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Direct Metal Laser Sintering

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***Abstract*: The work explains the functional advantages of additive manufacturing over conventional manufacturing by addressing one of its widely used methods for metals-DMLS. The work also points out the effect of laser power, scanning speed, laser beam radius, hatch spacing and pre-heating temperature of the powder bed in the finished product. The combination of material powders used and their mechanical characteristics were observed.**

***Keywords*: DMLS, scanning speed, hatch spacing, mechanical characteristics**

1. Introduction

Conventional manufacturing method follows subtractive manufacturing which involves cutting of materials successively from a solid block to get the desired shape. This results in wastage of material to a great extent [1]. Also, for producing complex shapes, these methods consume more time and even some outputs are not obtained as desired. In this case, the transition to additive manufacturing takes place.

A. Additive manufacturing

Additive manufacturing (AM) or 3D printing is the successive deposition of material to get a predesigned shape. It uses Computer Aided Design (CAD) software to direct the hardware to add the material, layer upon layer in precise geometric shapes. All the commercial AM machines use layer-based approach. It allows for the creation of parts (i.e.) product that we required, that this process presented to product development are the time and cost reduction, human interaction, and consequently the product development cycle , also the possibility to create almost any complex shape that could be difficult to machine, Since it forms like layer by layer. In addition to prototypes, complex components, houses, and even human body parts can now be 3D printed. With the rapid advancement of 3D printing and 3D bio-printing technologies, a huge body of research and practical applications exists for these technologies. Now, doctors can build a model of a damaged body to analyze it and plan better the procedure, market researchers can see what people think of a particular new product, and rapid prototyping makes it easier for artists to explore their creativity. Layered manufacturing of metal frameworks is a promising technology in dental practice.

The original design is drafted in a CAD program, where it is then converted to an STL (Standard Tessellation Language or Stereo- Lithography) file. The .STL file format, developed by Hull at 3D systems, has been accepted as the standard for data transfer between the CAD software and a 3D printer. The STL file was created in 1987 by 3D Systems Inc. when they first developed the stereolithography, and the STL file stands for this term. It is also called Standard Tessellation Language. There are other types of files, but the STL file is the standard for every additive manufacturing process. The STL file creation process mainly converts the continuous geometry in the CAD file into a header, small triangles, or coordinates triplet list of x, y, and z coordinates and the normal vector to the triangles. This process is inaccurate and the smaller the triangles the closer to reality [2]. The interior and exterior surfaces are identified using the right-hand rule and vertices cannot share a point with a line. Additional edges are added when the figure is sliced.

2. Additive manufacturing classification

Methods of additive manufacturing (AM) have been developed to meet the demand of printing complex structures at fine resolutions. Rapid prototyping, the ability to print large structures, reducing printing defects and enhancing mechanical properties are some of the key factors that have driven the development of AM technologies. They are classified according to their baseline technology as well as the raw material input.

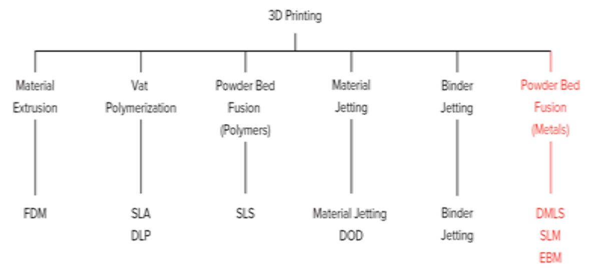

Fig. 1. 3D printing classification

Comparing the AM technologies, Direct Metal Laser Sintering (DMLS) shows the great promise for direct production of functional prototypes and tools. DMLS is a bed fusion process developed by EOS GmbH, of Munich, Germany and has been commercially available as EOSINT M 250 laser sintering machine since 1995. The process uses a laser that is directly exposed to the metal powder in liquid phase sintering. The EOS offers two powder systems: bronze-based powder and steel-based powder. Bronze based powder is processed with no control atmosphere whereas a nitrogen atmosphere is applied to the steel-based powder. For manufacturing mold inserts the dimensional accuracy and the surface quality are of special concern. DMLS produces strong, durable metal parts that work well as both functional prototypes or end use production parts [3].

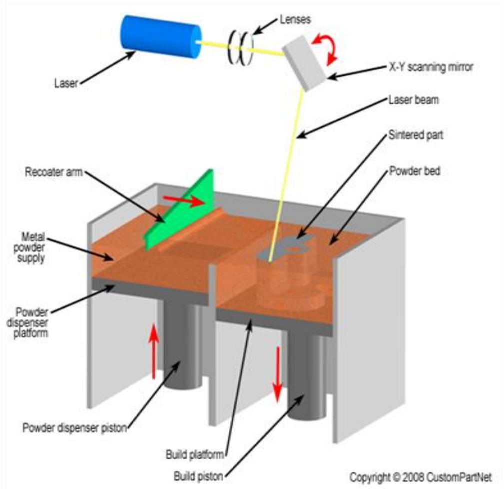

Fig. 2. DMLS process

3. Materials

Materials in additive manufacturing technology systems are defined by the fabrication processing technology. Each 3D printing technology transforms material through external heat, light, lasers and other directed energies. The ability of a material’s mechanical composition to react positively to a certain directed energy marries that material to a technology which can deliver the desired change. These material-technology partnerships will expand as materials are advanced and material chemistry explored. Advancing technologies encourages more positive material reactions, layer by layer, to directed external energies. The mechanism of material change-unique to individual 3D printing technologies and processes-defines the material in terms of state changes, final mechanical properties and design capabilities. By extension, developments in 3D printing materials correspond with developments in 3D manufacturing; as the build process improves to encourage more positive reactions from materials, material selections will expand. The 3D printing materials are available in different material types and states such as powder, filament, pellets, granules, resin etc.

DMLS process using various combination of metallic powders such as mixture of bronze, nickel and copper-phosphide, tungsten carbide and cobalt, low carbon steel, iron, Cu and pre-alloyed SCuP, CuSn–Cu–CuP, titanium, iron–graphite etc. DMLS is not only limited to fabrication of the above alloy material. The recent introduction of the AlSi10Mg Aluminium powder has broadened the application field to the fabrication of complex lightweight final products [5].

AlSi10Mg is a typical casting alloy with good casting properties and is typically used for cast parts with thin walls and complex geometry. It offers good strength, hardness and dynamic properties and is therefore also used for parts subject to high loads. Parts in EOS Aluminium AlSi10Mg are ideal for applications which require a combination of good thermal properties and low weight. They can be machined, spark-eroded, welded, micro shot-peened, polished and coated if required. Conventionally cast components in this type of aluminium alloy are often heat treated to improve the mechanical properties, for example using the T6 cycle of solution annealing, quenching and age hardening. The laser-sintering process is characterized by extremely rapid melting and re-solidification. This produces a metallurgy and corresponding mechanical properties in the as-built condition which is similar to T6 heat-treated cast parts. Therefore such hardening heat treatments are not recommended for laser-sintered parts, but rather a stress relieving cycle of 2 hours at 300 °C (572 °F). Due to the layerwise building method, the parts have a certain anisotropy, which can be reduced or removed by appropriate heat treatment.

The stainless steel manufactured by DMLS performs well in high strength applications requiring above average hardness mechanical properties. It can be heat treated to improve strength and hardness, and exceed the hardness properties of stainless steel 316L. It is magnetic. Its applications are it can be used in small parts, it can be used in prototypes, and it can be used in magnetic applications. Maraging steel has very good mechanical properties, and is easily heat-treatable using a simple thermal age-hardening process to obtain excellent hardness and strength. This material is ideal for many tooling applications such as tools for injection molding, die casting of light metal alloys, punching, extrusion etc., [4].

4. Characteristics

A. *Bonding strength*

The bonding strength of transferred pattern on the substrate determines its reliability. The bonding strength of copper pattern on glass substrate was evaluated by ultrasonication method. The morphology of copper pattern ultrasonically treated in deionized water under the power of 150 W for 10h. Some oxidized copper droplets on the surface of pattern were removed while the droplets at the interface of glass and pattern were still bonded on the glass under extremely high intensity ultrasonic cleaning. The cross section profile of glass-copper interface shows an irregular curve, which indicates that the bonding interface is rough [6].

B. *Hardness*

Micro hardness improves effectively with the increase of volume fraction of reinforcement. Before annealing, the mechanical structure of the products is brittle and hard. The micro mechanical structure also differs from the annealed ones. The increased hardness of the metals may suggest the increased inner stresses after manufacturing. The results of Barucca et al.'s TEM investigation are interesting for the understanding of these products' micro mechanical structure after manufacturing.

Under a noble gas atmosphere, the hardness decreases because of the decreased oxidation level [7].

C. Microstructure

The sintering behavior and microstructural features of the investigated multi -component powder blends Fine machining and polishing by abrasive papers were done on the gage length to improve the surface quality. The cooling rate determines the size of the α colonies and decomposition of martensite. Microstructure has a very fine acicular (plate-like) morphology. This is attributed to the inherent rapid cooling of the material during DMLS, resulting in a beta-to-martensite transition. However, because of the very large solidification undercooling, the microstructure may be interpreted as martensitic. This microstructure morphology exhibits a high strength and hardness and low ductility, and can be detrimental to fracture toughness. However, martensite impedes dislocation motion, which leads to a strengthening effect that can improve fatigue crack propagation- the ductility (per cent elongation) increased through the various heat-treatments, with the DA achieving the highest per cent elongation of 11.5 per cent. These results are consistent with the microstructural observations in that the larger grain structures provided a decrease in strength and an increase in ductility. DMLS parts do not normally have full density (although 99.8 per cent density can be achieved, and they have an anisotropy due to the inherent layer-wise building procedure [8].

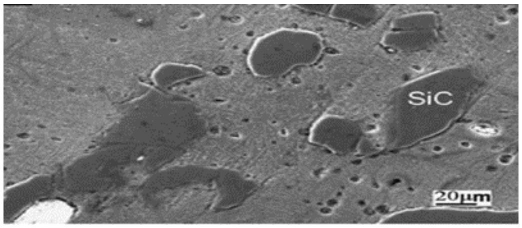

Fig. 3. SEM micrographs of laser sintered specimens after polishing and etching with Keller's reagent

5. Testing methods

A. Four-point flexural test

The four-point bending test provides values for the modulus of elasticity in bending, flexural stress, flexural strain and the flexural stress-strain response of the material. This test is very similar to the three-point bending flexural test. The major difference being that the addition of a fourth bearing brings a much larger portion of the beam to the maximum stress, as opposed to only the material right under the central bearing.

This difference is of prime importance when studying brittle materials, where the number and severity of flaws exposed to the maximum stress is directly related to the flexural strength [9].

It is one of the most widely used apparatus to characterize fatigue and flexural stiffness of asphalt mixtures. The test method for conducting the test usually involves a specified test fixture on a universal testing machine. Details of the test preparation, conditioning, and conduct affect the test results. The sample is placed on two supporting pins a set distance apart and two loading pins placed at an equal distance around the center. These two loadings are lowered from above at a constant rate until sample failure [10].

B. Three-point flexural test

The three-point bending flexural test provides values for the modulus of elasticity in bending, flexural strain and the flexural stress–strain response of the material. The main advantage of a three-point flexural test is the ease of the specimen preparation and testing. However, this method has also some disadvantages: the results of the testing method are sensitive to specimen and loading geometry and strain rate [11].

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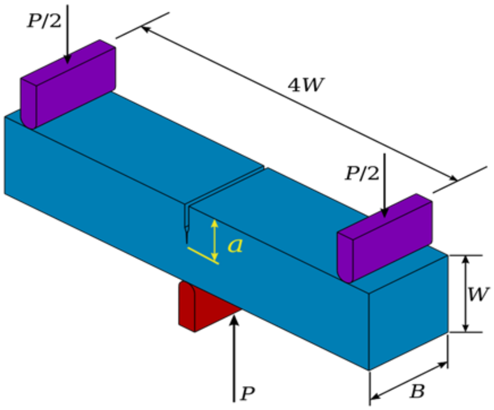

Fig. 4. Three point flexural test

Where, P is the applied load, B is the thickness of the specimen, is the crack length, and W is the width of the specimen. In a three-point bend test, a fatigue crack is created at the tip of the notch by cyclic loading. The length of the crack is measured. The specimen is then loaded monotonically. A plot of the load versus the crack opening displacement is used to determine the load at which the crack starts growing. This load is substituted to find the fracture toughness K [12].

C. Split hopkinson pressure bar testing

Using the split Hopkinson pressure bar (SHPB) test the horizontal and vertical samples can be tested under different compressive strain rate conditions. It is noted that, the samples were setup such that, the direction of compressive shock loads was parallel to the longitudinal axis of all the samples. The samples can be tested at each strain rate ranging from 180 s^{-1} to 3200 s^{-1} to ensure consistency and repeatability. It is important to note that all testing was performed at room temperature. Using compressed gas, a striker was fired to strike the incident bar in order to rapidly deform the test specimen sandwiched between the incident and transmitter bar. By increasing the gas pressure in the firing chamber, a higher impact velocity is achieved, which results in a higher strain rate. When the incident bar was struck, a strain wave travelled through it until part of it passed through the sample to the transmitter bar while the other part was reflected. These strains were measured by placing strain gauges on the respective bars [13].

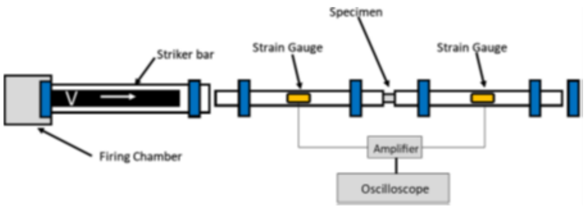

Fig. 5. Hopkinson pressure bar test

D. *Wetting test*

The wetting tests were carried out by classical sessile drop technique upon contact heating under vacuum. The experimental device has been described]. The TiB2 substrate ($12\times12\times2.5\ mm^3$) with Al-12Si sample (a weight of 46 mg) was placed on a boron nitride support situated in the middle of a molybdenum resistance furnace inside a stainless-steel chamber. The chamber was evacuated to about 10-5 mbar at room temperature. The Al-12Si/TiB2 couple was constantly heated from room temperature to 1200 °C and then cooled down to room temperature. The wetting behavior of the liquid alloy on the solid substrate was recorded in steps of 10 °C using a charge-coupled device (CCD) camera. The contact angles were determined at both sides of the drop by analyzing the digital photographs using DROP software. The total uncertainty of the average contact angle was about ±5°.

E. *Vickers hardness testing*

The Vickers hardness test method, also referred to as a micro hardness test method.

The Vickers method is based on an optical measurement system. The Micro hardness test procedure, ASTM E-384, specifies a range of light loads using a diamond indenter to make an indentation which is measured and converted to a hardness value. It is very useful for testing on a wide type of materials, but test samples must be highly polished to enable measuring the size of the impressions. A square base pyramid shaped diamond is used for testing in the Vickers scale. Typically loads are very light, ranging from 10gm to 1kgf, although "Macro" Vickers loads can range up to 30 kg or more.

The Micro hardness methods are used to test on metals, ceramics, composites - almost any type of material. Since the test indentation is very small in a Vickers test, it is useful for a variety of applications: testing very thin materials like foils or measuring the surface of a part, small parts or measuring individual micro structures, or measuring the depth of case hardening by sectioning a part and making a series of indentations [15].

Sectioning is usually necessary with a micro hardness test in order to provide a small enough specimen that can fit into the tester. Additionally, the sample preparation will need to make the specimen’s surface smooth to permit a regular indentation shape and good measurement, and to ensure the sample is held perpendicular.

6. Applications

The DMLS technology is used to manufacture direct parts for a variety of industries including medical, dental, aerospace that have small to high complex parts and in the tooling industry to make direct tooling inserts. DMLS is used both for rapid prototyping, as it decreases development time for new products and also in production [14].

In dentistry, DMLS is a new but increasingly widespread technique used in dental routines both for removable and fixed partial dentures [19].

A. *Bio materials*

The biomedical market represents 11% of the total AM market share today and is going to be one of the drivers for AM evolution and growth.

Biomedical applications need to be patient specific, from implants to drug dosage. AM is also used for planning surgeries, improving efficiency and effectiveness, and reducing the necessity of further operations to adapt the implant to the patient. AM will also be used for customizing drug dosage forms and releasing profiles [16].

Bio-fabrication involves the generation of tissues and organs through bio printing, bio-assembly and maturation .The main difference between bio-fabrication and conventional AM is the inclusion of cells with the manufactured biomaterials for producing the so-called bio-inks. Bio-printing with bio-inks is integrated with the laser induced forward transfer (Lift), inkjet printing and robotic dispensing. These specialized techniques are well discussed in the literature. The biomaterials combined with bimolecular and cells are then matured in the desired shape and tissue. The biomaterials are used as support and physical cues for the generation of the tissue structure while the bimolecular guide the tissue regeneration process [17].

B. *Aerospace*

AM techniques are ideal for aerospace components as they have the following peculiar characteristics:

Complex geometry: Complex shapes are necessary for integrated functions i.e., structural, heat dissipation and airflow. For example, SpaceX build a regenerative cooling- SuperDraco rocket engine chamber using EOS 3D metal printer. The part was made of Inconel (an alloy of nickel and iron) additively manufactured from direct metal laser sintering. The engines are contained in a printed protective nacelle (also DMLS printed) to prevent fault propagation in the event of engine failure [18].

Customized production: The aerospace industry is characterized by the production of small batches of parts. AM is more convenient economically than conventional techniques for small batches as it does not require expensive equipment such as molds or dies.

Both metallic and non-metallic such as meta materials parts for aerospace applications can be manufactured or repaired using AM such as aero engine components, turbine blades and heat exchangers [20].

Fig. 6. Conventional design of the steel cast bracket (upper left) that was environmentally assessed against the corresponding topology optimized design of the EOS titanium AM-made bracket (lower right corner)

7. Conclusion

The sintering behaviour and microstructural features of the investigated .Fine machining and polishing by abrasive papers were done on the gage length to improve the surface quality. Besides the influence of manufacturing parameters such as laser power and scan rate, powder characteristics are of special concern. The sintering activity is strongly affected by shape, size, and distribution of the particles, and the chemical constituents of the powder-In DMLS, when melting is induced by laser beam a step temperature gradient develops that leads to the surface tension distribution. The gradient in surface tension results in shear stress and convective movement of the melt pool (Marangoni effect). The liquid is likely to break up into a row of spheres in order to reduce the surface tension (“balling” effect). However, oxidation of the metal powder surface as well as segregation of the powder before and during the DMLS process has to be prevented. The shrinkage of the developed material during laser sintering is nearly zero. However, the heat-affected zone (HAZ) of the laser beam on the boundary of the part generates some dimensional offset. Therefore, pre-contouring and post-contouring techniques were used to decrease the HAZ and thus improving dimensional accuracy. In addition, the post-sintering treatment improves the surface quality. The fracture tensile strength ranges from 420 to 550MPa depending on the density. It was found that the powder characteristics such as size, shape, and distribution of the particles have a significant influence on the sintered density. A well-known limitation of powder bed additive manufacturing techniques for metals is the requirement of support structures on down-facing surfaces. Deviation between the actual and the nominal CAD geometries is computed, and results are processed following the tolerance unit method defined in international standards (IT grade). At the end of this study, the closest tolerance obtainable on self-supporting faces and related geometrical parameters are identified, limited to Direct Metal Laser Sintering (DMLS) of aluminium parts parameters are: laser power, scanning speed, laser beam radius, hatch spacing and pre-heating temperature of the powder bed. The predicted relative density decreases slightly with the increase of hatch spacing. Nevertheless, the value of hatch spacing must be chosen carefully. Longer hatch spacing leads to discontinuous densification of the powder, and very short hatch spacing will result in over sintering. A higher temperature distribution, and higher relative density, can be achieved by higher laser power and pre-heating temperature, and/or by lower scanning speed, laser radius and hatch spacing.

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