T.2 : Feature based Design and Manufacturing Technology using Laser Rapid Manufacturing

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Introduction

One of the methodologies of manufacturing technology has been conventionally dominated by material removal or subtractive processes since ages. These methodologies included not only the machining processes, but also the formative processes like- casting and forming. The introduction of "*Streolithography*" in 1987 marked the dawn of a new generation of the processes which is now popularly known as "*3D printing*" or "*additive manufacturing*" [1]. During last couple of years, this technology is being termed as technology opening the gate of third industrial revolution. The additive technology being developed at RRCAT is known as Laser Rapid Manufacturing (LRM). The technology is capable of fabricating engineering/prosthetic components directly from a solid model. At the process end, it is an extension of laser cladding in 3D. In this technique, a solid model of the component to be fabricated is made either by 3D imaging system or by designer using computer aided design (CAD) software or by math data as an output of numerical analysis. Thus obtained model is sliced into thin layers along the vertical axis. The thin layers are converted into corresponding numerical controlled (NC) code and are sent to LRM station in suitable format (e.g. G&M code). LRM station employs a laser beam as a heat source to melt a thin layer on the surface of the substrate/deposited material and feed material to deposit a new layer as per shape and dimensions defined in NC code. A number of such layers deposited one over another and it results in 3D components directly from the solid model. Figure T.2.1 presents the general scheme of LRM technique.

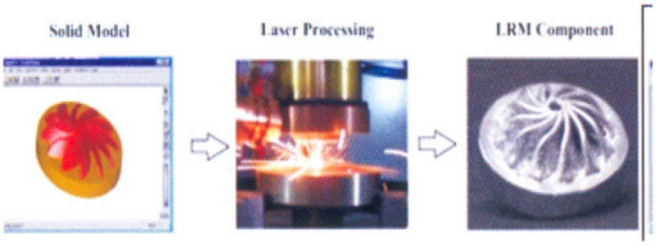


Fig T.2.1: General Scheme of LRM [1].

LRM eliminates many manufacturing steps such as materials-machine planning, man-machine interaction, intermittent quality checks, assembly and related human errors etc. Therefore, LRM offers many advantages over conventional subtractive techniques, such as reduced production time, better process control and capability to form functionally graded parts. It is also an attractive candidate for refurbishing applications because of low heat input, limited dilution with minimal distortion and capability of adding finer near-net shaped features to the components [1].

Recently, LRM found wide global attention due to steep step towards feature based design and manufacturing (FBDAM). FBDAM is systematic deployment of multiple materials through an integrated design and manufacturing approach in advanced engineering systems. This integrated approach considers all aspects of design (definition/specification, modelling, material selection, analysis, optimization and evaluation) and manufacturing (process selection, production planning, raw material shape and size, tool design/selection and CNC programming) to realize an optimized solution for immediate delivery of superior quality product with maximum possible features at lowest possible price.

Global scenario of LRM

LRM is finding wide-spread response from the researchers as well as industries. The list of its applications is appending very fast. By large, LRM is circumventing the material and manufacturing related industrial hurdles and is poised to conquer oil, gas, geothermal, and mining industries through its innovative deployment, in addition to the traditional sectors, i.e., automotive, manufacturing, defense, and medical industries. Manufacturing techniques, similar to LRM, are being developed with different names at various national laboratories/universities around the world[2]. At Sandia National Laboratory, USA, Laser Engineered Net Shaping (LENS™) is being developed with prime focus on creating complex metal parts in single day. National Research Council, Canada is developing Freeform Laser Consolidation for manufacturing of structural components for advanced robotic and mechatronic systems. Automated Laser Fabrication (ALFa) is being developed to produce low cost tungsten carbide components at the University of Waterloo, Canada. Selective Laser Cladding (SLC) at the University of Liverpool, UK and Direct Metal Deposition at the University of Michigan, USA are being used for depositing critical surfaces on prime components. Laser Powder Deposition (LPD) at the University of Manchester UK and Direct Metal Deposition/Laser Additive Manufacturing at Fraunhofer Institute, Germany are being augmented for the fabrication of high performance materials. The researchers at Tsinghua University, China are working on diverse area and evaluating the potential of technology for the development of graded Ti alloys for aeronautical, Nickel alloys for power plants and various in-situ repair applications. Thus, the ongoing global research is spearheading towards the deployment of this novel fabrication technology for improving qualities of the products, possibilities to engineer integrated multi-materials and multi-functional components and enhancing economic or procedural benefits [3].

Realizing the importance and potential of this technology, an activity of LRM was initiated in year 2003 at RRCAT. A comprehensive study for the fabrication of components using a number of pure metals/alloys and hard metals/ceramics in metal matrices have been carried out. RRCAT has two LRM stations, one is based on 3.5 kW CO_2 laser while another is based on 2 kW fibre laser[1]. The following section briefly presents some of the important development carried out using LRM.

LRM of High Performance Surfaces

In the realm of the hard materials, tungsten carbide (WC) in Co/Ni matrix is a popular choice for dies, tools, and wear-prone parts. Hence, WC reinforced nickel matrix through various composition of Inconel-625 were deposited on SS316L substrate using a 2 kW fiber laser based rapid manufacturing system and their erosion wear behavior was investigated[4]. In the study, Inconel-625 alloy (particle size: 45 to 105 µm) was used to provide nickel matrix for reinforcing WC particles. A number of test trails were made to identify the processing window for laser rapid manufacturing of continuous multi-layer overlapped deposition at various powder compositions. It was observed that the deposit got delaminated during the laser rapid manufacturing of second layer for 5% weight Inconel 625 due to insufficient wetting material. This problem was not observed for higher compositions. Figure T.2.2 presents a typical laser rapid manufactured WC reinforced nickel matrix on 316L Stainless Steel.

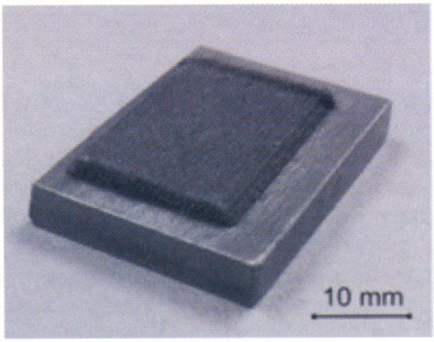


Fig.T.2.2: Typical laser rapid manufactured WC Reinforced Nickel Matrix on 316L SS.

The microscopic examination revealed that the dendritic microstructure of Ni-matrix originating from WC particles due to directional quenching (Figure T.2.3). The erosion wear performance of the laser rapid manufactured samples was evaluated as per L25 orthogonal array using Al_2O_3- air jet erosion test rig for Inconel-625 in deposit ranging 5-25 % weight, erodent jet velocity ranging 10-50 m/s, jet impinging angle ranging 0-68° and substrate temperature 50-250 °C.

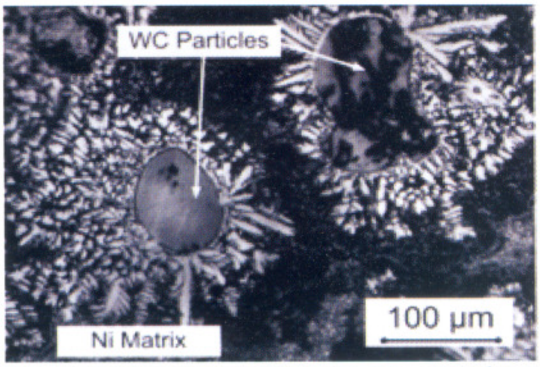


Fig.T.2.3: Micrograph depicting the WC particles in Ni matrix with dendrites.

Figure T.2.4 summarizes the contour plot of erosion wear rate (EWR) for various Inconel-625-WC composition and Jet impinging angle at erodent jet velocity = 30 m/s and substrate temperature = 150 °C. The study demonstrated that WC reinforced Ni-matrix laser rapid manufactured with 18 wt% of Inconel 625 has least EWR for the range of parameters under investigation. The erosion wear rate of laser rapid manufactured WC-Inconel-625 surface was nine times lower than that of bare SS316L surface.

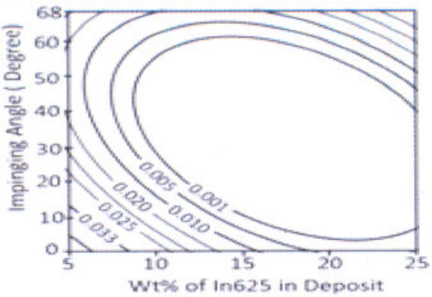


Fig. T.2.4: Contours depicting EWR for various composition and impinging angle at erodent velocity 30 m/s and substrate temperature 150 °C

The outcome of the study will be used for laser hardfacing of various engineering components, including seat and spool of valves.

LRM of Colmonoy-6 Bushes

Nickel-based alloys "Colmonoy" are preferred for hardfacing applications in nuclear power plants due to their outstanding wear resistance, high hardness at elevated temperatures and low induced radioactivity. Pre-fabricated Colmonoy-6 bushes are used as substitute to local hardfacing at complicated component geometry having limited accessibility. Conventionally, these bushes are made by casting/weld deposition followed by machining [2]. However, high capital cost for the low volume of fabrication makes it a prohibitive option. Therefore, these customized Colmonoy-6 bushes were fabricated by LRM (Refer Figure T.2.5 (a)) at our laboratory as an alternative to conventional processing [1].

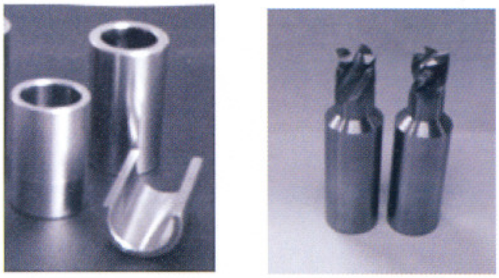


Fig. T.2.5: LRM fabricated (a) Colmonoy-6 bushes (b) WC-Co End-mill

LRM of Cemented Carbide Components

The most commonly produced commercial straight grades of WC-Co (used for machining, mining, metal cutting, metal forming, construction, and other applications)have cobalt contents ranging from 4 to 30% by weight, with grain sizes ranging from 0.5 to 10 microns. In case of conventional WC-Co sintering and continuous wave (CW) laser cladding, it is difficult to fabricate WC-Co deposits without the formation of higher carbides due to uncontrolled local heating and longer interaction time [3]. In laser rapid manufacturing, it could be achieved due to very low heat input, controlled local heating and inherent rapid cooling. Laser rapid manufacturing was deployed for the fabrication of low cost tools by depositing WC-Co on mild steel (refer Figure T.2.5(b)) [3]. The performance of these tools was found to be 80% of the conventionally processed tools.

LRM of Inconel-625 Components

Inconel-625 is one of nickel-chromium based alloys, which is widely used for various naval, aerospace and nuclear applications. Considering its wide spread applications, a number of samples at various processing parameters were fabricated and their mechanical and metallurgical properties were evaluated using standard characterization techniques, such as tensile testing, Rockwell hardness testing, Charpy impact testing, fracture and fatigue testing etc. and the results were found to be compatible with the conventionally processed Inconel-625 [4].

LRM of Functionally Designed Titanium Structures with Graded Porosity

The porous materials, solids with pores/voids, are quite common in nature. Bone, a naturally engineered porous structure, makes birds to fly due to lower density while animals can crawl on the ground due to relatively dense bones. Till recent past, porosity was considered as one of the harmful defects that impede efficiency or functional properties of the manufactured products, limiting its application to non-load bearing components, like filtration, flow control, thermal and/or acoustic management [5]. However, if porous structures with adequate mechanical strength can be produced, they can find direct applications as lightweight structural, functional materials, transportation materials etc. This encouraged research towards the development of porous structures with tailored mechanical properties. Conventional methods of fabricating porous structures, such as furnace sintering technique, space holder technique, replication technique, combustion synthesis technique ferromagnetic fiber arrays technique and vapor deposition technique, have limitations in fabrication of the porous structures with engineered mechanical properties due to inability to control precisely a number of parameters, like-pore-size, shape, volume fraction, pore-distribution, contaminations and their phases etc. Moreover, they cannot be used for generating functionally designed porous structures with graded porosity. Such structures can be fabricated using LRM [4].

Table T.2.1: Mechanical properties of human bone and bio-metals [6]

Material	Density (kg/m^3)	Elastic Modulus (GPa)	Tensile Strength (MPa)
Trabecular bone	110– 260	0.005 – 0.15	137.3
Cortical bone	1200 – 2100	0.5 - 50	130
316L SS	8030	211	650
Wrought Co - Cr Alloy	8330	541	1540
Cast Co -Cr Alloy	8330	241	690
Ti-6Al-4V	4430	121	1000

Stainless steel, Co-alloy, Ti alloys are the most commonly used metals for prosthetic applications due to conformance to bio-compatibility and in-vivo degradation. Table T.2.1 presents mechanical properties of human bone and bio-metals [6]. As there is large mismatch of the mechanical properties between bone and bulk metallic materials, the direct replacement of natural bone with prosthetic having same shape and size yields the *stress-shielding*. Stress shielding refers to the reduction in bone density (osteopenia). In a healthy person, the bones are remodeled in response to the stress that bone is placed under. If the implantation of prosthetics results in decrease in stress on bone, the bone becomes less dense and weaker because there is no stimulus for continued bone remodeling which is required to maintain bone density. As the metals have more density and higher strength, the porous metallic structures are the one of the solutions for stress shielding. The fabrication of prosthetics with porous structure having mechanical properties as that of natural bone is an attractive approach for direct bone replacement. It may further be noted that the properties of bone depend on age, health condition, anatomic site, loading direction and loading mode and they decrease with age, falling ~ 10% per decade. Hence, not only the shape and size of the bone, but also the mechanical properties of the bone needs customization for patient specific requirements.

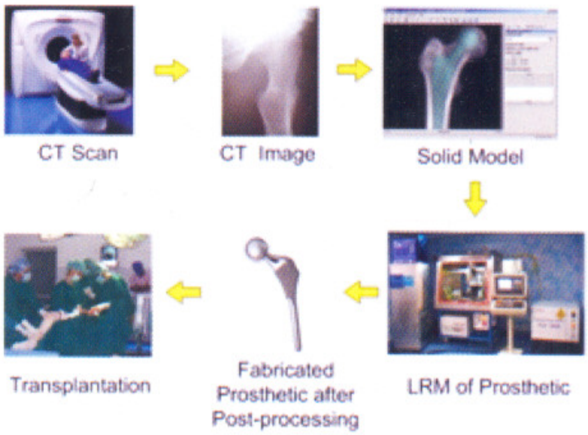


Fig. T.2.6: Road Map of LRM of Prosthetics.

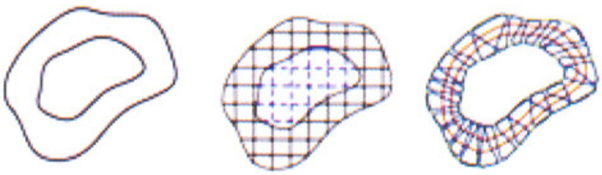
Figure T.2.6 presents the roadmap of LRM of prosthetics. First, a medical image of targeted bone for replacement is obtained from computed tomography (CT) or magnetic resonance imaging (MRI). This image is used to obtain the geometric and topological data for deducing Solid model. The model is then sliced. These slices are used for layer-by-layer fabrication of targeted prosthetic using LRM. In this layered manufacturing approach, the properties of bulk structure are governed by the architecture used for the fabrication of the layer. We have recently developed novel Z-shaped unit cell based architecture for the fabrication of functionally designed structures with graded porosity.

Novel Z-shaped unit cell based architecture

Figure T.2.7 (a) presents typical cross section of a bone. Most of the designed implants fabricated by additive manufacturing are based on regular porosity and follow along the x- and y- directions in the cartesian coordinate. In these methods, the porosity of the designed bone does not conform to the geometry of the replaced damaged tissue and simply approximates, as shown in Figure T.2.7(b). During the fabrication of these designed implants, jumps or motion without deposition is also highly substantial due to the nature of the trajectory, which is independent of the geometry. Such non-continuous and unnatural movements during fabrication degenerate uniformity of the deposited material shape and need to be avoided [7]. Thus, the major constraints for the fabrication of porous structure for bone replacement are as follows:

a. The external and internal surfaces should be conformal to the geometry of damaged tissue.
b. The pore size at the outer perimeter of the structure should be in the range 50 – 400 μm.
c. The trajectory should be continuous and non-overlapped.
d. The trajectory should not be intersecting in the same deposition plane.
e. The trajectory should be capable to generate a manifold, valid and untangled surface.

The newly developed architecture is presented in FigureT.2.7 (c) and it meets the above objectives by following the geometry of the damaged tissue while achieving the design porosity with interconnected and continuous deposition path planning appropriate for additive processes.



(a) (b) (c)

Fig.T.2.7(a) Typical cross-section of bone, (b) Conventional filling pattern(c) Filling using new Z-shaped unit cell based Architecture

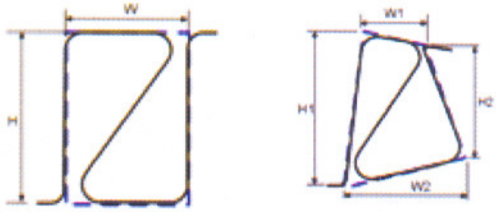


Fig. T.2.8(a) The unit cell of proposed Z-shaped unit cell based architecture (b) Z-shaped unit cell demonstrating adaptability to various shapes

Figure T.2.8 (a) presents a unit cell of new filling architecture. In this architecture, the Z-shaped unit cell is formed and it is repeated for filling the area at each slice. The linear dimensions of H1, H2, W1 and W2 (refer Figure T.2.8 (b)) can be varied as per the available area. If W1 > W2, the resultant unit cell will have shape suitable for top to bottom converging geometry and the unit cell with W1<W2 will have shape suitable for top to bottom diverging geometry. Similarly, the unit cell with H1<H2 will have shape suitable for left to right diverging geometry and the resultant unit cell having H1 > H2 will have shape suitable for left to right converging geometry. The size of the pores at the external perimeter can be controlled by the gap between two tracks at the corners of Z-shape.

LRM and testing of Porous Structures

Using the Z-shape unit cell architecture, Ti-structures up to 60% porosity were at our laboratory. There are four major processing parameters that define the shape and size of the single track. These are laser power, beam spot diameter, scanning speed and powder feed rate. It was observed that the laser power and powder feed rate could be combined by dividing these by scanning speed yielding laser energy per unit traverse length($E_{l/m}$) and powder fed per unit traverse length($m_{l/m}$). The experimental results confirmed the effectiveness of these combined parameters. It was observed that the track width was mainly governed by the beam spot diameter. The ranges of the parameters used in the present investigation were 25.7 - 180 kJ/m for laser energy per unit traverse length and 0.5 – 1.2 g/mm for powder fed per unit traverse length. Table T.2.2 summarizes the processing parameters and corresponding track geometry.

Table T.2.2: LRM processing parameters and corresponding track geometry

Sample ID	$E_{l/m}$ (J/mm)	$m_{l/m}$ (g/mm)	W (mm)	H (mm)
1291807	25.7	0.5	1.2±0.1	0.6±0.1
1291804	36.0	0.5	1.3±0.1	0.5±0.1
1291805	51.4	0.3	1.6±0.1	0.3±0.1
1291801	60.0	0.4	1.3±0.1	0.5±0.1
1291802	72.0	0.2	1.6±0.1	0.35±0.1
1291803	77.1	0.2	2.3±0.2	0.3±0.1
1291809	108.0	0.7	2.2±0.2	0.9±0.1
1291808	120.0	1.2	2.1±0.1	0.9±0.1
1291806	180.0	0.8	2.4±0.2	1.0±0.12

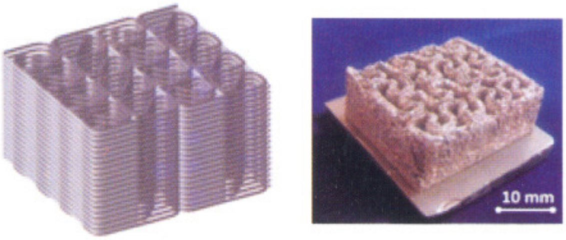


Fig. T.2.9 (a) A typical 3D model (b) Laser rapid manufactured Ti- structure.

The experimental investigations showed that threshold laser energy per unit traverse length of 25 J/mm is required for the deposition of regular and continuous tracks of Ti on pre-deposit /substrate of Ti. The processing head was lifted by ~90% of the track height for the good quality multi-layer deposition. During the study, it was observed that it is difficult to deposit the material of uniform height at the curved trajectory as it involved the acceleration and deceleration of various axes motion. This acceleration and deceleration changed the laser energy per unit length and powder fed per unit length resulting in non-uniform deposition. This issue was resolved by increasing the input scan speed at the curved section in such a way that there is uniform deposition. Figure T.2.9(a) and (b) presents a typical 3D model and laser rapid manufactured structure.

Compression Testing of Porous Structure

The laser rapid manufactured porous Ti-structures were subjected to compressive testing using 150 kN computerized servo-hydraulic controlled universal testing machine. Figure *T.2.10* presents a typical engineering stress-strain curve obtained during compressive strength testing of the laser rapid manufactured porous Ti-structures. The curve indicates that there is a sharp increase in stress with small compression in the beginning up to point A. This is a region of elastic and small plastic deformation. Therefore, this slope is not generally used to determine the Young's modulus of the porous structures. The associated plastic deformation in this region is responsible for mechanical damping. After the initial increase in stress, there is a change in the slope of curve due to a regime of plastic deformation, where small increase in stress resulted in larger compression up to point B. The measured value of porosity at this point is less than 10% of the initial value. After extended plateau regime, the curve finally enters into region of densification, when the porosity was negligible with neighboring tracks completely coalescing with each other. The measured value of porosity was negligible at this point. Figure T.2.11 presents the compressive yield strength of the laser rapid manufactured structure at various porosities in different direction of loading.

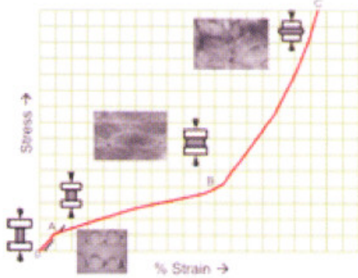


Fig.T.2.10: Typical engineering stress-strain curve obtained during compressive testing of laser rapid manufactured porous Ti-structures

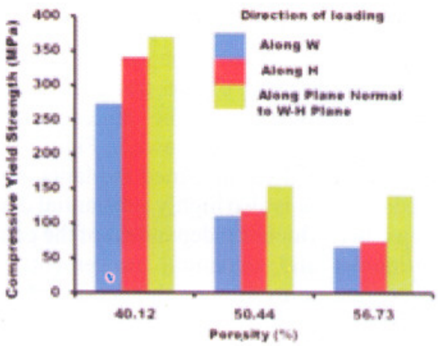


Fig.T.2.11: Compressive yield strength of the laser rapid manufactured Ti-structure at various porosities in different direction of loading.

LRM of functionally designed structures with graded porosity

The developed methodology was also deployed to fabricate the functionally designed Ti-structures with graded porosity from 0 – 60%. Small samples of 10 mm x 10 mm x 10 mm were cut and their porosity distribution in volume was evaluated using GE's Micro CT machine (model: phoenix microme|x DXR HD) at 130 kV, 120 µA with focal spot size of 14.04 µm and 200 ms exposure time. Figure T.2.12 presents the typical result obtained during Micro CT examination at the above parameters. Figure presents 3D rendered view of the porous structure exhibiting pore sizes in different color and bulk material in grey color. It may be seen that there is clear grading in the porosity from front to back. The bio-compatible testing of these porous structures is under progress in collaboration with Shri Chitra Institute of Medical Science and Technology, Thiruananthapuram.

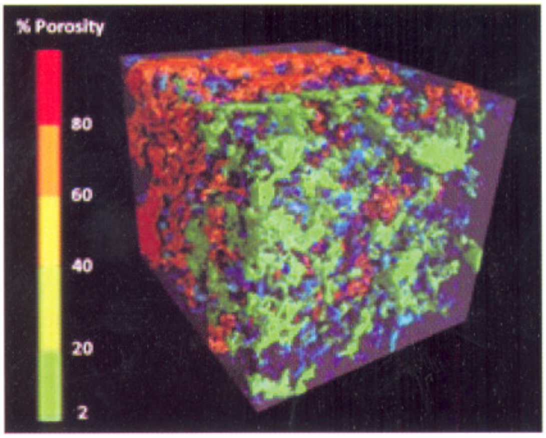


Fig.T.2.12: 3D rendered view of the porous structure exhibiting pore sizes in different color and bulk material in grey color obtained during Micro CT examination.

Conclusion

LRM is an extremely flexible technique with application in multiple areas from repair of large scale components to manufacturing of component with specific end application. It is now crossing the barriers of conventional component fabrication and entering into new era of "feature based design and manufacturing". The potential of the technology has been recognized and a comprehensive program has been initiated at RRCAT. The fabrication of Colmonoy-6 bushes, low cost tool of WC-Co, high performance surfaces of WC particles embedded Ni matrix and wear resistant alloy (T-700, Stellite-6 etc.) on engineering components are some of the results demonstrating the capabilities. The fabrication of functionally designed Ti-structures with graded porosity has new domain with immense potential finding application in bone-replacement. After initial studies using LRM, it is now geared up for taking more challenging assignment addressing the complex problems that cannot be resolved using conventional routes. The research efforts are being extended towards the exclusive solution involving multi-material and multi-functional components in synergy with global counterparts towards the third industrial revolution.

Acknowledgement

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