become Rapid Manufacturing (RM). Rapid Manufacturing applications using metal materials offer Direct Tooling (DT) making metal tool inserts without using any traditional methods.

Rapid Tooling, which is indirect method requiring more than one step to get tool inserts, is currently moving to Direct Tooling method which is a more robust tooling which can be made in a more rapid fashion [7].

Tooling Requirements

There are some basic requirements for tooling process [11]:

- Tough enough for high molding pressures
- Wear resistant to keep long-term accuracy
- Good surface finishing for easy part ejection
- Limited finishing operations
- Thermal conductivity of high temperature molding process
- Dimensional accuracy for accurate part production
- Appropriate cooling channels

These are basic requirements for tooling operations that have to be overcome. Rapid Manufacturing systems will be discussed with keeping in mind these parameters for tooling operations.

3. RAPID MANUFACTURING SYSTEMS

Rapid Manufacturing is an emerging term for rapid tooling processes in which techniques metal tooling inserts could be built directly by Direct Metal Fabrication processes.

A number of categorized Rapid Manufacturing processes are available for building fully dense metal parts. Jet solidification, 3D welding, shape-deposition manufacturing, Electron Beam Melting [12] and laser based manufacturing systems. High power laser based metal fabrication applications are most popular of RM processes.

Several laser based metal fabrication technologies have been developed and commercialized, and some systems are still under development. Some of the commercialized laser based metal fabrication technologies are based on metal sintering technology such as Selective Laser Sintering (SLS) of DTM Corp., all of patents and licensed rights were acquired by 3DSystems in the acquisition of DTM in 2001, and Direct Metal Laser Sintering (DMLS) of EOS, Inc. technologies. The others are based on laser fusion technique such as Directed Material Deposition System, which uses Laser Engineered Net Shaping (LENS) technique, of Optomec Design Corp.

Selective Laser Sintering

Selective Laser Sintering is somewhat similar to stereolithography as can be seen in Figure 1. A thin layer of powder material is spread across the surface of the build platform by a roller mechanism. A 100W CO_2 laser beam is then traced with the velocity of 7.5m/sec over the top of the powder to selectively melt and bond it to form a layer of the object [5]. Build platform moves down lowering the piston one layer thickness to accommodate to next layer of powder while the piston of the powder delivery system is moves upward to supply a measured quantity of powder for each layer. The process is repeated until the entire object is fabricated form bottom to top.

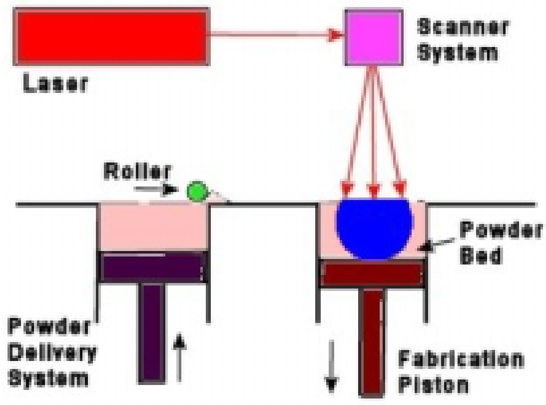

Figure 1 Selective Laser Sintering Process

Steel powder material is mixed a range of plastic material. The laser energy heats the plastic binder to a temperature above its melting point, bonding the stainless steel powder into a solid mass called “green” part. Resulting green part is processed in the furnace to remove the binder and sinter the steel particles after the whole object is complete. When steel sintering process is complete after 2-3 hours, the resulting part is called as “brown” part. The brown part is a 60% dense structure of stainless steel. The part is porous when it is in “brown” state. The brown part is infiltrated with bronze in a second furnace cycle. After the bronze infiltration process, resulting part is in a fully dense state [13].

Direct Metal Laser Sintering

This technology is similar to SLS technique from the view point of powder deposition method. DMLS does not use any plastic binder mix to hold steel based powder together in the DirectTool™ process. Moreover, any secondary sintering or infiltration process is not required to use metal parts produced with Direct Metal Laser Sintering technique as a tool insert for injection moulding and die casting applications. [14]

Only shot-peening process to control residual stresses by compressing surfaces and polishing to reduce roughness may be needed as secondary finishing operations. A 200W CO_2 laser beam is used with the velocity of 3m/sec to melt and bond it to a form the top layer of the object. [14]

Laser Engineered Net Shaping

LENS process is sometimes referred to by general term, laser fusing. Figure 2 shows the approach adopted by Sandia National Labs and being commercialized by Optomec Design Corp as Directed Material Deposition™ system which uses LENS technology.[15]

A high power laser (500-1000 W Nd:YAG Laser) is used to melt metal powder supplied coaxially to the focus of the laser beam through a deposition head. The laser beam travels through the center of the head and is focused to a spot by one or more lenses. The X-Y table is moved horizontally to fabricate each layer of the object. The head is moved up vertically as each layer is completed. A simple right angle mirror is shown to deliver the laser beam but fiber optics could be used.[15]

Metal powders are delivered and distributed through the head either by gravity, or by pressurized inert gas. Even in cases where it is not required for feeding, an inert shroud gas is typically used to shield the melt pool from atmospheric oxygen for better control of properties, and to promote layer to layer adhesion by providing better surface wetting.[15]

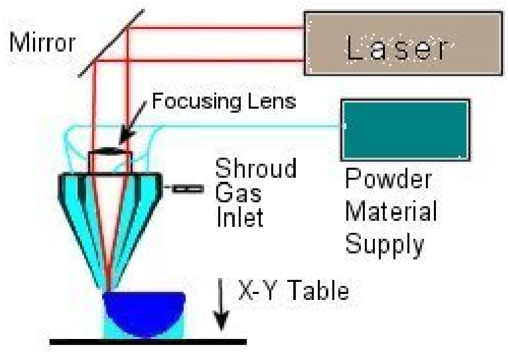

Figure 2 Laser Engineered Net Shaping Process

Several variations of this technique were initiated at several government and university laboratories and several other companies are commercializing similar processes both in the US and in Europe. Some of them are:

- Directed Light Fabrication of Los Alamos National Laboratory
- Aluminium Powder Spraying of University of Illioins of Urbana Champaign
- Laser Cladding of University of Liverpool
- Laser Generation of Fraunhofer-Institute of Production Technology
- Rapid Micro Product Development of MicroTec Mikrotechnologie mbH

4.COMPARISON OF SOME PARAMETERS

Material Variety

In SLS, only material used is a stainless steel/bronze matrix, which is not a common engineering alloy [13]. In DMLS, however, a number of steel and bronze based materials could be used. LENS has fewer material limitations than SLS and DMLS.

A variety of materials can be used such as stainless steel, inconel, copper, aluminium and titanium alloys. Furthermore, material composition can be changed dynamically and continuously while only one composition can be used at pre-deposited processes as in SLS and DMLS processes at a process. This also provides embedded structured metal parts, because completely different types of materials could be used at different locations or layers in a process.

This property also provides to produce multi-material structured parts. Only required areas can be produced with high quality material and at the rest of the part any other appropriate material can be used. For instance, only molding area can be produced with required material and the rest of the tool insert can be produced with any other material. It is obvious that this will reduce the cost of the tool insert.

Surface Quality (Roughness)

It is obvious that surface quality is dependent upon what type of material and powder characteristics is used, layer thickness and line spacing at the X-Y direction. Good surface quality could be achieved with SLS and DMLS processes, but it is impossible to get better surface quality in LENS process because very high power laser is used in LENS process.

It is obvious that the size of the agglomerates and interconnected pores increase with increasing laser power [16]. As a result; surface roughness increases with increasing laser power.

Density

Parts produced by SLS system are needed to be infiltrated to have fully density. Power of the laser used in SLS process does not enough for sintering metal powder particles in contrast with as in DMLS process. In SLS process, only binder material is sintered to bond metal particles together when laser processing. After the SLS operation is completed, resulting parts have to be fired to completely sinter of metal particles and infiltrated with bronze material to have fully density state.

On the other side, parts produced with DMLS are fully dense because either the power of the laser used in DMLS process is higher than SLS process or velocity of the laser is lower in DMLS in contrast with SLS. So, steel powder material is completely melted and sintered without requiring any furnace sintering process. It is obvious that lower laser scanning velocity increases the effect of the laser beam on the focal zone because laser generation duration time will be higher. This effect is also depends on some parameters such as material absorptivity, laser reflectivity, and layer thickness. [17].

In LENS process, metal powder material is completely fused with very high power YAG laser. So, parts are produced at fully dense state with good metallurgical and thermal properties without requiring secondary sintering process. They have good grain structure, and have properties similar to, or even better than the intrinsic materials.

Dimensional Accuracy

One of the most important problems of the rapid prototyping systems for tooling applications is dimensional accuracy because of shrinkage. [18, 19, 20] Shrinkage condition is also dependent on material as well as laser power and sintering conditions. So, it is obvious that shrinkage occurs in all laser assisted fabrication techniques because solidification occurs by thermal operation.

Separately, plastic binder in the metal powders is removed to make hard the part by firing in a furnace in SLS. Consequently, this additional firing operation causes the more loss of the dimensional accuracy because of shrinkage [18, 21, 22]. It should be noted that shrinkage allowance differs for different materials and it is a problem for LENS process when producing embedded parts, where it is possible to make multi-material structured parts in LENS process.

On the other hand, accuracy will be affected by increasing of the agglomerates and interconnected pores with increasing laser power as in roughness. So, surface milling operation should be processed in LENS process to achieve accuracy.

Support Structure

Support is needed for overhang and undercut areas. There is no need additional support structure generation for SLS and DMLS processes because unsintered excess material acts as support structure. In these processes, powder material is spread by roller mechanism over top of the layer, and just cross section of belonging layer is sintered, rest is removed after the whole part is complete.

Additional support structure is required for LENS process because powder material is deposited coaxially and simultaneously with laser beam. Metal powder which has lower melting point than base material is used as support structure. However, after the whole part is completed, removing of the support structure is difficult because both of the material is metal based material. This is important problem has to be overcome for LENS processes. Maybe, it is possible to use any non-metal based material as support structure.

Repairing Operations

Laser assisted material deposition systems could be used to repair damaged equipments. It is not possible to apply repairing operations with pre-deposited systems as in SLS and DMLS systems. Powder material should be deposited with a roller and it is not possible to achieve with these systems because roller will crash to the higher level of the part while spreading the material at the level of the damaged region of equipment.
Only coaxial powder deposition systems like LENS could achieve these types of operations.

LENS process is especially considered for emergency repairing operations. For example, the Mobile Parts Hospital (MPH), is a program being validated by the National Automotive Center, which operates within the U.S. Army Tank-Automotive & Armaments Command (TACOM), is considered to choose the Directed Material Deposition System, which uses LENS process, of Optomec Design Corp. to emergency repair damaged weapons during times of war for Phase-II Mobile Parts Hospital program. MPH is considers LENS process more than one reasons such as material variety, mechanical properties, and has fewer secondary operations rather than SLS besides material deposition system limitation of SLS system for Phase-II even if SLS system was installed at Phase-I.[23]

Finishing Operations

SLS process requires more additional processes than DMLS process which are secondary sintering in a furnace to bond metal particle together and bronze infiltration to have full density. Only shot-peening operation is may be needed in DMLS process. Secondary finish machining operation is needed in LENS process because parts produced with LENS process are near net shape.
On the other hand, removing of excess powder is easy for SLS and DMLS processes but it is difficult for LENS process because additional support structure is required for overhang areas and this support structure is made of metal material.

5 axis capability

It is not possible to apply 5 axis operations in SLS and DMLS processes because of pre-deposited powder material limitations. However, tilting and leading motions could be generated in LENS process.

Meanwhile, leading and tilting motions may eliminate the required support structure in LENS process when making the overhang features.

Cooling Channels for Tooling Inserts

Capability of producing uniform cooling channels is advantage of the whole of RM systems because layer by layer building technique provides complex structured parts. RM systems succeeds creating uniform cooling channels which can be restricted by mechanical constraints such as ejector pins and metal inserts as well as model's complexity in material subtractive methods.[24]

5. CONCLUSION

It can be seen that some systems have advantages over the others when comparing of some parameters of Direct Metal Laser Fabrication systems.

Compared systems are just currently commercialized systems and it is obvious that there are a lot of under research systems which are cool similar to these systems. It appears that further developments on SLS and DMLS processes are limited compared with LENS process. Only accuracy and material variety developments could be made in SLS and DMLS systems. It should be noted that processing steps should be decreased in SLS process. For instance, secondary sintering and infiltration steps are important disadvantages for the manufacturing sectors that paying attention on time and cost for production.

LENS process can be seen as future's technology among Rapid Prototyping and Manufacturing Technologies from the points of view such as material variety, multi-material structured part, fully dense in one step, repairing operations, 5 axis capabilities even if some of them are not completely fruitful for now. Nevertheless, some parameters such as surface quality, eliminating secondary finishing operation and support structure problem have to be overcome to be succeeded completely.

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