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Near Net Shape Production of Metal Components using LENS

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ABSTRACT

Rapid Prototyping and Near Net Shape manufacturing technologies are the subject of considerable attention and development efforts. At Sandia National Laboratories, one such effort is LENS (Laser Engineered Net Shaping). The LENS process utilizes a stream of powder and a focused Nd YAG laser to build near net shape fully dense metal parts. In this process, a 3-D solid model is sliced, then an X-Y table is rastered under the beam to build each slice. The laser / powder head is incremented upward with each slice and the deposition process is controlled via shuttering of the laser. At present, this process is capable of producing fully dense metal parts of iron, nickel and titanium alloys including tool steels and aluminides. Tungsten components have also been produced. A unique aspect of this process is the ability to produce components wherein the composition varies at differing locations in the part. Such compositional variations may be accomplished in either a stepped or graded fashion.

In this paper, the details of the process will be described. The deposition mechanism will be characterized and microstructures and their associated properties will be discussed. Examples of parts which have been produced will be shown and issues regarding dimensional control and surface finish will be addressed.

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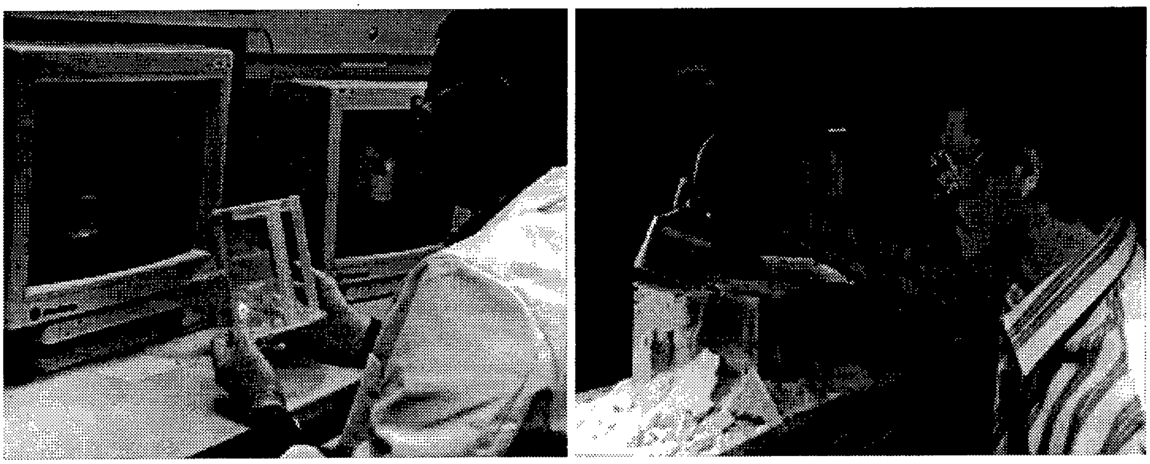
The computer revolution has drastically changed many aspects of modern life. The ability to handle data in new and more complex fashions has provided the impetus for a true metamorphosis of our daily life. The fusion of various technologies with this processing power is resulting an evolution in most everything we do. Applications ranging from navigation to how our food is prepared, from home entertainment to skis, are all impacted by the rapid pace of technology development and data fusion. Although consumer products are the most obvious manifestation of this revolution, it has had no less of an impact on the manufacturing sector.

Within the manufacturing sector, the first significant change is often said to have been the introduction of CNC (Computer Numerically Controlled) machining. This advance allowed a computer to control conventional machine tools. Although there had been template matching machines available for years, the introduction of CNC capabilities is perhaps the first true step along the road towards a new manufacturing paradigm. As CNC capabilities expanded, the focus shifted to the tools required to get the design from the engineer, to the shop floor, with the minimum amount of effort and the greatest degree of integrity. This requirement engendered the development of complex 3D solid model design tools and automated machine tool path planning.

DISCLAIMER

Concurrent with the advances in computer capabilities have been an advances in technology areas as well. One such area is in the field of lasers. As CNC technology advanced, the laser began to be recognized as a potential manufacturing tool. Spot welding and cutting applications being examples of niches where numerically controlled laser processes quickly demonstrated their value. Recently, this marriage of laser and computer has resulted in the introduction of rapid prototyping technology, a development that has garnered considerable attention within the manufacturing sector. Figure 1 is an example of two such processes.

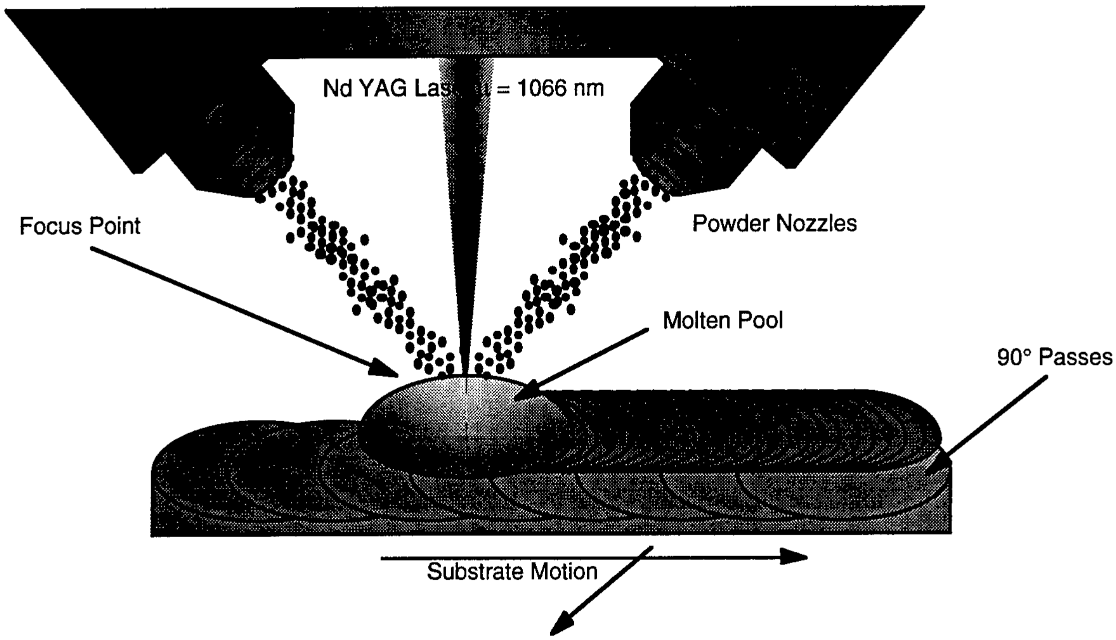


Stereolithography (SLA)   Selective Laser Sintering (SLS)
Rapid Prototyping
Figure 1

These rapid prototyping processes introduced a precision manufacturing technology that was significantly different than typical manufacturing. This difference lies in the fact that both SLA and SLS are additive processes. In these processes, rather than removing material from a block as in conventional machining, material is added. In the SLA process a laser is used to cure a liquid acrylic, whereas in the SLS process the laser sinters powder. In both cases a solid part is produced. From this basis, similar technologies are being developed for the production of metal parts.

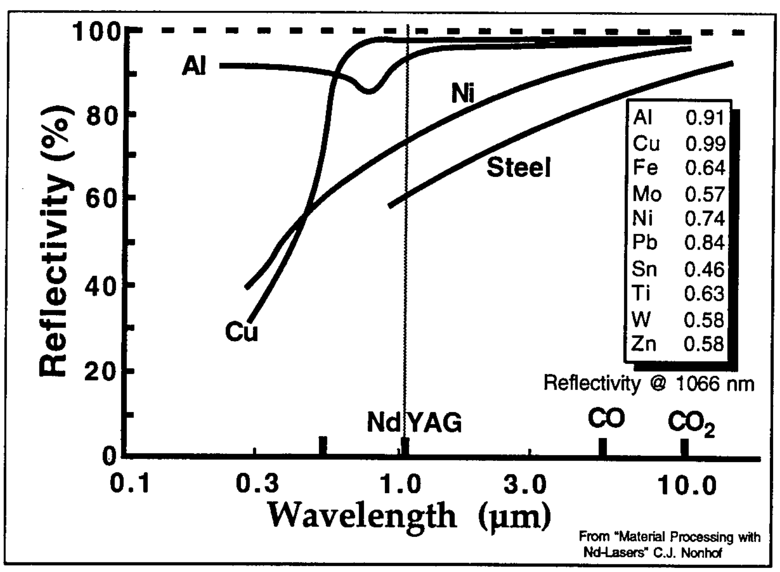
The Laser Engineered Net Shaping process (LENS)[1,2] being developed at Sandia, the Directed Light Fabrication process (DLF)[3], Laser Cladding work at the University of Illinois[4], plus work at Penn State, Carnegie Melon and Stanford, to name just a few, are all extending the knowledge obtained in the field of rapid prototyping towards the production of metal parts. These processes are similar in that they are all intended to produce functional metal parts. They differ in the type of laser, laser power, deposition rate, number of axes and metal delivery. In most cases metal powder is used as the feedstock although work with droplets is also underway[5]. For the purpose of this work, the LENS process will be used as an example.

In the LENS process, a Neodymium doped Yittria Alumina Garnet (Nd-YAG) solid state laser is used as the energy source. As shown in figure 2, the laser is focused onto a metal substrate. The focused laser radiation, typically about 300 watts, but as high as 750 watts, melts the target material and a molten pool forms. Powder in the size range of 40 microns to 180 microns (-80 +325 mesh) is entrained in argon and injected into the molten pool.



LENS Deposition Process
Figure 2

Multiple powder nozzles are used and the system is set up such that the intersection points of the powder streams and the laser focus point are coincident. Once the powder enters the molten pool it quickly melts and the molten pool expands into a bead of molten metal. The growth of this molten metal bead, when coupled with the X-Y motion of the table results in condition of asymmetrical bead morphology and heat input that causes the bead to expand unidirectionally.

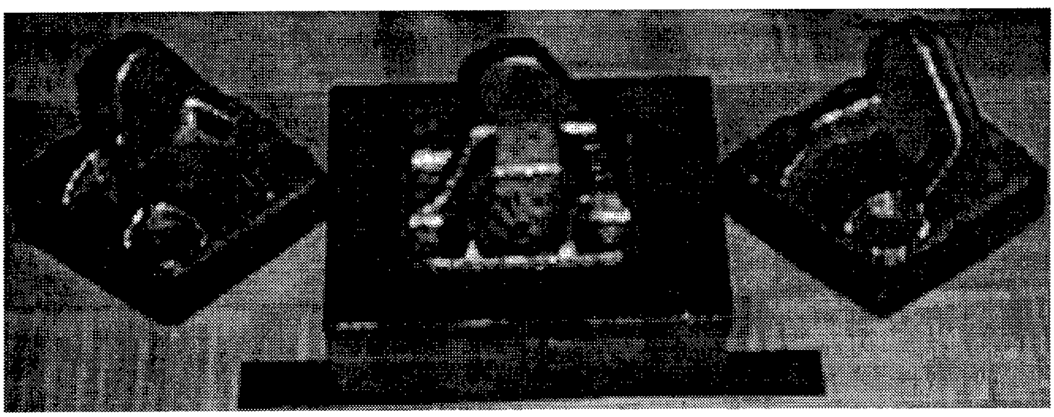


Reflectivity as a Function of Wavelength
Figure 3

In this fashion metal is continuously deposited in a controlled fashion such that three dimensional parts may be produced. There are however some process challenges. For example, the absorption of the laser wavelength by the material being processed is not constant from material to material.

Figure 3 is a plot of reflectivity vs. wavelength. As may be seen in the figure, the reflectivity (1 / absorption) of metals is strongly dependent on the incident wavelength. In particular, the Nd YAG (1066 nm) wavelength does not couple well to aluminum or copper. As such, it is critical that the interaction characteristics of the laser and the material being processed are reviewed prior to the assembly of the equipment.

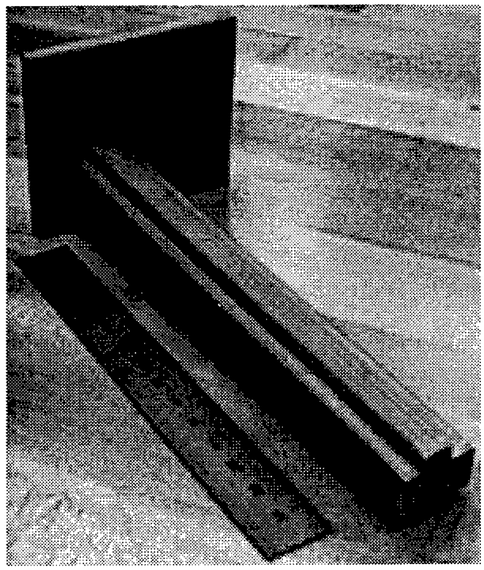
At Sandia, the Nd YAG laser has been used in the LENS process for the production of fully dense metal parts out of a variety of materials. Figure 4 below is a photograph of some Ti-6-4 components suitable for marine applications. The scale in the foreground is 150 mm long. These parts have been measured at 99.996% dense, the limit of the equipment. Yield strengths of similarly produced test bars have been measured at 144 ksi with ultimate strengths at 150 ksi. These values compare favorably to the typical properties of 120 ksi yield and 130 ksi ultimate. The difference in strength is probably due to the solidification which seems to have involved a massive transformation to alpha from the beta phase. This also explains the low elongation, 2.8%, as contrasted to the more typical number of 10%. It should be noted that due to its affinity for oxygen, the casting of titanium is somewhat difficult. As a result, the near net shape capability of LENS and similar processes represents a potentially valuable technique.



Titanium 6-4 Brackets
Figure 4

Another of the major advantages of the LENS process is that it is capable of producing very high aspect ratio parts. Figure 5 is a photograph of a 316 stainless steel part. This part is roughly 150 mm long and 25 mm across. As produced, it is distortion free and looks much like an extrusion. However as opposed to an extrusion, the LENS part could be as easily produced out of H13 tool steel or tungsten. The ability to produce such shapes out of materials that are typically very difficult to machine is of obvious value and is the primary reason that direct metal deposition processes are being evaluated for the production of tooling. To date the materials which have been successfully processed at Sandia via LENS include: Nickel alloys 718,625 & 690, stainless steels 304 and 316, H13 tool steel, Tungsten, Titanium and NdFeB magnet alloy. Each alloy processed requires slightly different processing parameters in order to obtain optimum build rates, density, grain structure and surface quality. As such, some parametric studies are usually indicated whenever a new material is used. On the other hand, experience indicates that as long as the material being processed has a sufficiently low reflectivity at the ND YAG wavelength, then the that material should be amenable to LENS type processing.

Since these direct metal deposition processes have been shown to be compatible with a wide variety of materials, the obvious extension is towards graded structures. This capability is achieved by modifying the powder composition in a continuous fashion over some portion of the part. It does not require much imagination to envision the advantage of such a scheme. Applications include matching CTE (Coefficient of Thermal Expansion), transitions and locally tailoring properties such as thermal conductivity, hardness, toughness or resistance to corrosion. This realization of this capability is predominately an issue of the control of the powder feeders. In fact the production of graded parts has been demonstrated, and as an example. Michelle Griffith of Sandia has built parts which transition from 316 stainless steel to 304 stainless steel as well as parts which transition from 304 stainless steel to A690.



Extrusion Shape
Figure 5

Despite the progress made to date, there are still some areas in need of improvement. For example, part complexity is an issue that has been mentioned. This concern arises from the lack of overhang capability in LENS that is available with most rapid prototyping processes. However, the overhang issue can be addressed with an appropriate combination of hardware and software and in fact, Gary Lewis of Los Alamos has demonstrated full 3D fabrication capability using DLF. As a result, part geometry is seen as more of a developmental issue.

Another item of note is the deposition rate. Present deposition rates at Sandia are somewhat slow, on the order of two hours per cubic inch. However, work at Penn State[6] has shown much greater deposition rates. The process at Penn State uses a fluidized powder bed and a 14 kW CO_2 laser. Whereas at Sandia the maximum laser power used to date is about 700 watts. The implication is that as the power is increased, the achievable deposition rate will increases as well. As a result, obtaining greater deposition rates does not seem an insurmountable obstacle.

Perhaps the most significant area in need of development is associated with the surface quality of parts produced. John Smugeresky of Sandia has shown that with the LENS process, the surface roughness is primarily a function of powder size and appears to be associated with powder overspray. It is known that not all of the powder that flows through the nozzle is incorporated into the part. It is therefore surmised that some of the powder is impinging upon solidifying material and sticking. This does not create a problem in the bulk of the part since subsequent deposition passes melt any powders stuck to the surface. However, since external faces are not remelted and covered, such adhering powders end up being a significant surface feature. Thus surface quality is an area where significant work is underway.

In summary, direct metal deposition technology is under going a rapid advancement. The number of organizations active in the research of such technologies is growing at a rapid pace and the capability of direct metal deposition processes is expanding daily. Research organizations the world over have demonstrated that the technologies have application and as a result, today we stand on the brink of commercialization.

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