UNIT-4

POWDER BED FUSION AND MATERIAL EXTRUSION

4.2 Selective Laser Melting (SLM)

There are many companies which make commercially available laser-based systems for direct melting and sintering of metal powders: EOS (Germany), Renishaw (UK), Concept Laser (Germany), Selective Laser Melting (SLM) Solutions (Germany), Realizer (Germany), and 3D Systems (France/USA). There are competing terminologies for these technologies. The term selective laser melting (SLM) is used by numerous companies; however the terms Laser Cusing and DMLS are also used by certain manufacturers. For this discussion, we will use mLS to refer to the technologies in general and not to any particular variant.

mLS research in the late 1980s and early 1990s by various research groups was mostly unsuccessful. Compared to polymers, the high thermal conductivity, propensity to oxidize, high surface tension, and high laser reflectivity of metal powders make them significantly more difficult to process than polymers. Most commercially available mLS systems today are variants of the selective laser powder re-melting (SLPR) approach developed by the Fraunhofer Institute for Laser Technology, Germany. Their research developed the basic processing techniques necessary for successful laser-based, point-wise melting of metals. The use of lasers with wavelengths better tuned to the absorptivity of metal powders was one key for enabling mLS. Fraunhofer used an Nd-YAG laser instead of the CO2 laser used in pLS, which resulted in a much better absorptivity for metal powders (see Fig. 5.13). Subsequently, almost all mLS machines use fiber lasers, which in general are cheaper to purchase and maintain, more compact, energy efficient, and have better beam quality than Nd:YAG lasers. The other key enablers for mLS, compared to pLS, are different laser scan patterns (discussed in the following section), the use of f-theta lenses to minimize beam distortion during scanning, and low oxygen, inert atmosphere control.

One common practice among mLS manufacturers is the rigid attachment of their parts to a base plate at the bottom of the build platform. This is done to keep the metal part being built from distorting due to residual stresses. This means that the design flexibility for parts made from mLS is not quite as broad as the design flexibility for parts made using laser sintering of polymers, due to the need to remove these rigid supports using a machining or cutting operation

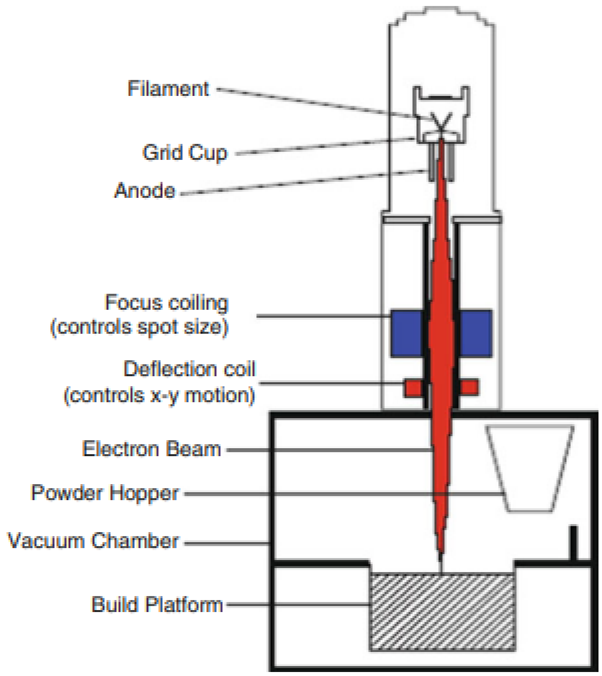
Over the years, various mLS machine manufacturers have sought to differentiate themselves from others by the features they offer. This differentiation includes laser power, number of lasers offered, powder handling systems, scanning strategies offered, maximum build volume, and more. Some machine manufacturers give users more control over the process parameters than other manufacturers, enabling more experimentation by the user, whereas other manufacturers only provide “proven” materials and process parameters. For instance, Renishaw machines have safety features to help minimize the risk of powder fires. EOS, as the world’s most successful metal PBF provider, has spent considerable time tuning their machine process parameters and scanning strategies for specific materials which they sell to their customers. Concept Laser has focused on the development of stainless and hot-work steel alloys suitable for injection mold and die cast tooling. 3D Systems (after their acquisition of Phenix Systems) has developed machines which can be held at an elevated temperature, thus enabling efficient sintering of ceramic powders, in addition to melting of metal powders. Another unique characteristic of the 3D Systems machine is its use of a roller to spread and then compact powder, making it the only manufacturer which can directly change the powder bed packing density on-the-fly.

3D-Micromac, Germany, a partner of EOS, produces the only multimaterial, small-scale mLS machine. It has developed small-scale mLS processes with small build cylinders 25 or 50 mm in diameter and 40 mm in height. Their fiber laser is focused to a particularly small spot size, for small feature definition. In order to use the fine powder particle sizes necessary for fine feature reproduction, they have developed a unique two-material powder feeding mechanism, shown in Fig. 5.14. The build platform is located between two powder feed cylinders. When the rotating rocker arm is above a powder feed cylinder, the powder is pushed up into the feeder, thus charging the hopper. When the rocker arm is moved over top of the build platform, it deposits and smoothens the powder, moving away from the build cylinder prior to laser processing. By alternating between feed cylinders, the material being processed can be changed in a layer-by-layer fashion, thus forming multimaterial structures. An example of a small impeller made using aluminum oxide powders is shown in Fig. 4.5.

Fig 4.5 3D Micromac Powder Feed System. In this picture, only one of the powder feeders (located over the build cylinder) is filled with powder (courtesy: Laserinstitut Mittelsachsen e.V.

4.5 Electron Beam Melting

Fig. 5.16 Schematic of an EBM apparatus (courtesy: Arcam)



Electron beam melting (EBM) has become a successful approach to PBF. In contrast to laser-based systems, EBM uses a high-energy electron beam to induce fusion between metal powder particles. This process was developed at Chalmers University of Technology, Sweden, and was commercialized by Arcam AB, Sweden, in 2001.

Similarly to mLS, in the EBM process, a focused electron beam scans across a thin layer of pre-laid powder, causing localized melting and resolidification per the slice cross section. There are a number of differences between how mLS and EBM are typically practiced, which are summarized in Table 5.1. Many of these differences are due to EBM having an energy source of electrons, but other differences are due to engineering trade-offs as practiced in EBM and mLS and are not necessarily inherent to the processing. A schematic illustration of an EBM apparatus is shown in Fig. 5.16.

Laser beams heat the powder when photons are absorbed by powder particles. Electron beams, however, heat powder by transfer of kinetic energy from incoming electrons into powder particles. As powder particles absorb electrons they gain an increasingly negative charge. This has two potentially detrimental effects: (1) if the repulsive force of neighboring negatively charged particles overcomes the gravitational and frictional forces holding them in place, there will be a rapid expulsion of powder particles from the powder bed, creating a powder cloud (which is worse for fine powders than coarser powders) and (2) increasing negative charges in the powder particles will tend to repel the incoming negatively charged electrons, thus creating a more diffuse beam. There are no such complimentary phenomena with photons. As a result, the conductivity of the powder bed in EBM must be high enough that powder particles do not become highly negatively charged, and scan strategies must be used to avoid build-up of regions of negatively charged particles. In practice, electron beam energy is more diffuse, in part, so as not to build up too great a negative charge in any one location. As a result, the effective melt pool size increases, creating a larger heat-affected zone. Consequently, the minimum feature size, median powder particle size, layer thickness, resolution, and surface finish of an EBM process are typically larger than for an mLS process.

As mentioned above, in EBM the powder bed must be conductive. Thus, EBM can only be used to process conductive materials (e.g., metals) whereas, lasers can be used with any material that absorbs energy at the laser wavelength (e.g., metals, polymers, and ceramics).

Electron beam generation is typically a much more efficient process than laser beam generation. When a voltage difference is applied to the heated filament in an electron beam system, most of the electrical energy is converted into the electron beam; and higher beam energies (above 1 kW) are available at a moderate cost. In contrast, it is common for only 10–20 % of the total electrical energy input for laser systems to be converted into beam energy, with the remaining energy lost in the form of heat. In addition, lasers with beam energies above 1 kW are typically much more expensive than comparable electron beams with similar energies. Thus, electron beams are a less costly high energy source than laser beams. Newer fiber lasers, however, are more simple in their design, more reliable to maintain, and more efficient to use (with conversion efficiencies reported of 70–80 % for some fiber lasers). Thus, this energy advantage for electron beams may not be a major advantage in the future.

EBM powder beds are maintained at a higher temperature than mLS powder beds. There are several reasons for this. First, the higher energy input of the beam used in the EBM system naturally heats the surrounding loose powder to a higher temperature than the lower energy laser beams. In order to maintain a steady-state uniform temperature throughout the build (rather than having the build become hotter as the build height increases) the EBM process uses the electron beam to heat the metal substrate at the bottom of the build platform before laying a powder bed. By defocusing the electron beam and scanning it very rapidly over the entire surface of the substrate (or the powder bed for subsequently layers) the bed can be preheated rapidly and uniformly to any preset temperature. As a result, the radiative and resistive heaters present in some mLS systems for substrate and powder bed heating are not used in EBM. By maintaining the powder bed at an elevated temperature, however, the resulting microstructure of a typical EBM part is significantly different from a typical mLS part (see Fig. 5.17). In particular, in mLS the individual laser scan lines are typically easily distinguishable, whereas individual scan lines are often indistinguishable in EBM microstructures. Rapid cooling in mLS creates smaller grain sizes and subsequent layer scans only partially re-melt the previously deposited layer. The powder bed is held at a low enough temperature that elevated temperature grain growth does not erase the layering effects. In EBM, the higher temperature of the powder bed, and the larger and more diffuse heat input result in a contiguous grain pattern that is more representative of a cast microstructure, with less porosity than an mLS microstructure.

Although the microstructures presented in Fig. 5.17 are representative of mLS and EBM, it should be noted that the presence of beam traces in the final microstructure (as seen in the left image of Fig. 5.17) is process parameter and material dependent. For certain alloys, such as titanium, it is not uncommon for contiguous grain growth across layers even for mLS. For other materials, such as those that have a higher melting point, the layering may be more prevalent. In addition, layering is more prevalent for process parameter combinations of lower bed temperature, lower beam energy, faster scan rate, thicker layers, and/or larger scan spacing for both mLS and EBM. The reader is also referred to the presentation of material microstructures and process parameter effects of the DED processes in Sects. 10.6 and 10.7, since the phenomena seen mLS and EBM are similar to those observed in DED processes

One of the most promising aspects of EBM is the ability to move the beam nearly instantaneously. The current control system for EBM machines makes use of this capability to keep multiple melt pools moving simultaneously for part contour scanning. Future improvements to scanning strategies may dramatically increase the build speed of EBM over mLS, helping to distinguish it even more for certain applications. For instance, when nonsolid cross sections are created, in particular when scanning truss-like structures (with designed internal porosity), nearly instantaneous beam motion from one scan location to another can dramatically speed up the production of the overall product

In EBM, residual stresses are much lower than for mLS due to the elevated bed temperature. Supports are needed to provide electrical conduction through the powder bed to the base plate, to eliminate electron charging, but the mass of these supports is an order of magnitude less than what is needed for mLS of a similar geometry. Future scan strategies for mLS may help reduce the need for supports to a degree where they can be removed easily, but at present EBM has a clear advantage when it comes to minimizing residual stress and supports

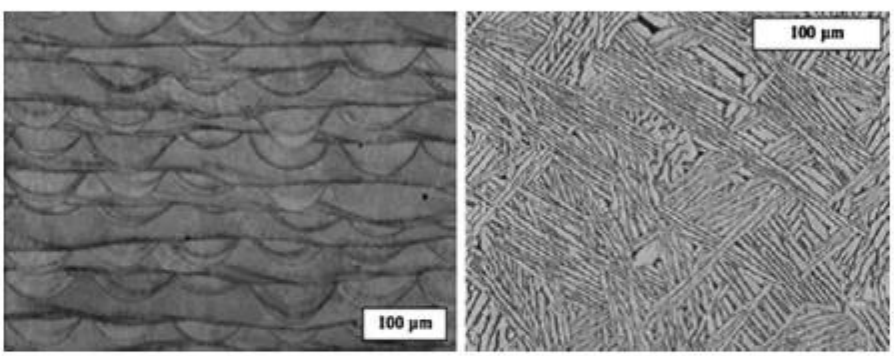


Fig. 5.17 Representative CoCrMo mLS microstructure (*left*, courtesy: EOS), and Ti6Al4V EBM microstructure (*right*, courtesy: Arcam)