Chapter 2
Laser Additive Manufacturing (AM): Classification, Processing Philosophy, and Metallurgical Mechanisms

Abstract Laser sintering (LS), laser melting (LM), and laser metal deposition (LMD) are presently regarded as the three most versatile laser-based additive manufacturing (AM) processes. Laser-based AM processes generally have a complex nonequilibrium physical and chemical metallurgical nature, which is material- and process-dependant. The influence of material characteristics and processing conditions on the metallurgical mechanisms and resultant microstructural and mechanical properties of AM-processed components needs to be clarified. This chapter starts with the definition of LS/LM/LMD processes and operative consolidation mechanisms for metallic components. Powder materials used for AM, in the categories of pure metal powder, prealloyed powder, multi-component metals, alloys, metal matrix composites (MMCs) powder, and associated densification mechanisms during AM are addressed. An in-depth review of material and process aspects of AM, including the physical aspects of materials for AM and the microstructural and mechanical properties of AM-processed components, is presented. The purpose of this chapter is to establish a general relationship among material, process, and metallurgical mechanism for laser-based AM of metallic components.

2.1 Classification of Laser AM Processes and Metallurgical Mechanisms

Although laser additive manufacturing (AM) processes share the same material additive manufacturing philosophy, each AM process has its specific characteristics in terms of useable materials, processing procedures, and applicable situations. The capability of obtaining high-performance metallic components with controllable microstructural and mechanical properties also shows a distinct difference for the various AM processes.

As revealed in Fig. 2.1, according to the different mechanisms of laser-powder interaction (i.e., pre-spreading of powder in powder bed before laser scanning vs. coaxial feeding of powder by the nozzle with synchronous laser scanning) and the various metallurgical mechanisms (i.e., partial melting vs. complete melting), the prevailing AM technology for the fabrication of metallic components typically has

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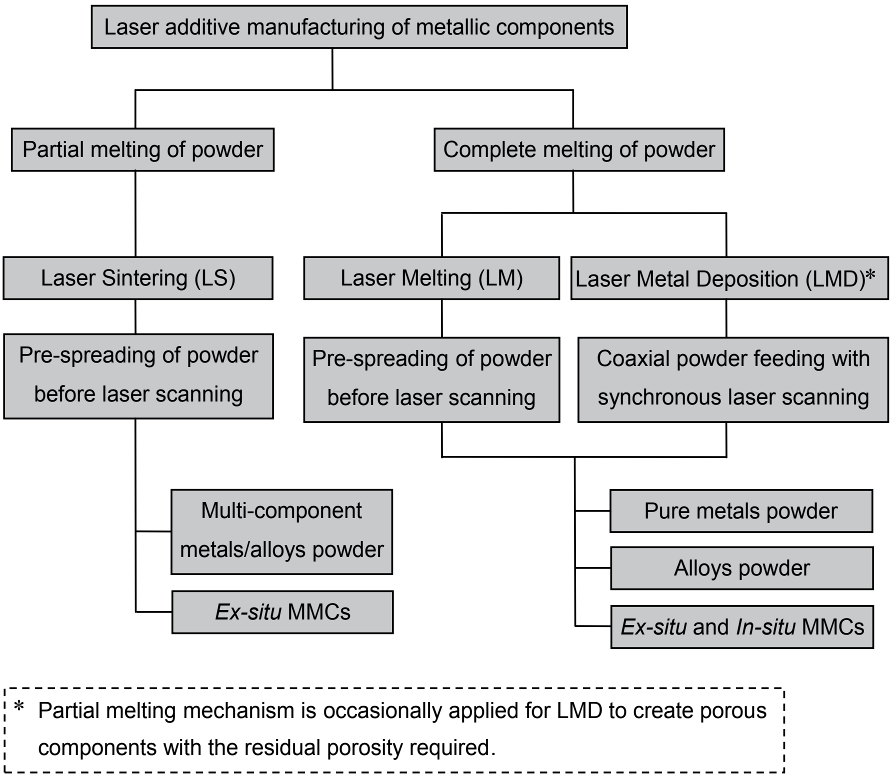

Fig. 2.1 Classification of laser AM processes based on different mechanisms of laser-material interaction

three basic processes: laser sintering (LS), laser melting (LM), and laser metal deposition (LMD). Their deposition mode, deposition rate, processing conditions, and attendant microstructural/mechanical properties are summarized in Table 2.1 and will be addressed in detail as follows.

2.1.1 Laser Sintering (LS)

Laser sintering (LS) is a typical AM process based on the layer-by-layer powder spreading and subsequent laser sintering. As schematically shown in Fig. 2.2, the LS system normally consists of a laser, an automatic powder layering apparatus, a computer system for process control, and some accessorial mechanisms (e.g., inert gas protection system and powder bed preheating system). Different types of lasers are used, including CO_2 [1], Nd:YAG [6], fiber lasers [7], disc lasers [8], etc. The

Table 2.1 Comparisons of some representative laser-based AM processes

Process	Deposition mode	Layer thickness (μm)	Deposition rate	Dimensional accuracy (mm)	Surface roughness (μm)	Ref.
Direct metal laser sintering (DMLS)	Laser sintering	20–100	Depend on laser spot size, scan speed, and size, number, and complexity of parts	High, ±0.05	14–16	[1]
Selective laser melting (SLM)	Laser melting	20–100	ibid	High, ±0.04	9–10	[2]
Direct metal deposition (DMD)	Laser cladding	254	0.1–4.1 cm^3/min	N/A	~40	[3]
Laser engineered net shaping (LENS)	ibid	130–380	N/A	X–Y plane ±0.05; Z axis ±0.38	61–91	[4]
Directed light fabrication (DLF)	ibid	200	10 g/min (1 cm^3/min)	±0.13	~20	[5]

choice of laser has a significant influence on the consolidation of powders, mainly because:

- The laser absorptivity of materials greatly depends on the laser wavelength
- The operative metallurgical mechanism for powder densification is determined by the input laser energy density

The general processing procedures of LS are as follows:

- A substrate for part fabrication is fixed on the building platform and leveled
- The protective inert gas is fed into the sealed building chamber to reduce the interior oxygen content below a required standard
- A thin layer of the loose powder with a thickness normally below 100 μm is deposited on the substrate by the layering mechanism
- The laser beam scans the powder bed surface to form layer-wise profiles according to CAD data of the components to be built
- The above procedures including powder spreading and laser treatment are repeated and the parts are built in a layer-by-layer manner until completion

During LS, the duration of the laser beam on any powder particle depends on beam size and scan speed, and is typically between 0.5 and 25 ms [9]. Under this extremely short thermal cycle, the processing mechanism must be rapid and thus a solid-state sintering mechanism is not feasible. Melting/solidification approach is the only mechanism suitable for the rapid consolidation of powder during LS [10]. LS, as is implied in its name, is processed based on a liquid phase sintering (LPS)

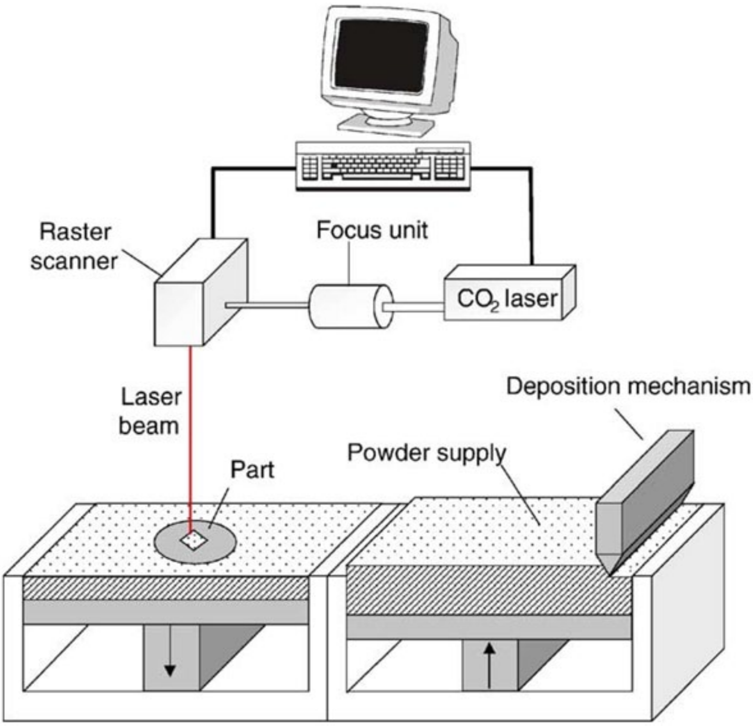

Fig. 2.2 Schematic of LS apparatus, see Ref. [13]

mechanism involving a partial melting of the powder (i.e., semi-solid consolidation mechanism). So far, LS has demonstrated the feasibility in processing multi-component metal powder and prealloyed powder [11, 12]. Powder characteristics and laser processing conditions should be carefully determined in order to realize the favorable metallurgical mechanism for powder consolidation.

The multi-component powder mixture is generally composed of a high-melting-point metallic component acting as the structural metal, a low-melting-point metallic component, taken as the binder, and a small amount of additives such as a fluxing agent or deoxidizer [14]. The operative LS temperature is carefully determined between these two different melting temperatures by adjusting laser processing parameters. The binder, thus, melts completely, while the structural metal retains its solid cores in the liquid. Densification of the solid/liquid system occurs as a result of the rearrangement of solid particles under the influence of capillary forces exerted on them by the wetting liquid. The liquid/solid wetting characteristics and the capillary force exerted on particles determine the particle rearrangement rate and resultant success of LS. LS of a multi-component Cu-based powder consisting of pure Cu powder and prealloyed SCuP powder has been performed by Zhu et al. [1, 15]. The SCuP with a lower melting point (645 °C) acts as the binder, while the Cu

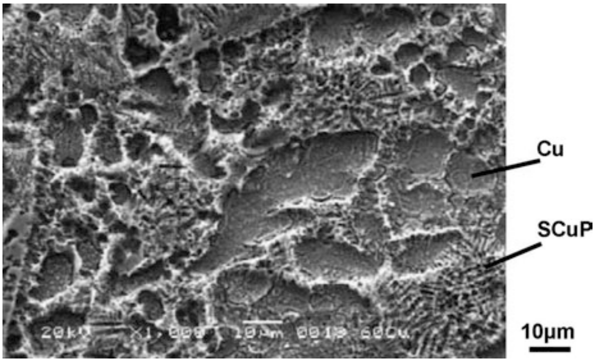

Fig. 2.3 Microstructure of LS-processed Cu–SCuP multi-component Cu-based powder, see Ref. [1]

with a higher melting point (1083 °C) acts as the structural metal (Fig. 2.3), revealing a semi-solid LPS mechanism involved in the LS process.

In contrast to pure metals with a congruent melting point, prealloyed powder exhibits a mushy zone between solidus and liquidus temperatures, within which liquid and solid phases coexist during the melting/solidification process (Fig. 2.4a). As laser processing parameters are optimized, the preferable LS temperature is in the mushy zone to produce a semi-solid system. This process, termed supersolidus liquid phase sintering (SLPS), acts as the feasible metallurgical mechanism for LS of prealloyed powders. As illustrated in Fig. 2.4b, prealloyed particles melt incongruently and become mushy once a sufficient amount of liquid is formed along grain boundaries. The liquid flows and wets solid particles and grain boundaries, leading to a rapid densification of semi-solid system by means of rearrangement of solid particles and a solution-reprecipitation process. Niu et al. [16] have demonstrated that the SLPS mechanism is operative during LS of high speed steel powder. The thick ring microstructure reprecipitated around the austenitic grain boundaries indicates the formation of liquid phase along grain boundaries within particles during SLPS (Fig. 2.4c).

It should be noted that LS of prealloyed powders through the SLPS mechanism requires a strict control of laser processing parameters to realize the incongruent melting of particles within the mushy zone. However, due to the localized, rapid nature of the thermal cycle during LS, there exists a significant difficulty in controlling the sintering temperature between solidus and liquidus, which in turn handicaps the successful operation of the SLPS mechanism. Processing problems (e.g., insufficient densification, heterogenous microstructures and properties, etc.) tend to occur in LS-processed prealloyed powders. Therefore, postprocessing treatment such as the furnace post-sintering [17], hot isostatic pressing (HIP) [18], or secondary infiltration with a low-melting-point material [19] is normally necessary to obtain sufficient mechanical properties.

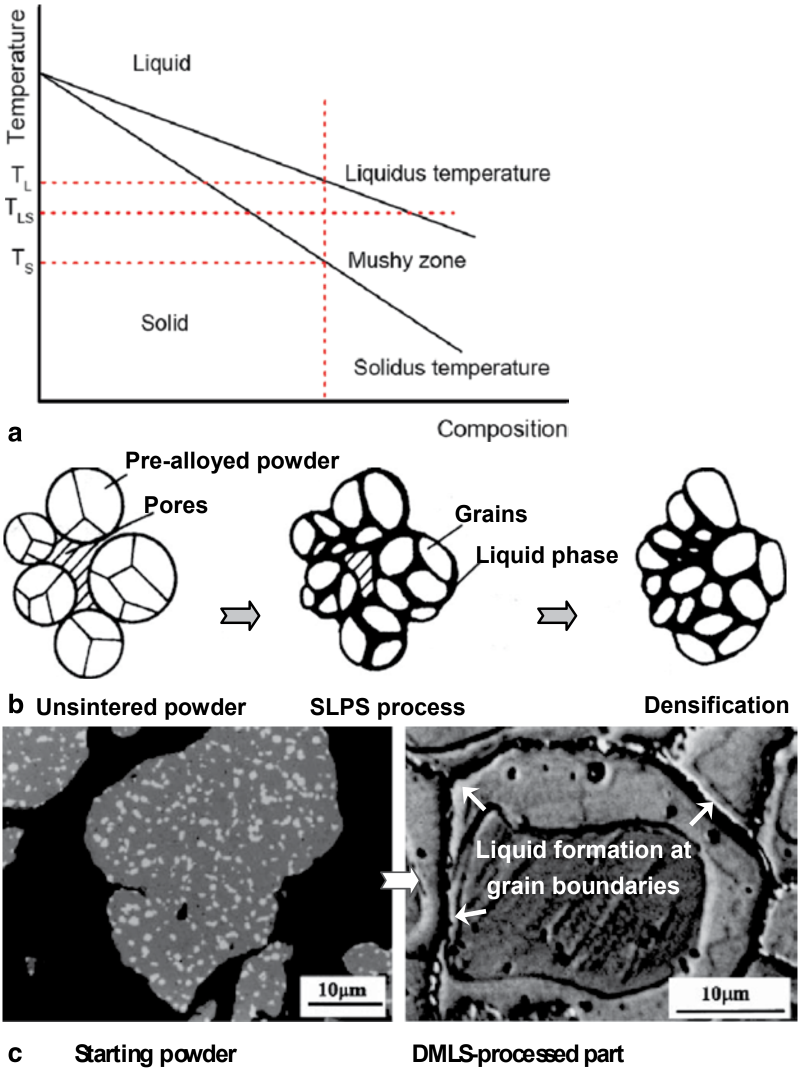

Fig. 2.4 **a** An idealized temperature-composition equilibrium phase diagram for a prealloyed binary metal system, **b** Schematic of SLPS densification of prealloyed particles, see Ref. [21], **c** Microstructural development during LS of high speed steel powder, see Ref. [16]

2.1.2 Laser Melting (LM)

Driven by the demand to produce fully dense components with mechanical properties comparable to those of bulk materials, and by the desire to avoid time-consuming postprocessing cycles, laser melting (LM) has been developed. LM shares the same processing apparatus and procedures with LS. The only difference is that

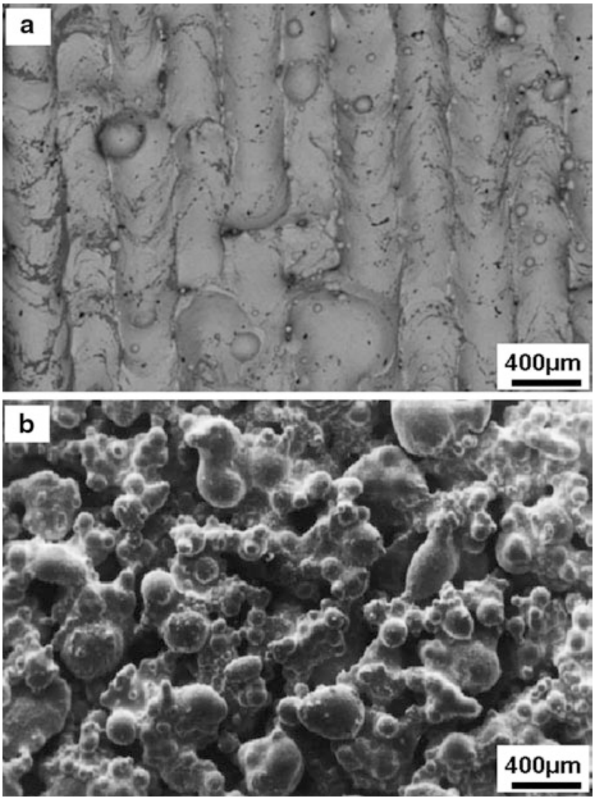

Fig. 2.5 Surface morphologies of M2 high speed steel components processed by **a** LM, see Ref. [22] and **b** LS, see Ref. [23]

LM of metallic powders is based on a complete melting/solidification mechanism. The idea of full melting is supported by the continuously improved laser processing conditions in recent years (e.g., higher laser power, smaller focused spot size, smaller layer thickness, etc.), leading to significantly improved microstructural and mechanical properties as relative to those of early time LS-processed parts [20]. LM, thus, shows better suitability to produce full dense parts approaching 99.9 % density in a direct way, without post infiltration, sintering, or HIP.

Simchi [22] and Niu et al. [23] have processed M2 high speed steel using LM and LS methods, respectively. The densification rate, surface smoothness, and microstructural homogeneity of LM-processed parts under optimal processing conditions show a significant improvement upon those of LS-processed parts (Fig. 2.5).

Another major advance of LM lies in its high feasibility in processing nonferrous pure metals, e.g., Ti [24], Al [25], Cu [26], etc., which to date cannot be well processed using the LS partial melting mechanism. Early attempts to process pure metals using LS have proven to be unsuccessful, due to the considerably high viscosity and resultant balling phenomenon caused by the limited liquid formation

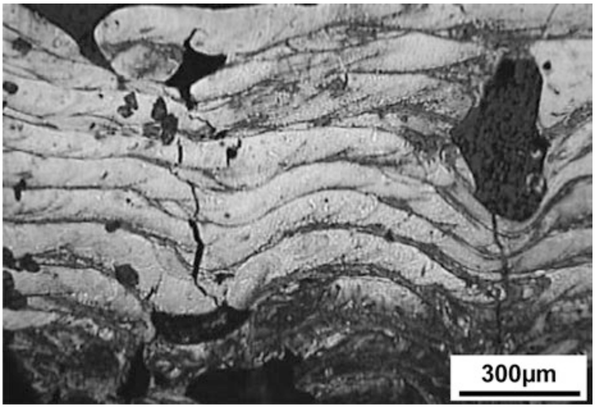

Fig. 2.6 Distortion and crack formation in LM-processed Cu–H13 powder, see Ref. [30]

[27, 28]. In contrast, the density of LM-processed pure metals is highly controllable and can be improved significantly up to 99.5 % through the full melting mechanism of LM [25, 26].

Nevertheless, LM requires a higher-energy level, which is normally realized by applying good beam quality, high laser power, and thin powder layer thickness (i.e., long building time). Consequently, LM is at significant risk for the instability of the molten pool due to the full melting mechanism used. A large degree of shrinkage tends to occur during liquid/solid transformation, accumulating considerable stresses in LM-processed parts [29]. The residual stresses arising during cooling are regarded as key factors responsible for the distortion and even delamination of the final products. Pogson et al.'s work [30] on LM of Cu–75 % H13 reveals that the incorporation of Cu into tool steel during LM produces the overheating Cu-rich region around the austenite grain boundaries, which increases the risk of cracking by hot tearing (Fig. 2.6). Furthermore, the melt instabilities may result in spheroidization of the liquid melt pool (known as balling effect) and attendant interior porosity. Therefore, proper care should be taken in the reasonable selection of both laser processing and powder depositing parameters to determine a suitable process window, in order to yield a moderate temperature field to avoid the overheating of the LM system.

It is noted that the period for rapid development of LM technology began from the year 2000. In contrast, the intensive research attempts on laser metal deposition (LMD) technology started from 1993—the production of metallic parts with favorable mechanical properties by LMD has been reported in the nineties. For instance, Mazumder et al. have reported DMD fabrication of fully dense aluminum 1100 parts as early as 1993, demonstrating to provide metal properties equivalent to a wrought process [3, 31]. Conversely, LM production of complex shaped aluminum components meeting industrial standards has been successfully performed at the Fraunhofer ILT in 2008 [25].

2.1.3 Laser Metal Deposition (LMD)

2.1.3.1 Process Overview

Although the processing strategy of LMD follows the general additive manufacturing principle, the manner of powder supply changes from prespreading in the LS/LM process to coaxial feeding in the LMD process (Fig. 2.1). The LMD powder delivery system consists of a specially designed powder feeder that delivers powder into a gas delivery system via the nozzles. The high-energy laser beam is delivered along the *z*-axis in the center of the nozzle array and focused by a lens in close proximity to the work piece. Moving the lens and powder nozzles in the *z*-direction controls the height of the focuses of both laser and powder. The work piece is moved in the *x*–*y* direction by a computer-controlled drive system under the beam/powder interaction zone to form the desired cross-sectional geometry. Consecutive layers are additively deposited, producing a three-dimensional component. With the integration of a multi-axis deposition system, multiple material delivery capability, and, in some instances, the patented closed loop control system [32, 33], LMD can coat, build, and rebuild components having complex geometries, sound material integrity and dimensional accuracy. LMD, accordingly, has a highly versatile process capability and can be applied to manufacture new components, to repair and rebuild worn or damaged components, and to prepare wear- and corrosion-resistant coatings [34].

The DMD, LENS®, and DLF (Table 2.1) are regarded as three representative processes of LMD technology. It is worth noting that the DMD technology developed by Mazumder's group at the University of Michigan is equipped with a feedback system that provides a closed loop control of dimensional accuracy during the deposition process. The feedback loop is, thus, regarded as a unique feature of DMD that differentiates from LENS® and DLF processes [35].

2.1.3.2 Constitutes of DMD System

A typical DMD system is schematically depicted in Fig. 2.7 and some of the main features are as follows [35]:

- Patented closed loop feedback control for DMD process

This unique system serves as the key tool for producing a near net-shape product. High speed sensors collect melt pool information, which is directly fed into a dedicated controller that adjusts the input processing parameters to maintain dimensional accuracy and material integrity.

- Coaxial nozzle with local shielding of melt pool

The coaxial nozzle design is based on a patent [36], and offers equal deposition rates in any direction. Inert gas blown through the nozzle helps both in powder

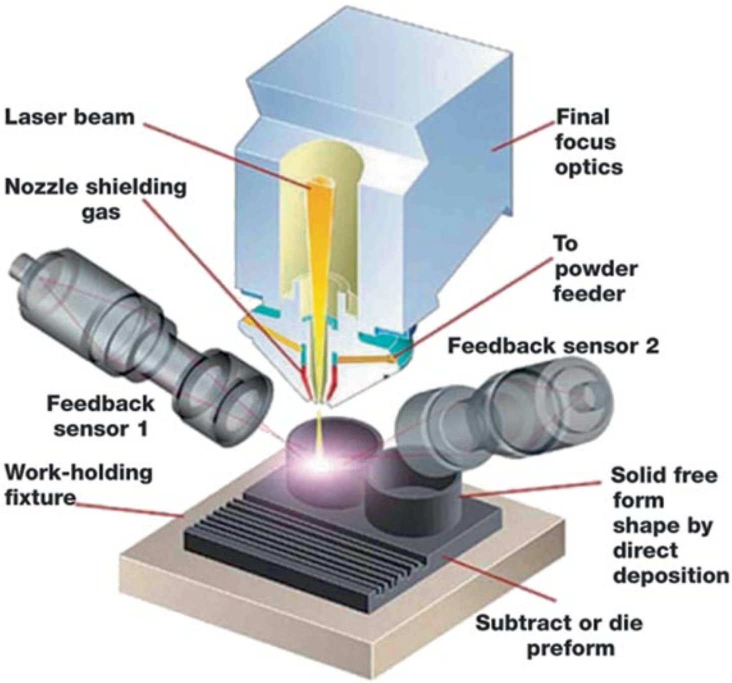

Fig. 2.7 Schematic of closed loop DMD system, see Ref. [35]

delivery and shielding the deposit from oxidation. Shielding strategy is a delicate balance between the adequate pressure to drive away the ambient air and the powder delivery without causing excessive disturbance within the molten pool.

- Six-axis computer-aided manufacturing (CAM) software for AM

Six-axis DMD CAM software for AM, which includes an integrated DMD database with process recipes as a part of the software, builds a CAM tool path directly from CAD data. Contour, surface, and volume deposition paths are provided in three dimensions, and accordingly, multi-layer deposition paths can be prepared in a single operation. Simulation and collision-detection modules are included and, thus, enable the user to detect any possible collision of the processing head and the part while creating the deposition tool path.

- DMD vision system

The DMD vision system has been developed for deposition on small objects with fine features. The system locates the coordinate position of a part in the machine and allows easy tool path generation for accurate deposition. This eliminates manual part pick-up, which is practically impossible for very small components with fine structures. Faster operation and better repeatability improve productivity considerably.

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