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Improving Implants Using Laser-Based Metal Deposition Technologies

Additive manufacturing technologies (a.k.a. rapid prototyping, 3D printing, rapid manufacturing and solid freeform fabrication) have dramatically impacted the design, prototyping and manufacture of engineered products since their introduction 20 years ago. These technologies are used to build parts layer-by-layer based on a digital file, with little or no human intervention. Some of the benefits of these technologies are the ability to produce features internal to parts, and fabrication of novel material compositions, including functionally graded material (FGM) constructs, which have gradual changes of material composition and microstructure throughout the part. Recent collaborative research by the authors related to the fabrication of biomedical implants using laser-based metal deposition (LBMD) additive manufacturing technologies has indicated that substantial improvements to implant design and longevity may be possible with the appropriate application of LBMD.

Implant Design

The advancement of materials for medical implants has immensely improved the quality of life for many people. Devices such as prosthetic hip, knee, shoulder and other joints have enabled people who would otherwise suffer from chronic pain and physical limitations to live more active and comfortable lives. However, continuous improvements to such devices have confronted surgeon developers, scientists and engineers with technical challenges in the area of materials science and manufacturing, such as bonding of biocompatible materials with different physical and mechanical properties to each other. Our collaborative development is based on the premise that components of implants can be optimized by using LBMD additive manufacturing technologies to build multi-material and FGM constructs out of different combinations of materials that have differing mechanical properties and varying structural morphology.

Generally, the base structures of orthopaedic implants are designed to fit into a constrained space and undergo upwards of ten million cycles of loading during their lifetime. Thus, the materials used to form an implant's base structure must have excellent static mechanical and fatigue properties. Other individual components of an orthopaedic implant, such as bearing surfaces or bone ingrowth pads, are traditionally manufactured using techniques that result in relatively uniform material properties (e.g. machined wrought alloys, cast alloys, forged materials and powder metal-based components). These traditional manufacturing methods produce implant components with bulk properties that are optimized for particular design criteria, such as biocompatibility, strength, flexibility, wear resistance or bone ingrowth properties.

In order to enhance their properties, implant devices are typically constructed from different components, often made from different materials, which are bonded or mechanically attached together. For example, joint prostheses are often constructed from strong, mechanically compliant materials such as titanium alloys. A porous material such as tantalum may then be bonded to the base component, and then a bearing component made from a third wear resistant material, such as alloys of cobalt and chrome or ceramic materials, may be mechanically attached to the base component as well. One challenge to this traditional method is achieving sufficiently strong, permanent bonds between the implant sections that will not fail under the fatigue loading imposed by the body of the patient. When these components are assembled together to form an implant, the transition from one component to another is traditionally abrupt and not optimized. In addition, components made from dissimilar metals may experience galvanic corrosion or form brittle intermetallic phases when bonded together. These challenges can be addressed by manufacturing implant components using LBMD technologies to form FGM or multi-material constructs. These LBMD constructs can be directly deposited on a base component or separately fabricated and then bonded or assembled to a bulk implant component to form a complete orthopaedic implant.

We have demonstrated various fabrication methods using LBMD technologies to repeatably and reliably manufacture multi-material and functionally graded implant components that are made from combinations of different materials with optimized transitional regions.

continued on page 24

Metal Deposition Technologies, continued from page 22

Laser-Based Metal Deposition

LBMD processes are a subset of additive manufacturing processes that enable the deposition of various metal powders onto substrate geometries. Several companies and organizations have developed LBMD processes over the past ten years. The most well known process to date was developed by Sandia National Laboratories, and is known as Laser Engineered Net Shaping (LENS®, a registered trademark of Sandia Corporation and Sandia National Labs). Optomec Design Company of Albuquerque, New Mexico makes and sells equipment based on Sandia's LENS process. One of these machines is in place at Utah State University and was used for this research. The Optomec LENS 750 machine at Utah State University is a three-axis deposition system equipped with a 500W Nd:YAG laser and multiple powder feeders that allow multiple types of powder to be fed directly into a laser focus area. The multi-material capabilities of LENS makes possible FGM implant constructs made of different materials (e.g. CoCrMo, titanium, tantalum) and like materials with differing microstructure with optimized transitional regions. The deposition apparatus is enclosed in an airtight, argon environment that can be purged below 5 ppm oxygen. This low oxygen content is necessary for the deposition of Ti and other alloys that oxidize readily at elevated temperatures.

In general, an LBMD machine, including LENS, is controlled by means of software that converts a 3D CAD file into tool paths to deposit metal powder onto a substrate. The tool paths are composed of a series of lines that are scanned by the laser as the powder is fed into the melt pool created at the substrate surface due to the laser. The melted metal from each deposit slightly overlaps, allowing for a relatively uniform thickness of deposit. A schematic of an LBMD process is shown in Figure 1.

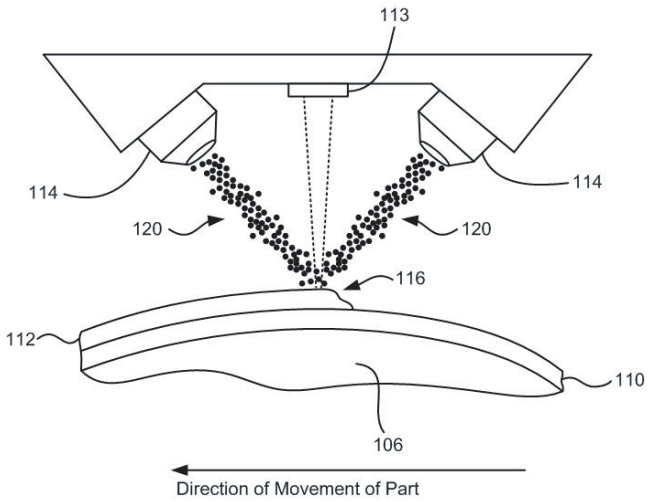

Figure 1. Laser-Based Metal Deposition Process (U.S. Patent 7,001,672)

The various components of a LBMD process, as illustrated in Figure 1, are:

- a focused laser beam (113)
- powder deposition nozzles (114)
- powder sprayed at the substrate (120)
- a substrate (106)
- a laser/powder interaction region wherein the powder is melted and deposited onto the substrate surface (116)
- the deposited material (110 and 112)

LBMD enables a highly focused laser beam to melt a very small amount of powder over a short period of time. Because the substrate acts as a heat sink, this process results in a rapidly cooled LBMD deposited material. This rapid cooling has many potential benefits for implant materials.

1. Rapid cooling of metals results in a fine grain structure, and thus an increase in hardness relative to an as-cast structure.
2. Rapid cooling can suppress equilibrium brittle intermetallic formation between dissimilar metals, and thus improve toughness and fatigue life.
3. In a carbon rich powder, additional small, evenly distributed carbide precipitates form, resulting in a harder, more wear resistant material.
4. Rapid cooling results in a small heat affected zone (HAZ) when compared to traditional welding and bonding processes.

In our work, we have seen each of these benefits in LBMD deposited materials. Figure 2 illustrates how the rapid cooling associated with LBMD processing results in a finer distribution

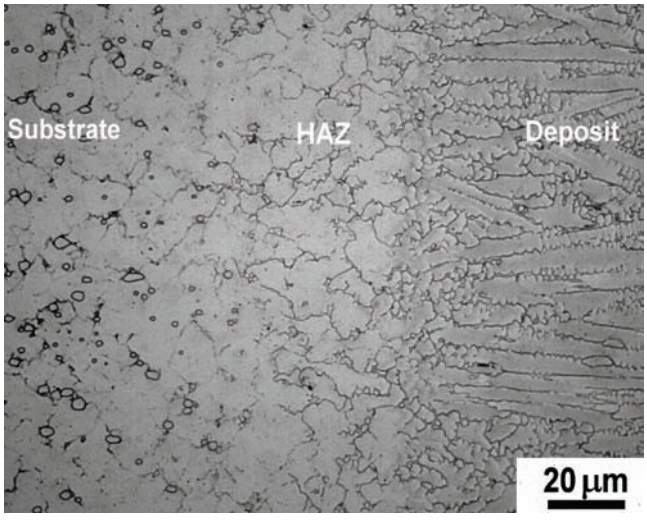

Figure 2. Optical micrograph of a CoCrMo LBMD deposit on a wrought substrate illustrating a refined carbide structure in the deposit and a small heat affected zone (HAZ).

of secondary particles, increased hardness and a small heat affected zone when deposited on a wrought substrate (Stucker, Esplin and Justin, 2004). In other work, we have demonstrated the ability to use LBMD to join CoCrMo to Ti, and CrCrMo to porous Ta both directly and with the use of intermediate material layers such as zirconium and stainless steel (Smith and Stucker, 2005; Kumar and Stucker, 2005). This joining is possible under certain machine operating conditions when the formation of intermetallic brittle phases is suppressed due to rapid cooling. Lastly, we are in the process of investigating the formation of carbide precipitates within Ti (TiC) and CoCrMo (CrC) to strengthen and increase the wear resistance of these alloys.

Conclusions and Future Work

With the advent of LBMD processing, it is now possible to build an orthopaedic implant that transitions from ingrowth materials, such as porous Ti and porous Ta, directly to high hardness bearing surfaces, such as Ti (TiC) and CoCrMo (CrC), or to structural materials, such as Ti6Al4V ELI. This development has the potential to significantly improve the design and functionality of future implant devices. Utah State University and MedicineLodge, Inc. are in the process of investigating the use of LBMD for implant fabrication using various biomedical alloys. As part of our current and future work, we are undertaking a study of the mechanical and wear properties of LBMD deposited materials to ascertain the true benefits of LBMD for implant fabrication.

References

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Dr. Brent Stucker joined the Mechanical & Aerospace Engineering Department at Utah State University in 2002. His research efforts focus on advanced manufacturing techniques and their applications, with particular attention to new materials development for biomedical implants and aerospace/satellite structures. To learn more about laser-based metal deposition technologies, attend Dr. Stucker's presentation at OMTEC 2006. (See information included in this issue.) Dr. Stucker can be reached at brent.stucker@usu.edu.

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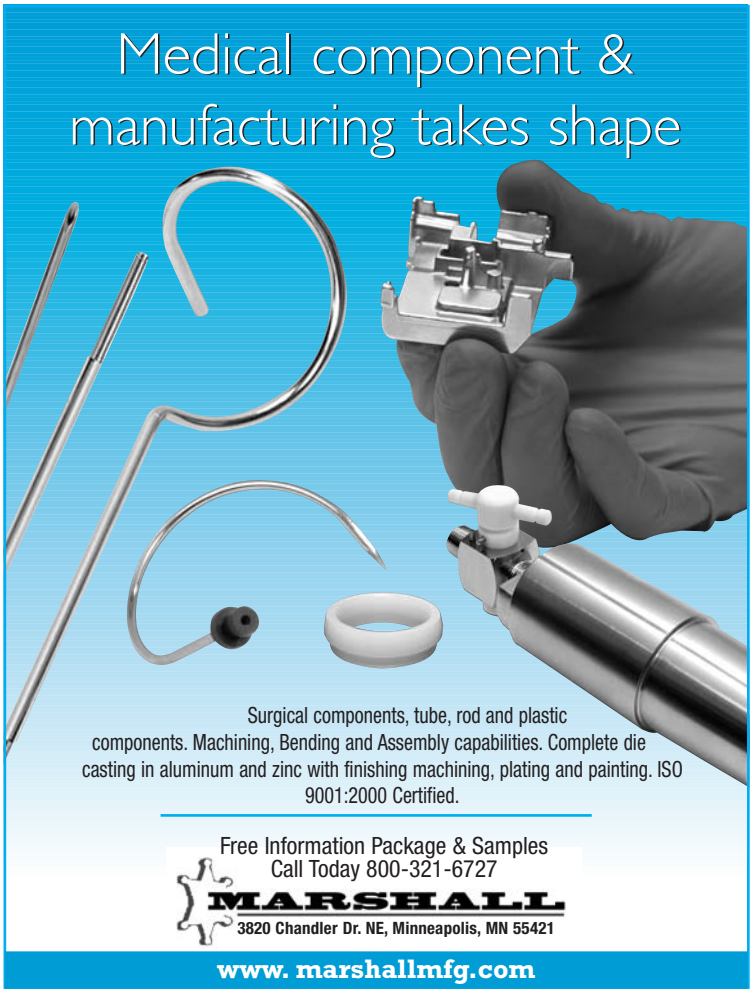
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