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Introduction

With the rapid growth of laser applications and the reduced cost of laser systems, laser material processing has gained increased importance in a variety of industries. Automotive, aerospace, navy, defense, and many other sectors are widely adapting laser technology for welding, cutting, and hardening. Among the applications of laser technology, laser cladding has received significant attention in recent years due to its diversified potential for material processing such as metallic coating, high-value components repair, prototyping, and even low-volume manufacturing.

1.1 What is Laser Cladding?

Laser cladding is an interdisciplinary technology utilizing laser technology, computer-aided design and manufacturing (CAD/CAM), robotics, sensors and control, and powder metallurgy.

Laser cladding utilizes a laser heat source to deposit a thin layer of a desired metal on a moving substrate. The deposited material can be transferred to the substrate by several methods: powder injection, pre-placed powder on the substrate, or by wire feeding. Among these methods, laser cladding by powder injection has been demonstrated to be most effective. In this process, the laser beam melts the powder particles and a thin layer of the moving substrate to deposit a layer of the powder particles on the substrate. A great variety of materials can be deposited on a substrate using laser cladding by powder injection to form a layer with thicknesses ranging from 0.05 to 2 mm and widths as narrow as 0.4 mm.

In addition to metallic coating applications, the laser cladding process offers a revolutionary layered manufacturing and prototyping technique. Integration of the laser cladding technology with a three-dimensional CAD solid model, which is sliced into many layers, provides the ability to fabricate complex components without intermediate steps.

The development of the laser cladding technology depends on enhancement of the technologies involved. Understanding the interconnections between the involved technologies and the process quality is a major step for the development of laser cladding. However, numerous interactions between the technologies involved in laser cladding not only increase the complexity of the process but also increase the number of process parameters.

1.2 Different Names, Same Technology

A survey of the literature indicates that many names have been given to laser cladding technology based on its highly diversified applications. For example, in the coating applications, in addition to "laser cladding", researchers use the terms "laser coating" [1, 2], "laser powder deposition" [3, 4] or "laser surfacing" [5, 6, 7].

In the rapid prototyping or layered manufacturing applications, numerous names have been used. In prototyping by pre-placed powder laser cladding, the technology is called "selective laser sintering of metals" (SLSM) [8, 9], or "direct metal laser sintering" [10].

In the powder injection laser cladding process, which is the focus of this book, a wide variety of names have been used as outlined below.

- At Sandia National Laboratories, a process has been developed for rapid prototyping, which is called "Laser Engineered Net Shaping™" (LENS®) [11, 12, 13].
- At the University of Michigan in Ann Arbor, the developed process is called "direct metal deposition" (DMD™). This process incorporates features of laser cladding, CAD/CAM package, vision and control system [14, 15]. The University of Missouri at Rolla also uses the same name for the process [16, 17].
- "Laser direct casting" (LDC) is used at the University of Liverpool to describe the process, in which a coaxial nozzle is utilized to produce 3D components from a selection of metal powders [18].
- The Integrated Manufacturing Technologies Institute (IMTI) of National Research Council of Canada (NRC) uses the term "laser consolidation" for this process [19, 20, 21, 22].
- The term "laser powder fusion" (LPF) is used by some industries that are involved in turbine blade repair [23].
- At the Laser Aided Manufacturing Processes Laboratory at the University of Missouri at Rolla and at Swiss Federal Institute of Technology the process is named "laser metal forming" (LMF) [24, 25].
- "Directed light fabrication" (DLF) is the name used at Los Alamos National Laboratory in which a process has been developed for free forming and prototyping [26, 27, 28].

- "Laser powder deposition" (LPD) has been used by several research groups in China and England [29, 30].
- At the University of Waterloo, an automated laser cladding technology has been developed for coating and prototyping, which is named "automated laser powder deposition" (ALPD) [31].
- At Stanford University, Carnegie Mellon University, and Penn State University, the process is called "solid free-form fabrication" or "shape deposition manufacturing" [32].
- "Laser rapid forming" (LRF) is the name used by a research group at Shanghai Jiaotong University [33]. This name can be confused with another laser-based technology, laser bending, which is also called laser rapid forming.
- Finally, "laser additive manufacture" (LAM^{SM}) is the acronym used by AeroMet Corporation of Eden Prairie at Minnesota, fully owned subsidiary of MTS Systems Corporation [34].

Despite the variety of names, in practice all of the terms describe technology that share several common features: deposition of thin layers of powder particles melted by a laser heat source on a substrate. The process will be termed "laser cladding" throughout this book.

1.3 Why Laser Cladding?

Laser cladding offers many advantages over conventional coating processes such as arc welding and plasma spraying. The laser cladding technique can produce a much better coating, with minimal dilution, minimal distortion, and better surface quality.

There are also a number of advantages to use this technique as a rapid prototyping technique. Rapid prototyping can be used to produce a mechanical component in a layer-by-layer fashion, which enables the fabrication of part with features that may be unique to laser cladding prototyping, such as a homogeneous structure, enhanced mechanical properties, and one-step production of complex geometries. Parts fabricated using the technique are near net shape, but will generally require final machining. They also have good grain structure, and have properties similar to, or even better than the intrinsic materials. Both pre-placed and powder injection laser cladding offer these features; however, laser cladding by powder injection has fewer material limitations than pre-placed in which it does not require secondary placing powder laminating operations and it can be used to repair parts as well as to fabricate them.

Due to its additive nature, laser cladding can be applied in a variety of ways to parts, tools and advanced manufacturing to overcome the limitations of existing metal fabrication technologies. This results in a number of benefits as follows:

1. **Reduction of production time**: The length of time required to build a prototype is a problem for new product development. In many cases, both prototype and production tooling are needed; therefore, the length of time to produce a prototype and the necessary tooling can be several months. The laser cladding process can reduce this time by fabricating tools and main prototypes directly from the CAD solid model [14].

2. **Enhancement of thermal control**: The laser cladding process offers a well-controlled heat-treated zone due to the nature of the laser beam. A high-power laser beam is well confined and tense and, as a result, the rapid heating and cooling that occur in the process have little effect of heat on the base material. Therefore, the original properties of the base material are affected to a limited extent only. In addition, this thermal zone can be monitored and optimized during the process, which can significantly improve the quality of the tools produced. Laser cladding also offers a controllable energy over the surface of the desired tool to control the rate of solidification, which is the main parameter in the formation of microstructure and mechanical properties [35].

3. **Parts repair**: Current tool repair technology relies on destructive, high-temperature welding processes. In addition, machining errors or last-minute engineering changes can affect on-time delivery of tooling, and potentially impact the introduction date of a new product. Laser cladding can be applied as a safe technology to repair tooling, especially on critical contacting surfaces. Laser cladding increases tool life and in many cases can save a high-value tool that would otherwise need to be replaced [20, 36].

4. **Production of a functionally graded part**: In conventional metallic fabrication, it is difficult to produce a part from different materials layers. Laser cladding offers a method to produce functionally graded parts by injecting different materials during the fabrication of the parts. It is also possible to produce desired alloys by injection of different powders through various nozzles around the process zone [37, 38].

5. **Production of smart structure**: In conventional metallic fabrication methods, embedding objects into the tools is impossible due to the nature of manufacturing. Laser cladding, with its additive nature, offers the ability to create "smart structure" by embedding objects such as sensors and magnets during fabrication. Encapsulating these objects reduces the potential for damage or failure from temperature and environmental conditions [39].

Despite its obvious benefits, laser cladding is not yet widely utilized in metallic coating or prototyping applications. While laser cladding clearly offers a number of advantages over conventional fabrication technologies, the process can also have some drawbacks. Due to disturbances in the process, the clad quality may vary significantly. Variations of the quality may even be observed between processing cycles performed using the same operating conditions. This poor reproducibility arises from the high sensitivity of laser cladding to small changes in the operating parameters such as laser power, beam velocity and powder feed rate, as well as to process disturbances such as variations in absorptivity. Finding an optimal set of parameters experimentally and using them in an open-loop laser cladding process may not result in a good quality clad due to random or periodic disturbances in the system. Therefore, development of an intelligent closed-loop control system is essential for overcoming the effects of disturbances in the process.

High investment cost, low efficiency of the laser sources, and lack of control over the cladding process are disadvantages of the use of this technology in coating and prototyping processes. However, with continued technological developments in high-power diode lasers (HPDL), fiber lasers, and sophisticated knowledge-based controllers, the laser cladding process shows a great industrial potential for use in metallic coating and prototyping applications.

1.4 History of Laser Cladding

The invention of the first working laser by Maiman [40] in the 1960's was a breakthrough in science. Immediately after this invention, scientists claimed that the laser was the answer to a multitude of scientific problems that might not have been even known during those years. These problems had arisen in many areas resulting in lasers being adapted to many technologies to dissolve the problems with their unique features. One of the areas that benefited from the lasers technology was material processing, which was rapidly developing in the 1970's when the efficiencies and power of commercial lasers became higher and higher. The development of high-power gas lasers (e.g., CO_2 lasers) in 1975 made laser welding, cutting and metal hardening possible in that decade. Among the laser material processing technologies, laser cladding was used by Gnanamuthu at Rockwell International Corporation in Thousand Oaks of California in the late 1970's [41]. A pre-placed laser cladding method was used to investigate the feasibility of the process in applying dense ceramic cladding to metallic workpieces.

At about the same time, several research groups around the world began projects to develop apparatus and systems for development and improvement of the process. Among these groups, the project conducted by William M.

Steen first at Imperial College of University of London, England and subsequently at Liverpool University, where he moved in April 1988, had a great impact on the development of laser cladding technology [6, 42]. He along with Vijitha Weerasinghe introduced laser cladding by powder injection to academia and conducted a number of projects to evaluate the developed process [43, 44, 45, 46]. The other research group, led by Jyoti Mazumder, at the University of Illinois at Urbana-Champaign, Urbana, USA, contributed many fundamental principles to this area in the 1980's. Mazumder's group not only developed models for this process and studied the mechanism of the process [47, 48, 49], but they also applied the technology to many metals and ceramics to investigate their potential for cladability, and also wear and corrosion resistance [50, 51, 52, 53, 54].

A review of the literature shows that the number of papers and patents related to this technology increased significantly in the 1980's. These papers disclosed the devices for enhancement of the technology, such as development of powder feeders, cooling systems, hemispherical reflecting device for re-absorbing the reflected light, etc. [55]. The applications of the technology for wear and corrosion resistant alloys were also reported by many research groups in the 1980's [56, 57].

The features of this technology received attention from industry in the 1980's as well [58]. Laser cladding was identified as a process with a significant edge over the conventional processes for wear and corrosion resistant coating. The research projects being conducted by different industries were even ahead of academic projects. The first reported use of the laser cladding by industry was the hard-facing of Nimonic turbine blade interlock shrouds for the RB-211 jet engine at Rolls Royce in 1981. In 1983, at Pratt and Whitney, the nickel-base alloy turbines of JT8 and JT9 engines were hard-faced using pre-placed laser cladding [59]. Hard-facing of turbine blade shroud tips and z-notches by laser cladding continued to gain acceptance by different companies. The technology was being accepted by leading engine manufacturers such as General Electric, Pratt & Whitney, Allied Signal, Rolls-Royce, Allison, Solar and MTU. From a commercialization point of view, several companies, such as Avco Everett Metalworking Lasers Inc. and United Technologies Industrial Lasers Inc. were established in the 1980's to address the needs of industry for metallic coating and repair in North America and Europe.

In the automotive industry, laser cladding technology was transferred to the market for the engine valve seat coating by some European and Asian automotive companies, such as Fiat [58], Toyota [60], and Mercedes Benz.

In the component repair market, laser cladding brought a huge amount of consideration in the 1980's. Laser cladding was successfully utilized for rebuilding and coating of the H-dimension (airfoil section thickness) of worn turbine vanes, the tip of the turbine blades, and turbine bolts [58, 61, 36, 62, 63]. A number of different companies and research groups around the world have utilized laser cladding technology for turbine blade repair, including Huffman Corporation and Gorham Technologies in the USA, Starrag in Switzerland, Sultzer in the Netherlands, SIFCO Turbine Components in Ireland, and many others.

Another application of laser cladding, rapid prototyping or layered manufacturing, received a great deal of attention in the 1990's and continues to be explored in the new millennium. In 1986, a new process for prototyping complex parts called "stereolithography" was patented. This process used ultraviolet lasers to selectively cure photo polymer materials. In 1988, the first commercial stereolithography machine was sold and a new industry in rapid prototyping was established. Stereolithography gave product developers the ability to quickly and accurately visualize, iterate, optimize, and fabricate new designs directly from a three-dimensional CAD solid model. Although most commercial systems used polymers and photopolymers, the industry was looking for features to rapidly fabricate the metallic prototypes that could be directly used in real machines. Global competition was also forcing product manufacturers to look for new ways to reduce new product design time and manufacturing costs. In response to these demands, efforts began to utilize laser cladding technology for the development of machines for direct metal prototyping.

At the University of Illinois at Urbana, the Mazumder research group extended their project to the development of systems for rapid prototyping, which was later called "direct metal deposition" (DMD^{TM}) [64]. The group examined building parts in one and two dimensions, taking into consideration both the time and cost involved in the process compared with traditional methods. Due to the success of their project, the research group moved to the University of Michigan to conduct their research with more emphasis on automotive manufacturing. In the late 1990's, the developed technology was licensed to Precision Optical Manufacturing Inc. (POM Inc.) at Plymouth, Michigan to supply molds and dies fabricated by the developed technique to the automotive industry of the Michigan area.

Many other research and development groups initiated projects to develop methods for prototyping metallic parts based on laser cladding by powder injection. Among them, Sandia National Laboratories, which is a multi-program laboratory operated by the Lockheed Martin Corporation, was funded by the Departments of Energy of the US government to conduct research for development of laser near shape fabrication methods. The University of Liverpool research group, led by Steen, also began projects for laser direct manufacturing, which contributed extensively to this field [65, 66].

In the late 1990's, a research group under the leadership of Xue and Islam of the Integrated Manufacturing Technologies Institute (IMTI) of National Research Council (NRC) of Canada developed apparatus and methods for layered manufacturing called "laser consolidation" [19, 20, 21, 22]. Their achievements had a great impact in this field due to the unique surface quality of the parts produced using their technique.

In the last few years, a research group at the University of Waterloo conducted research for the development of an intelligent laser cladding apparatus.

The main focus of the research is in the direction of development of intelligent modeling techniques and knowledge-based controllers for the process. These knowledge-based controllers will be eventually used in an autonomous laser cladding machine, which can not only deposit a wide range of alloys, but can also make the complex shapes without the need for the presence of specialists [31, 67, 68].

The flexibility of laser cladding is beginning to be recognized by many industries and research groups. The potential of this technology is great as research groups continue to contribute to its growth through research programs and training of students in laser cladding techniques technology.

1.5 Applications and Market Opportunities

As mentioned earlier, laser cladding has several diverse applications. In the following sections, various attempts by research groups and industry to adapt the process to different applications are explained.

1.5.1 Coating

Coating results in deposition of a thin layer of material (e.g., metals and ceramics) onto the surface of a selected material. This changes the surface properties of the substrate to those of the deposited material. The substrate becomes a composite material exhibiting properties generally not achievable through the use of the substrate material alone. The coating provides a durable, corrosion-resistant layer, and the core material provides the load bearing capability. A number of different types of metals, such as chromium, titanium, nickel, copper, and cadmium, can be used in the metallic coating process.

There are many coating deposition techniques available. However, selecting the best depends on many parameters such as size, metallurgy of the substrate, adaptability of the coating material to the technique intended, level of adhesion required, and availability and cost of the equipment.

Although laser cladding has the potential for utilization in different industrial divisions for metallic coating, its application to metallic coating is limited due to the high cost and the low process speed. However, with improvement of laser efficiency, reduction in the cost of lasers, and the development of new generation of lasers such as high-power diode and fiber lasers, there is a strong potential for laser cladding to be widely used for coating applications in several major industries. Another indication of the potential of laser cladding for coating of a variety of materials is the increase in the number of published papers and reports concerning the technology in the recent years. Based on information from the Compendex search engine, the number of papers dealing with applications of laser cladding to coating of different materials has risen from 620 papers in the 1990's to more than 750 papers from 2000 to 2004.

The majority of published papers related to the metallic coating by laser cladding address the use of several major materials in aerospace, medical, and automotive industries. Titanium-based alloys [69, 70, 71, 72], nickel-based superalloys [73, 74, 75, 76, 77, 78], and cobalt-based alloys [79, 80, 81] are some of the important alloys that are deposited on different substrates such as unalloyed steels, alloyed steels, hardened steels, stainless steels, aluminum alloys, cast irons, and nickel or cobalt-based alloys. POM Inc. in Michigan performed the deposition of wear-resistant and high-temperature materials (e.g., cobalt-based Stellite and nickel-based alloys) onto tool surfaces that are exposed to harsh high temperature, thermal shock environmental conditions, to increase their lives [82].

Recently, the biocermics coating on titanium alloys was also performed by laser cladding; the coated parts are then used in orthopedic implants with a calcium phosphate layer in order to promote the growth of the bone when the implant is inserted in the body [83]. Laser cladding along with other laser surface treatment methods has also been examined for the production of glassy metallic layers, which provide superior resistance against wear and corrosion [84].

The most leading metallic coatings market for laser cladding is the coating of commercial aircraft gas turbines. The world original equipment manufacturer's (OEM) market for coatings used in commercial aircraft gas turbine sections is estimated to be approximately $460 million per annum, based on the information released by Gorham technologies. In response to demands for the development of a higher efficiency, lower cost industrial gas turbine engine, high-strength, high-temperature capability materials, such as nickel-based superalloys, are coated on the turbine bodies to meet the needs of the hot gas path components. The shroud interlock between turbine blades has been also hardfaced with Triballoy to reduce the wear due to sliding between blades during the warm up and cold down the engine. Laser cladding has been recently used in this sector to deposit the mentioned materials on the spacecraft components. With recent technological improvements in the new generation of lasers, it is expected that laser cladding technology will take on an increasingly important role in this market.

In addition, laser cladding also has several other coating applications for industrial parts to produce surfaces, that are resistant to abrasive, erosive and adhesive wear; wet corrosion; and high temperature oxidation and corrosion. Some of the products that have received metallic coating by laser cladding are:

- Shafts used in drilling tools
- Engine valve seats

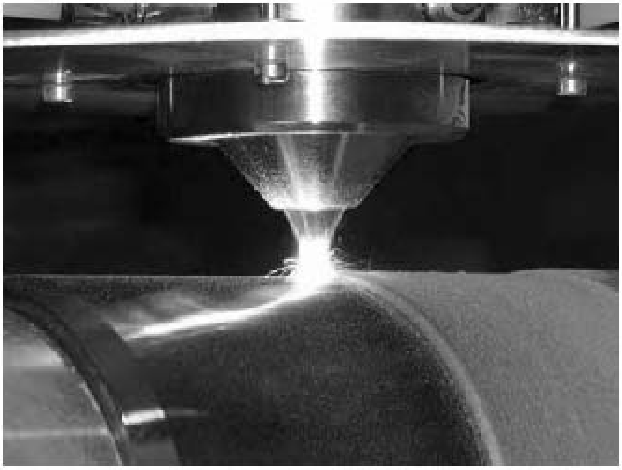


FIGURE 1.1
Coating of oil drilling tools by laser cladding (*Source*: Courtesy of Fraunhofer Institute for Material and Beam Technology, Germany [85]).

- Tools hardfacing
- Hydraulics pump components
- Molds

Figure 1.1 shows one of the applications of laser cladding for coating of oil drilling tools, which are subjected to significant wear in their operation [85].

1.5.2 Parts Repair and Refurbishment

A major application of laser cladding is in the repair and refurbishment of high-value components such as tools, turbine blades and military components. Laser cladding can be used to rescue high-value components which are overmachined due to the errors in design or machining process. These engineering or machining errors can easily jeopardize the entire effort of the design and manufacturing of high-value tools or components.

Conventional methods use welding to retrieve these damaged components; however, these methods are usually destructive due to the highly distributed temperature over the area of repair. This thermal destruction causes a low mechanical quality, crack, porosity and very short life of the component. Laser cladding can provide a permanent structural repair and refurbishment on many alloys (e.g., aluminum alloys) that are generally considered unweldable by conventional methods. The success of the laser cladding technology in this area is due to the small heat zone, rapid solidification, increased cleanness, lower dilution, and increased controllability over the depth of heat-affected zone. An example of the repair by laser cladding of a shell made from high strength aluminum alloys (i.e., unweldable 7075/7175 aluminum alloys) is shown in Figure 1.2. This shell is used in undersea weapon components, which sustain wear and damage as a result of handling, operation and the corrosive nature of the saltwater environment. Laser cladding has been applied to repair of such components. The results are promising such that the repairs are permanent. They stop corrosion and increase structural integrity [86].

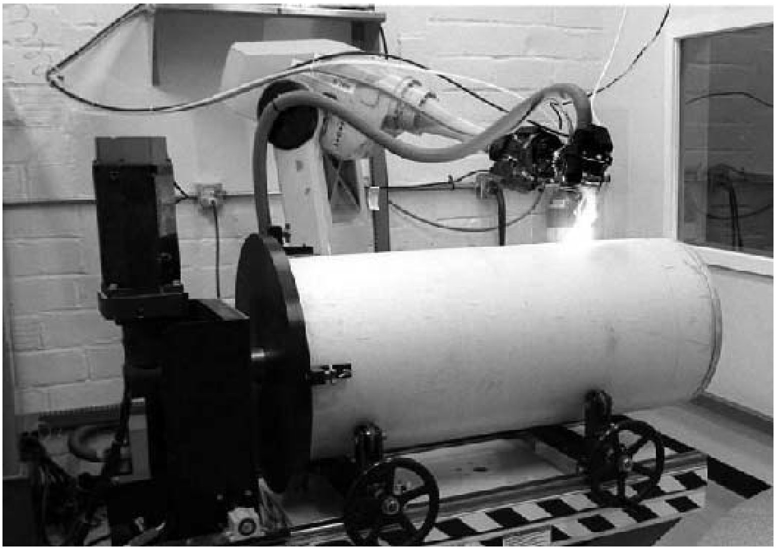


FIGURE 1.2
Repair by laser cladding of a shell made from high-strength aluminum alloys (*Source*: Courtesy of the Naval Undersea Warfare Center (NUWC), USA).

One of the other areas, in which laser cladding plays an important role is turbine blades repair and refurbishment. Turbine blades are under very high thermal and mechanical stresses (i.e., centrifugal force and thermal gradient) in an aggressive environment. The blades usually suffer a variety of damage during operation, such as creep, life cycle fatigue, hot corrosion, impact of external particles on their surfaces, etc. Therefore, in terms of maintenance requirements, manufacturing difficulties and costs, the blades are the most critical item of today's gas turbines. As a result, blade manufacturing and maintenance companies are looking for repair technologies that not only repair the defected blades superiorly, but also maintain the original mechanical and metallurgical features of the repaired components.

The low heat input property of laser cladding is the most unique characteristic of this technology that makes it highly attractive for jet engine components repair applications, in which metal depositions are required to be applied to superalloys. These superalloys are highly susceptible to strength loss and physical distortion when exposed to excessive temperature variations. Conventional repair techniques, such as tungsten inert gas, metal inert gas, plasma and electron beam welding, usually cause a large amount of heat during weld metal deposition which results in large temperature increases in the body of the component. The temperature increases above certain limits cause the base alloy to be weakened. This weakening along with component distortion can cause irreversible damage to the part. In contrast to conventional weld repair, the laser cladding process transfers heat only to localized areas, typically using a 0.5 mm diameter laser beam. As a result, heat inputs are at least one order of magnitude lower than the heat input incurred during conventional welding, which results in reduced residual stresses and distortion and a substantially smaller heat-affected zone [87].

An even greater repair market potential exists for the application of laser cladding in turbine engines. Advanced gas turbines, are now being fitted with single crystal and directionality solidified components in order to achieve maximum thermal efficiencies by operating the engines at higher turbine inlet temperatures. In the fabrication and repair of such engines, laser cladding is rapidly being recognized as a critical and essential technology. In some cases, it is also recognized as the only repair technology because the oriented airfoil castings are highly susceptible to re-crystallization when subjected to the intense heat induced during conventional weld repair [36, 20, 62].

Figure 1.3 shows the application of laser cladding to repair a tip of turbine blade performed in Sulzer Elbar, which is one of the constitute companies that form Sulzer Turbomachinery Services [88]. The turbine blade is made from precipitation-hardened CC-superalloy Inconel 738.

The size of the repair and refurbishment market is immense. However, there seems to be no concrete data that defines the size of this market. One of the key aspects of this market is aircraft engine components maintenance. Aircraft engine maintenance accounts for 30 percent of the total cost of aircraft maintenance, which is a good indication of the size of available market for the technology. The global market of the repair of aircraft engine turbines and compressor blades, used in civil and military applications, has been estimated to be about 1.2 billion dollars per annum [89].

1.5.3 Rapid Prototyping and Tooling

A new and major application of laser cladding is in rapid prototyping (RP) and rapid tooling (RT) markets for rapid fabrication of complex components and tools. Production of tools such as cutting tools, dies and molds, which have traditionally been fabricated by highly-skilled tool and mold makers

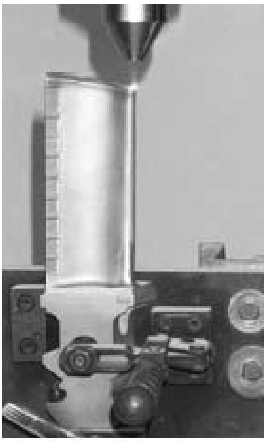


FIGURE 1.3
Application of laser cladding to repair of a tip of rotor blade made of precipitation-hardened CC-superalloy Inconel 738 (*Source:* Courtesy of Sulzer Elbar, The Netherlands).

using CNC and electrical discharge machining, has always suffered from cost problems and slow turnaround times for manufacturers. If tools are fabricated late, market opportunities will be missed, which is often the death knell for a new product. As a result, rapid tooling has received significant attentions in recent years from manufacturers looking for technologies that are able to produce high-value tools and components with high integrity, high density, and good surface quality, at low manufacturing costs with a short manufacturing time [90].

The market for RP and RT is significantly large with a significant annual growth. The worldwide tooling market is estimated in the tens of billions of dollars per annum. The market size for RP was approximately $800 million in 2002, when 4.5 million parts were produced by the available units in the market [91]. The applications of RP in North America are categorized within the following sectors: 25 percent consumer products, 24 percent automotive, 11 percent business machines, 11 percent medical, 8 percent academic, 8 percent aerospace, 5 percent government and 8 percent other. However, many of the customers for RP units are looking for a reliable metallic prototyping machine that will not only be intelligent enough to prototype the components without the need for highly qualified personnel, but that will also be robust enough to produce the components with high quality [92].

Laser cladding technology has the potential to address the current gap for metallic rapid prototyping. Laser cladding has demonstrated promising capabilities for tools and components fabrication. A recent survey by the National

Center for Manufacturing Science (NCMS) revealed that laser cladding could reduce the time of die production by 40 percent, if the process is controllable over the dimensions of the product. It has been reported that for the production of surgical tools, the technology can reduce 62 steps into 7 steps [14].

In recent years, researchers have been working on enhancement of laser cladding to construct prototypes and production tooling, even for precision metal parts made from different commercial alloys such as H13 tool steel, 316 and 304 stainless steels, nickel-based superalloys (e.g., Inconel 625, 690, 718, 2024), aluminum, composite, and titanium-based material (e.g., Ti-6Al-4V). The feature of the technology provides the functionally graded material deposition capability, which are applicable in many aerospace components in which a light weight but hard external surface are requested.

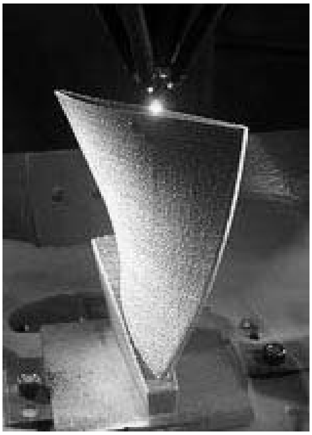


FIGURE 1.4
Fabrication of a blade by LENS® (*Source*: Courtesy of Sandia National Laboratories).

Laser Engineering Net Shaping™ (LENS ®) [12], developed at Sandia National Laboratories, is one of the rapid metal forming processes that has demonstrated the feasibility of laser cladding to produce near-net shape metal parts. The system utilizes a CAD solid model to build an object one layer at a time. The solid model is sliced into a series of layers that are subsequently used to generate the motion to deposit each layer of material. These layers are then deposited in a subsequent fashion to build the entire part.

Figure 1.4 shows the fabrication of a blade by the LENS® technology. Also, Figure 1.5 shows a special housing which has been fabricated by LENS® to reduce the secondary machining time.

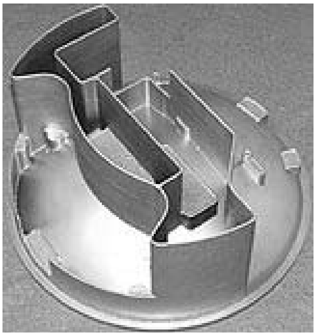


FIGURE 1.5
A housing part fabricated by hybrid fabrication method including the LENS® technology (*Source*: Courtesy of Sandia National Laboratories).

Among the materials used for part manufacturing and prototyping, titanium-based alloys have received significant attention due to their use in the aerospace industry. Many efforts have been made to obtain the required processing parameters to produce high-quality titanium alloy material, in terms of mechanical and metallurgical properties. One of the premiere companies in this field is AeroMet Corporation, which has developed the "laser additive manufacturing" (LAM^{SM}) technology. Their results demonstrate the capability of producing shaped structures (e.g., ribbed structural) from Ti, Ti-6Al-4V and other alloys such as Ti-5Al-2.5Sn, including extra low interstitial (ELI) grades. Figure 1.6 shows several components made by LAM^{SM}, which were then machined to meet the required dimensions and tolerances. The required production time and the quality of products are significantly better than those for forging methods. AeroMet's current production facility includes an 18 kW CO_2 laser and a five-axis manipulation capable of producing component sizes within $3 \times 3 \times 1$ m. Figure 1.7 shows the AeroMet equipment for performing LAM^{SM}.

Another key player in components manufacturing by laser cladding is the IMTI-NRC in Canada. As mentioned earlier, the technology used by the NRC is called "laser consolidation". This technology can produce metallurgically sound parts from IN-625, 316L Stellite 6, and M4 without porosity and crack. The samples showed an excellent dimensional accuracy and surface finish. The produced parts from LC IN-625 alloy and 316L stainless steel were shown to have stronger strength than the respective cast and even wrought materials [21, 19]. Figures 1.8 and 1.9 depict some of the parts fabricated by the NRC. Figure 1.8 depicts the components of a robot fabricated by laser consolidation to evaluate the potential of the process as a rapid functional prototype manufacturing process for the production of structural components using Ti-6Al-4V alloy. The figure also indicates the steps of production. These parts

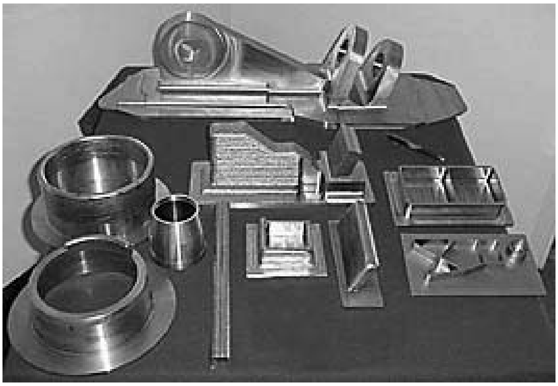


FIGURE 1.6
Different components fabricated by laser forming technology (*Source:* Courtesy of AeroMet Corporation, USA).

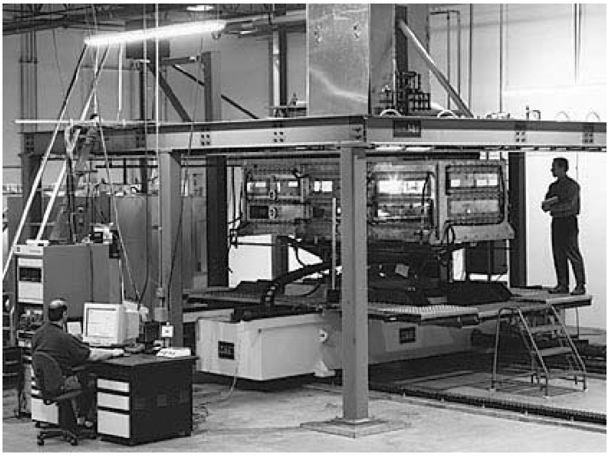


FIGURE 1.7
AeroMet equipment including a 18 kW CO_2 laser for performing laser forming (*Source*: Courtesy of AeroMet Corporation, USA).

were used in the Advanced Robotic Mechatronics System (ARMS) project, which was initiated by MD Robotics and supported by the Canadian Space Agency (CSA) [22].

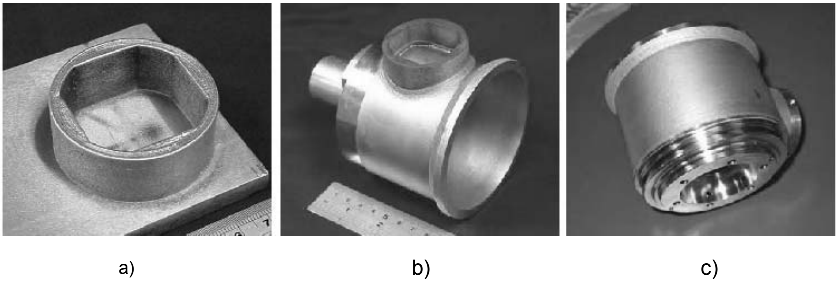
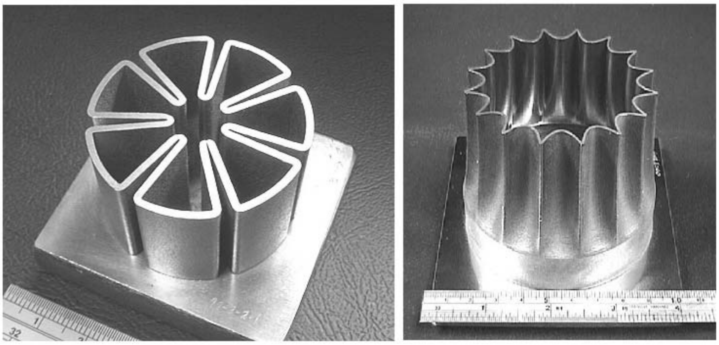


FIGURE 1.8
A robot's joint, fabricated by laser consolidation made from Ti-6Al-4V: a) original interface on the flat substrate, b) fabrication of housing on the interface, c) joint after final machining (*Source*: Courtesy of the NRC's Integrated Manufacturing Technologies Institute).

Figure 1.9 depicts two industrial parts: Figure 1.9a shows a part made from wear-resistant Stellite 6; Figure 1.9b shows a part which is a half-part of a complex flextensional transducer shell made from IN-625 [21]. The produced shell has an excellent dimensional accuracy and wall integrity.

Direct metal deposition (DMD) is being developed to fabricate molds and dies as well as for parts repair using the laser cladding technology. The wide application of DMD in the aerospace and medical fields is due to its large potential cost savings. Koch et al. [93] demonstrated the application of laser-aided DMD to generate components with a dimensional accuracy of 0.25 mm using a closed-loop control of process parameters. The dimensional accuracy of their part depends on the uniformity and repeatability of the process [14]. The commercialization of this technique, which incorporates a closed-loop system, has been successful and a machine called DMD5000 has been introduced to the market by POM Inc., Michigan. This machine provides features for direct metal fabrication. The DMD5000 machine is an integration of a 5-kW CO_2 laser integrated with a flying optic, a gantry robot plus a XY table CAD/CAM system, and several special powder feeders. The machine has a workspace with size of $1.5 \times 0.5 \times 0.45$ m.

Laser cladding technology has been under investigation at the University of Waterloo with more emphasis on the development of an automated machine for this technology. The developed machine has been used for production of complex parts made from H13 and nickel-based superalloy. The developed



a) b)

FIGURE 1.9
Two fabricated parts by laser consolidation: a) a component made from Stellite 6, b) a complex flextensional transducer shell made from IN-625 (*Source*: Courtesy of the NRC's Integrated Manufacturing Technologies Institute).

technology integrates vision-based detectors and knowledge-based controller with conventional laser cladding equipment to control the process parameters such as laser power, process speed, and powder feed rates, which enables control of the clad geometry in real-time. Figure 1.10 shows a logo made from H13, which was fabricated using the system developed at the University of Waterloo.

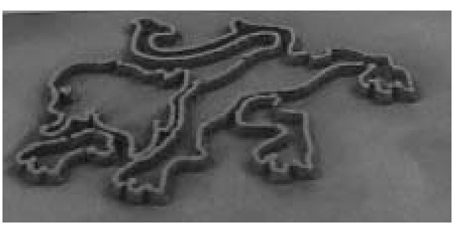


FIGURE 1.10
A logo fabricated from H13 tool steel at the Mechanical Engineering Department of the University of Waterloo.

1.6 Future Direction of Laser Cladding Technology

Laser cladding technology is in the early stages of commercialization and will offer a revolutionary new manufacturing technique to the industry in the new millennium. Due to its promising features, many industries keep their eyes on the technology.

Research groups and companies involved in the development of the technology should canalize their efforts in several main directions to resolve the current shortcomings of this technology. The main focus of research efforts should be the development of autonomous machines for the process, which can not only deposit a wide range of alloys, but can also make complex shapes without the need for the presence of specialists. The development of an automated machine may not be possible without string collaborations between the researchers with different disciplines. The development of a knowledge-based controller for such a machine needs expertise of scientists with control, automation, and also metallurgical backgrounds.

Additional research efforts should focus on increasing the speed of the process as the current processing speed is slow compared to the competitive techniques such as plasma and thermal spraying. Laser cladding applications to the aircraft industry and the effects of laser cladding on substrate also require further investigation. The investigation of laser cladding and effects on the applications requires an understanding of the process and the relationship between laser energy, process speed, powder feed rate, and mechanical and metallurgical properties. Therefore, efforts should be dedicated to modeling of the process.

In the turbine blade repair market, customers are looking for a machine that has the capability to repair the turbine blade in-situ without removing the blades from the rotor. To do this, it is necessary to develop a sophisticated positioning device that will provide a sufficient maneuverability around the rotor. The capability of cladding on an inclined surface is also essential for in-situ turbine blade repair.

In the recent years, micro- and nanotechnology have received a significant attention. Scientists say any technology can have applications in micro- and nanotechnology, if it can be miniaturized in the right fashion. Having said that, laser cladding has a great potential to benefit these cutting-edge technologies [94, 95], as laser cladding techniques can provide a revolutionary technique for maskless micro structure fabrication. In recent years, Optomec Inc., a company in the USA, has developed a process called M^3D, which makes it possible to coat different substrates in the range of 10 to 50 μm. The 10 μm deposition makes it attractive particularly for space-limited applications in the electronic technology. The concepts of their work are based on the pre-placed laser cladding process; however, the Optomec Inc.'s technology utilizes the spray of liquid droplets mixed either with metals or organic elements. Post-heat treatment is then performed by the laser to sinter the metal particles. Figures 1.11 and 1.12 show two samples made using the Optomec Inc.'s technology. Figure 1.11 shows silver lines with 50 μm width deposited over a 500 μm step of a micro-mirror. Figure 1.12 shows a tapered spiral GPS antenna. Due to the fascinating features of this technology, such as deposition on a non-planar micro substrate with 10 μm coating width, it is anticipated that many research groups will concentrate on this field in the Micro Electro Mechanical Systems (MEMS) prototyping development.

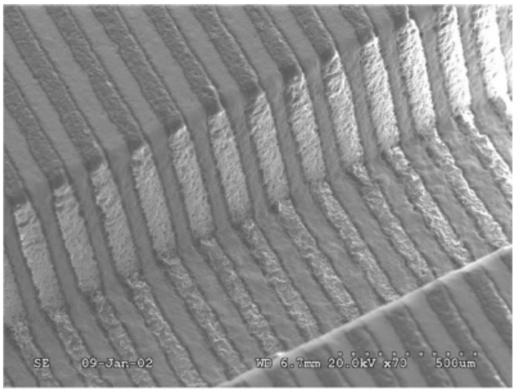


FIGURE 1.11
Silver lines with 50-micron width deposited over a 500-micron step by M^{3}D (*Source*: Courtesy of Optomec Inc., USA).

Recently, the NRC of Canada successfully tested laser cladding technology for the use in fabrication of space-related structures, such as the main parts of a robotic arm. These tests resulted in the production of robotic arm components with excellent mechanical properties, which is a significant indication of the potential of laser cladding technology for in-space manufacturing facilities [22]. In June 2003, the NASA Marshall Space Flight Center brought a variety of national engineering and manufacturing specialists to Huntsville, Alabama, for a workshop in "In-Space Manufacturing of Space Transportation Infrastructure". This workshop addressed strategies for developing a robust in-space transportation infrastructure that may eventually include permanent refueling stations and maintenance platforms in space, as well as cargo vehicles that haul supplies across the shipping lanes of space. A discussion of the characteristics of laser cladding technology identified its potential to lead in-space manufacturing processes, as it would allow space dwellers and explorers to quickly design and produce replacement parts in the space. Therefore, it is anticipated that the laser cladding process will play an important role in the

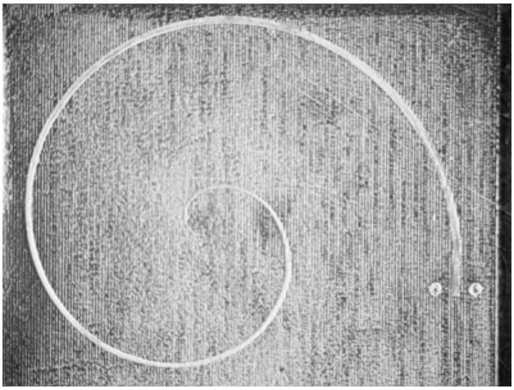


FIGURE 1.12
Tapered spiral GPS antenna by M^3D technology (*Source*: Courtesy of Optomec Inc., USA).

development of possible in-space manufacturing methods in the near future.

Last but not least, market development should be taken into consideration as a very important issue for exploring the technology by the manufacturing sectors. A number of industries still consider the laser a "fancy" device. This results in a large technological barrier between conventional and advanced manufacturing experts. This barrier has to be brought down through a close dialog between these two groups along with end-users. It is important to expect users to request appropriate features for a particular process; therefore, a partnership between the conventional and advanced manufacturing experts should be conducted to satisfy end-users. The authors believe that breakthroughs in laser cladding will require a hybridization of advanced and conventional techniques, which may not be possible without a close interaction between conventional and advanced specialists on one side and end-users on the other side.

Education of highly qualified people in this area can minimize the current technological gap between the advanced and conventional manufacturing sectors. Unfortunately, current laser material processing programs in universities are very limited, most likely due to the lack of high-power laser in institutes. In Canada, just a few universities are equipped with high-power lasers; therefore, the opportunities for education in the field of laser material processing are very limited. In addition, the field is multidisciplinary and requires training in a number of different scientific fields, such as laser, optics, automation, control, robotics and material science.

1.7 Looking Ahead

This book consists of seven chapters. An introduction to the potential applications of laser cladding technology in industry was explained in Chapter 1. Chapter 2 reviews the background of laser cladding. In Chapter 3, the equipment used in laser cladding (i.e., laser, positioning device, and powder feeder and nozzles) will be explained. In Chapter 4, the physics of the process will be discussed and different modeling approaches for the process will be presented. The application of experimental-based modeling techniques to laser cladding including stochastic and artificial neural network techniques will be also addressed in Chapter 4. Chapter 5 addresses the control aspect of the technology, as well as the design, simulation and implementation of several classical and fuzzy controllers applied to laser cladding. Chapter 6 explains the mechanical and metallurgical characteristics of laser cladding for different metallic alloys. Also, the effects of process parameters on the clad bead quality and a methodology for evaluation of clad bead quality using the combined parameters will be developed in this chapter. Chapter 7 ends the book by explaining safety issues related to the laser and powder materials.