ELECTRON BEAM PROCESSES FOR ADVANCED ENGINEERED MATERIALS AND THE APPLICATION OF DIGITAL MANUFACTURING PRINCIPLES

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ABSTRACT

Aerospace and space products depend, probably more than any other products in industry, on advanced materials. While there are many ways of producing aerospace parts, in many cases the process does not allow the design of the metallurgical properties according to the part or product requirements in accordance with its mechanical configuration. Key to the next level of innovative manufacturing is the capability to control the amount of energy applied to the process, as well as the addition of materials in form of vapor or solid particles such as powder in order to build up the metallurgical composition required.

With the development of a high speed pulsed laser-electron beam source, the LASTRON™ technology, we deliver the basic requirement for a digital manufacturing process of aerospace and space products. This technology, combining Laser and electron beam, finds application in welding, drilling-machining, and is currently modified to allow digital coating (PEB-PVD) methods. In addition to the coating, a powder metallurgical process, called Rapid Manufacturing (RM), will allow the precision melting of parts based on CAD/CAM files. The RM process and the digital coating will allow the production of graded aerospace alloys in parts for jet engines and aero-structures.

INTRODUCTION

Traditional manufacturing methods are usually described as subtractive manufacturing [1] procedures, or analog processes, which means removing material from a solid block and forming raw material into a specified shape. This top-down method does not allow engineers to design the chemical composition within the material, which is an integral step to accommodate advanced functions of parts in the future. Today, we already use CAD/CAM technology to design and build aircraft from the ground up and the engineering process is so stable that mock-ups, used in the past, are not required for pre-production planning.

Moreover, this digital design and planning technology is transferred to traditional (analog) manufacturing methods such as milling, turning and others. Digital manufacturing principles add the material component to the design process and in addition to the geometric shaping of the part, an engineer of the future will then be able to embed metallurgical functions into the product. In order to explain the digital manufacturing principle I would like to list two samples that describe this functional design concept.

In the future an aircraft wing spar might be designed to be stiff at the wing root, and flexible at the wing tips. This could be done by changing the spar cross section, but also by changing the characteristics of the material used, such as flexibility or strength, as the spar from the wing root to the wing tip.

Engines are another important part of the aircraft; higher temperatures of the engine will allow lower fuel consumption and/or higher speeds. In addition, pilots need to have more detailed information on engines such as compression and condition of rotating engine parts. Also, today’s engines occasionally have problems where the pilot has to guess the reason for the loss of thrust. Such operational problems are compressor surge, foreign object damage and others. Therefore, our target should be to include sensors into engine components that will allow a better situational awareness for the pilot. Both, higher temperatures and sensors, have extreme impact on the material properties used for such advanced engine parts.

After establishing the basic requirements for digital manufacturing, we will focus on the transfer of the chemical composition information into digital data, which could be used for a new generation of machine tools. Key to this production strategy is to build machine tools that will use raw materials, such as powders, wire or other forms of material supplies, and build the part from the ground up. In this paper we will describe digital manufacturing principles by utilizing a pulsed electron beam for rapid manufacturing and digital coating.

DIGITAL ENCODING OF CHEMICAL PROPERTIES

In order to establish a manufacturing procedure that can continuously change or modify material properties, the desired chemical composition of a part requires to be encoded into a digital matrix, which can be transferred into a control system. The control system can then synchronize a pulsed electron beam and a material delivery device, such as a powder dispenser. The production of the desired chemical composition can be achieved by two (2) methods, namely the element method or the alloy method. Each method offers a different means of producing a new material.

Since the digital matrix is loaded into a process controller, the user can change the exact composition during the process. This means the process can be started with one composition, and changes gradually to another composition in one continuous manufacturing run.

The following diagram shows the fundamental steps of the process, starting from element or alloy initiation. Elements or alloys are labeled from A to F to show how different materials are used during the process initiation.

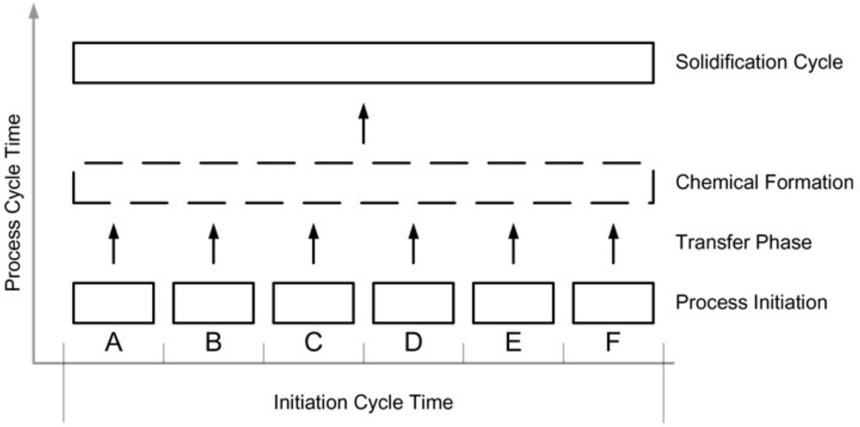

Figure 1: Process Cycle Outline

Usually, the process initiation is followed by a transfer phase; a mass flow occurs, starting from element or alloy source to the product position where the newly formed material solidifies. During the transfer phase, the formation of the alloy of the chemical composition starts and continues till the solidification cycle is completed.

Digital Manufacturing – The Element Method

The element method starts by defining the required chemical composition at every point in the part that is to be produced. These compositions are then encoded in a matrix that fully defines the part both physically and chemically at each point. The following two tables are examples of how the composition of Inconel 600 and Hastelloy might be encoded.

Table 1 Chemistry Encoding – Inconel 600

Element	C	Cr	Cu	Fe	Mn	Ni	Si	Total
Wt. %	0.15%	17%	0.50%	8%	1%	72%	0.50%	99.15%
Value for 16 bit Byte	98	11,141	328	5,243	655	47,186	328	64,979
Number of pulses of beam	75	8,500	250	4,000	500	36,000	250	49,575

Table 2 Chemistry Encoding - Hastelloy

Element	C	Co	Cr	Fe	Mn	Mo	Ni	
Wt. %	0.01%	0.50%	0.50%	0.99%	1.00%	28.00%	69.00%	1
Value of 16 bit Byte number	7	328	328	649	655	18,350	45,220	65,536
Number of pulses of beam	5	250	250	495	500	14000	34500	50000

After establishing the digital data (byte number) for each element, the data is transferred into a controller that will synchronize the energy source, a pulsed electron beam, with an element delivery system containing the individual elements. In order to create a truly flexible concept, we establish a process initiation time that defines the time it takes to execute one cycle initiating all elements. Initial trails showed that this initiation time is a variable, ranging from 20 ms to 800 ms. In order to build up larger structures, the process cycle will be repeated as long as it takes to produce the required shape of material.

To produce graded materials, it is possible to change the composition in-between the initiation cycles. This is done by modifying the byte number for the elements and, therefore, the chemistry can be changed before starting any initiation cycle. A certain number of process cycles are required in order to grade the material layer by layer.

Digital Manufacturing – The Alloy Method

The alloy method is very similar to the element method described in the previous section, but instead of using single elements, more complex alloys are used as source materials for the process. By using ready-made alloys, it is possible to form larger quantities of graded materials by utilizing the same basic concept of process initiation; followed by transfer and formation phase, and ending with the solidification of the materials.

Encoding the chemical composition or modeling this process is more complex since a larger number of individual elements are involved in the forming the desired material. When combining different alloys, the interaction of various elements during the alloy formation must be considered.

DIGITAL COATING (PEB-PVD)

Digital coating is a term that describes a process utilizing different devices in a synchronized procedure in order to form complex coatings. The chemistry of such coatings can be produced by evaporation of single elements or alloys, or a combination of both. The devices used in the digital coating process are

- process chamber
- pulsed electron beam system
- target holding and handling rotary
- motion system for substrate (part) handling
- process controller synchronizing all devices
- vacuum system with process gas capability

In traditional coating procedures, the chemical composition of the material applied to a substrate surface is determined by the composition of the target material. Because of complex interactions during transfer and deposition, the target composition is in general not the same as the desired coating composition. These procedures are therefore expensive because they require the production of complex alloy targets on a trial and error basis to produce the required coating composition.

Digital pulsed electron beam physical vapor deposition is evaporating chemical elements in a cloud, where a formation of materials occurs. It utilizes pulsed high-energy electron beam with short pulse duration to vaporize the target material.

The initiation of the process is achieved by placing different targets into the path of the pulsed electron beam while rotating the target device. The electron beam pulses are synchronized with the target position, so that the user can digitally control the number of pulses on a particular target (as outlined previously in the encoding of materials). The mass of material being vaporized by a single pulse can be experimentally determined prior to the actual coating operation.

By applying a digitized composition matrix, the user can precisely control the amount of different materials evaporated by varying the number of pluses on a particular material. The chemical composition can be changed before each initiation cycle starts; the result is an extremely versatile coating system, where the user can dynamically change the mixing ratio from a number of targets or alloyed materials, merely by changing the software that controls the number of pulses on different materials.

The following two graphs show the coating process by using six material targets. The target device holds up to six materials and spins the targets at a controlled speed around the vertical axis. While a particular target is in the beam path, a defined number of electron beam pulses are triggered, resulting in a defined percentage of the target material being vaporized. The amount of material vaporized depends on the number of electron beam pluses and the individual properties of the target material. The position of the beam pulse on the target can be controlled either by timing, or by position of the electron beam on the target.

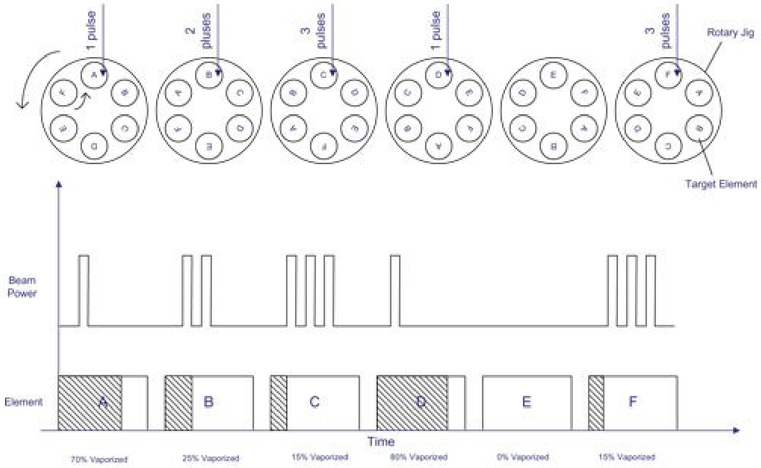

Figure 2: Evaporation of elements by changing the number of pulses

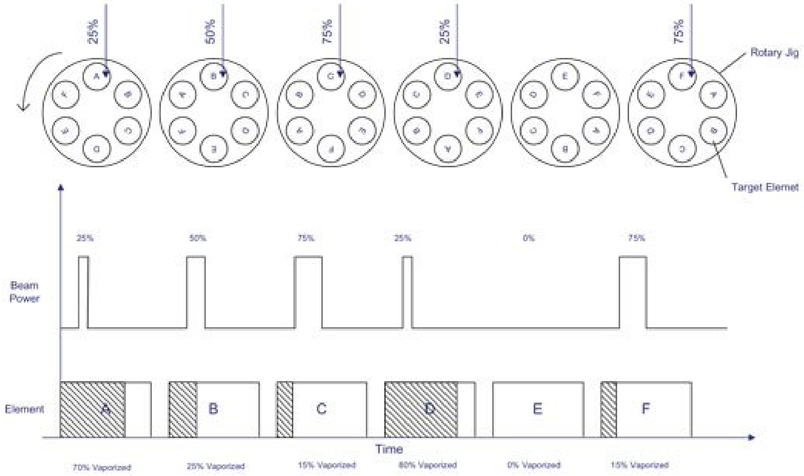

Figure 3: Evaporation of elements by changing the duty cycle of the pulses

Figure 3 shows the evaporation of targets A to F by changing the duty cycle of pulses, which could be in combination with the number of pulses. If the target device is rotating at 1,200rpm, the maximum beam travel for a 0.02ms long beam pulse (50kHz) would be approximately 0.5mm. On a 3” diameter target, the number of pulses per revolution could vary from a single pulse to about 300 pulses. The time required for one revolution would be 50ms. By combining several revolutions into one group, the user can achieve more varieties of mixing ratio. With six material targets, four pulse number settings and three revolutions as a group, the user can choose between 157,000 different mixing ratios.

PRECISION MELTING - RAPID MANUFACTURING

Precision melting or Rapid Manufacturing (RM) is an umbrella term that covers many areas of research dealing with the manufacturing technology of very complex formed parts. The proposed technology to be realized with our beam (Electron / Laser) system should melt different powder materials and solidify these materials to complex formed parts. This technology will enable its users to design and manufacture very complex shapes, including internal structures such as cooling channels, and to solidify these parts from new materials. It is based on powder metallurgical melting and sintering techniques in order to join particles in the size range of 500 µm to 5 µm. The RM process will not only allow the combination of materials, but also allow the deposition of different materials in such areas of the part where functional characteristics require different metallurgical properties. In addition, it is planned to embed structures that will allow sensing the live status of the part during operation, thus making it a “smart” product. A typical RM machine that can be used for the RM process has to consist of the following components

- process chamber
- pulsed electron beam system
- a system having up to 5 axes motion for part handling
- powder delivery device
- process controller synchronizing all devices
- vacuum system with process gas capability

The following figure describes the concept of the RM procedure, including system devices and process parameters.

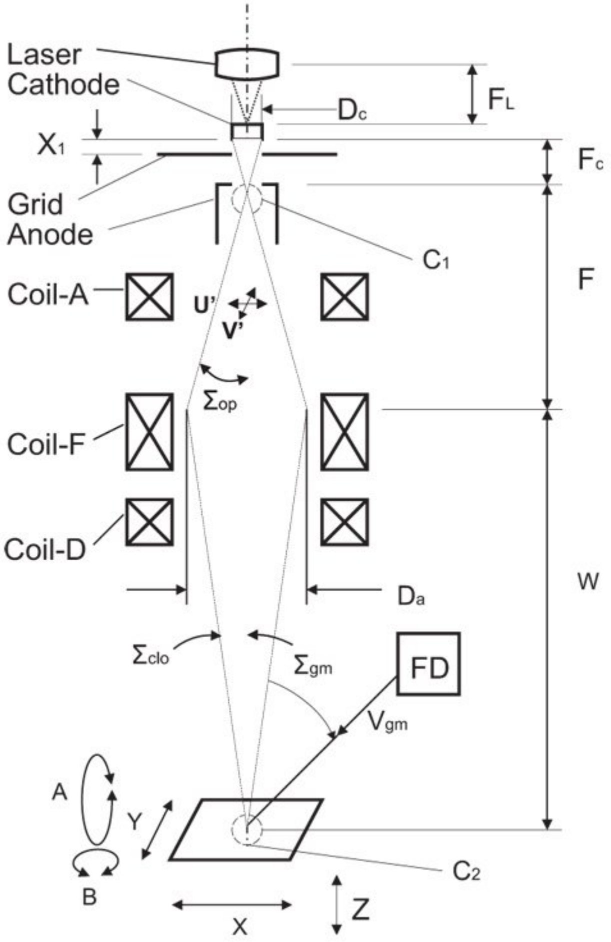

Figure 4: RM Process Layout

The following table describes process parameters as shown in Figure 4

Table 3: Process Parameters and Definitions

ID	Definition
Dc	Dimension of cathode
C1	First crossover of beam
U’	Beam alignment in X
V’	Beam alignment in Y
U	Beam deflection in X
V	Beam deflection in Y
Da	Beam diameter at aperture
FD	Powder feeding device
Σgm	Trajectory angle of granular matter relative to beam
Vgm	Velocity of granular matter
C2	Crossover beam and granular matter
W	Focal distance target
X-Y-Z	Linear motion system
A-B	Tilt (B) rotary (A) system option

Before a part can be manufactured to its geometric net shape, its technological function and chemical composition must be defined. At the moment, it is required to use existing design tools, such as CAD or FEA software. These programs are not able to recognize different chemical properties with changing mechanical attributes; this may, however, change in the future. Today, all CAD systems usually use standard export functions to transfer the part geometry in a file format that can be imported in other software, such as CAM packages.

One option to import the geometric data is using the .STL [6] file format for importing the geometric part data. This is commonly used in rapid-prototyping and slices any complex geometric design into two dimensional layers. Based on the layered model, the process trajectory can be calculated so as to build the part layer by layer. Having defined the trajectory, the metallurgical definitions have to be added as digital data, using the element or the alloy technique. In addition, the metallurgical data will be synchronized with the process trajectory. Digital manufacturing will require developing software, which allows the programmer to add the metallurgical properties to the geometric data.

Once the data are downloaded into the machine, the process can start with manufacturing the product layer by layer. The material delivery device will be synchronized with the part motion and the beam pulsing. One of the most interesting features of this technology is that internal structures, such as cooling channels or pockets, can be integrated from the very beginning.

CONCLUSIONS

Digital manufacturing principles will change today's manufacturing strategies by building the shape from the bottom-up. Instead of buying standard-sized row materials, such as bars and plates, the part will be formed close to its final net shape. This process will have economic benefits by optimizing the use of resources.

In order to advance existing aerospace materials, parts need to have their desired material properties at all points in the parts. Engineering in the future will include CAD, CAM and digital manufacturing principles (DMP). These principles will allow engineers to add more functionality to the part, such as grading materials, sensing components, and others.

The procedures described in this paper, namely the digital coating and the rapid manufacturing process, are two upcoming procedures for future manufacturing. There will be many more complementary technologies, such as allowing the production of aircraft wings with optimized root and tip properties, or high temperature alloys for jet engines. In addition, by producing integrated parts such as turbine blades and rotors from one piece, weight will be reduced, cooling optimized and, therefore, the efficiency of the engine will increase - resulting in reduced engine operation costs.

FIGURES

TABLES

REFERENCES

[1] Manufacturing is the transformation of raw materials into finished goods for sale, by means of tools and a processing medium, and including all intermediate processes involving the production or finishing of component parts ("semi-manufactures"). It is a large branch of industry and of secondary production. Some industries, like semiconductor and steel manufacturers use the term "fabrication".

http://en.wikipedia.org/wiki/Manufacturing