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Analysis of Factors Affecting the Quality of Products Manufactured by Selective Laser Melting Technology

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Abstract

Additive technologies are currently actively developing, in particular selective laser melting (SLM), which allows for the layer-by-layer production of products from metal powder using high-power laser radiation. The development of SLM technology is aimed at increasing the productivity of installations and the quality of the manufactured product. The article considers the main factors influencing quality: related to the modes and strategies of laser processing, related to the accuracy of the geometric dimensions of the computer model of the manufactured product, related to the design solutions of a specific installation, related to the consumable powder material. In the first case, it is necessary to experimentally or numerically select the process parameters (power, scanning speed and interval, layer thickness, etc.) and synchronize the control signals of the laser and the scanning system (delays on, off, transition, etc.). In the second case, it is necessary to establish a balance between the accuracy of triangulation and the size of the 3D model file, or implement step-by-step reading. In the third case, solutions to the problems discussed (wall deformation, spatter) are proposed to achieve high print quality. In the fourth case, control of the particle size distribution and morphology of the consumable powder material is necessary, especially when reusing it. It is also necessary to improve the accuracy of beam positioning by calibrating the installation and providing additional control systems: quality control of the applied powder layer, control of the geometry of the grown part using photo/video cameras, control of the thermal fields of each layer using thermal imagers, pyrometers, or other methods, control of the working atmosphere parameters in the build chamber, control of the hopper fill level. Software products also exist for compensating for process deformations in additive manufacturing, based on scanning manufactured parts and their re-production taking into account the obtained deviations, which leads to an increase in the production cycle of the product. Thus, improving the quality of a product obtained using SLM technology is achieved through a comprehensive solution covering all stages of its creation: from the formation of a 3D model to post-processing.

Keywords: Product Quality, Control System, Selective Laser Melting, Additive Technologies.

Introduction

Selective laser melting (SLM) is currently an advanced technology for the production of complex metal parts, including those optimized for topology. The use of SLM as a form of additive manufacturing offers numerous advantages: reduced production cycles, minimized mass and number of components, production customization, and more. However, the physical picture of the process is complex; rapid heating and cooling in a thin layer can lead to a number of defects, including pores, cracks, balling up, and splashes from the melting pool. The temperature gradient leads to thermal stress and, consequently, to part deformation. This hinders the widespread adoption of this technology and degrades print quality, which requires controlled geometric dimensions, minimal residual porosity, and the required physical and mechanical properties. To improve the quality of the manufactured part, a number of factors must be considered. They can be conditionally divided into four groups: related to the accuracy of the geometric dimensions of the computer model of the manufactured product, related to the properties of the material, related to the characteristics of the installation, related to the technological parameters.

Factors Affecting Quality

3d Model Accuracy

The geometric dimensional accuracy of a computer model is determined by the accuracy of triangulation when converting it to an STL file. It is important to find a balance between accuracy and file size. Complex models with numerous small elements, such as gyroid structures (Fig. 1), for which the data size of the processed files for a single layer is on the order of several tens of megabytes, may not be readable by slicing software (a program for splitting an STL file into hundreds or thousands of flat horizontal layers, setting laser processing modes and scanning strategies) and the 3D printing machine control software [1, 2]. One solution to this problem is to split the source file into several batches and read them in stages.

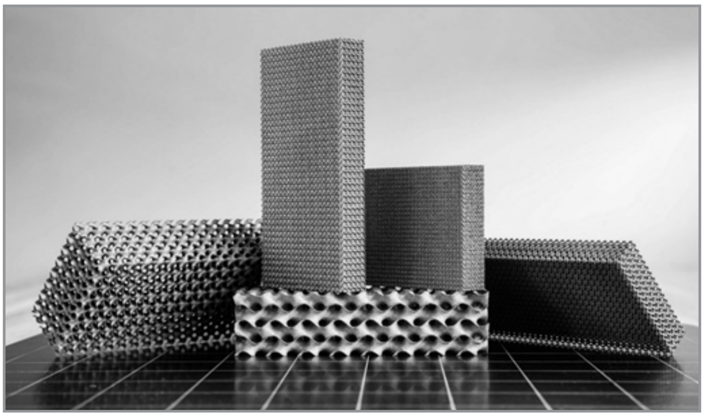


Figure 1: Gyroid structures manufactured on an M250 machine

Metal Powder Properties

One factor affecting the quality of the final product is the consumable (metal powder). The requirement for its particles is a spherical shape. This is due to the fact that such particles fit more compactly into a given volume and ensure the required fluidity in material delivery systems with minimal resistance [3].

Typically, the particle size distribution fluctuates between 10 and 60 µm. Upon receipt of a new batch of powder, an incoming inspection is carried out for particle size distribution, chemical composition, and particle morphology. After printing, excess powder is poured into receiving containers. Experience shows that this powder can be reused; however, in this case, each material behaves differently. General trends can be identified - a change in the particle size distribution (the number of small particles decreases as a result of sintering of the particles with each other).

By sifting and mixing with the primary powder, the desired particle size distribution can be restored. With a small amount of recycling, no significant changes in the chemical composition and morphology of the powder (titanium, nickel, aluminum, steel) were detected. With a large amount of recycling (more than 30 times), the powder does not have time to recover, the shape of the particles becomes more elongated, drop-shaped [4]. High quality can be achieved by testing both powder characteristics and its flowability and packing density. This leads to reduced production costs, providing SLM with economic and environmental benefits.

Machine Specifications

A typical SLM design includes a sealed build chamber, an inert atmosphere system, a growth table, a layer formation system, unfused powder tanks, and a laser channel [5]. The build chamber is filled with an inert gas (argon or nitrogen), which reduces the reaction of gaseous particles with the powder and prevents combustion and explosion. Residual stress and porosity are reduced, among other things, by reducing the overall temperature gradient within the part, which can be achieved by preheating the growth table. This also contributes to the development of a temperature gradient within the build chamber, resulting in geometric deformations of its walls. Therefore, in SLM systems, it is preferable to thermally stabilize the walls, thereby improving the accuracy of beam positioning.

In the build chamber, the feed powder is stored in a hopper (Fig. 2). From the hopper, the powder is fed to the build platform. A distinction is made between bottom and top feed. In the first case, two build wells of equal volume are required, which increases the overall dimensions of the entire setup. However, this approach allows for more accurate powder feed onto the growth table, which is important for light alloys (e.g., aluminum alloys). In the second case, the situation is reversed: the setup is more compact due to the reduced hopper size. To prevent powder carryover by the inert gas flow, more complex feed systems are required, such as the use of a labyrinth system. With this feed system, powder can be added during the manufacturing process. Improved quality is ensured by controlling the fill level of the hopper.

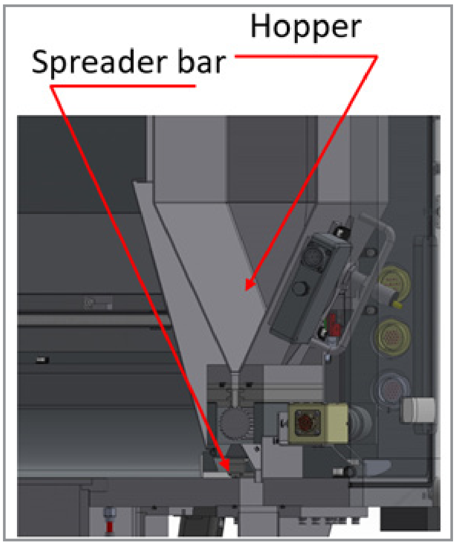


Figure 2: Example of Top Feed

Also, to improve print quality, it is necessary to ensure uniform powder distribution across the growth table or above the printed layer. Uneven powder bed formation is caused by protruding elements of the printing parts (due to thermal stresses), defects or wear of the leveling blade (resulting in streaks in the powder bed parallel to the application device's movement), and insufficient powder supply (after applying the layer, not all areas of the working platform are evenly coated with new powder). Monitoring powder bed formation can improve print quality. This can be achieved with a video camera and optimal lighting using image processing algorithms (Fig. 3). Multiple light sources can increase the number of defects detected, as shadow areas illuminated from a specific direction are created. A new development in the field of uniform layer formation is the use of electroplating technology, which utilizes electrostatically induced oscillations of powder particles. The device can be installed immediately behind the spreader bar.

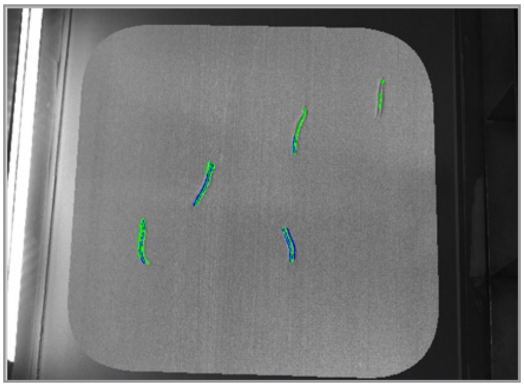


Figure 3: Powder Bed Inspection

The build chamber is continuously purged to remove melt products from the laser-exposed area. The primary requirement for purging is to ensure a laminar flow uniformly distributed over the growth table. To generate such a flow, a flat nozzle divided into fragments can be used, resulting in the formation of a fine-scale structure of longitudinal vortices (Fig. 4). Numerical modeling revealed a narrowing of the laminar flow (non-uniform field) near the outlet manifold, caused by its interaction with the counter-flow reflected from the walls of the build chamber. This problem can be solved by increasing the size of the inlet.

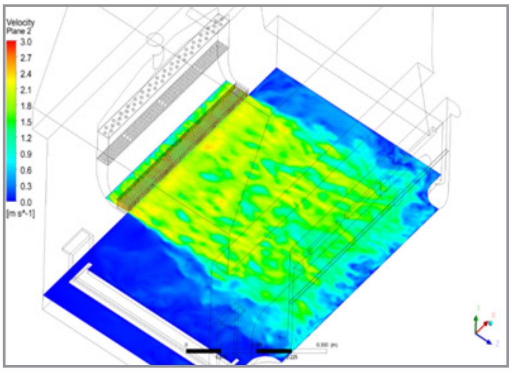


Figure 4: Velocity Field Above the Growth Stage

Since the internal working volume becomes contaminated with fine dust particles and metal vapor, it is necessary to provide additional purge air near the top wall to protect the windows through which the laser beam is introduced from the deposition of particles on the surface, which would reduce the power and distort the beam trajectory. The direction of this airflow may coincide with the direction of the airflow over the growth stage (Fig. 5). As a result, the internal chamber can be divided into two volumes: the lower (contaminated) and the upper (clean). This improves the quality of the manufactured part.

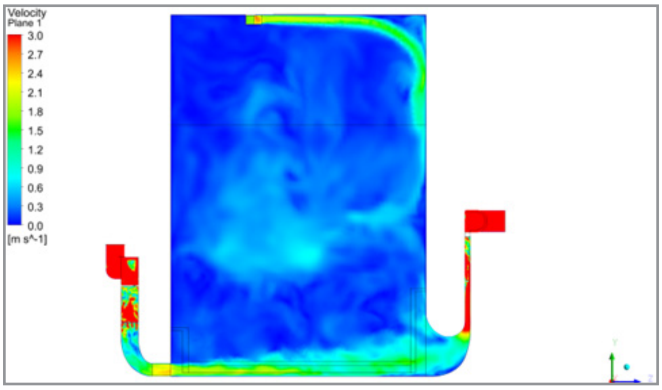


Figure 5: Velocity Field in Cross-Section

Practical experience shows that during long manufacturing runs (several days), the "clean" volume with this nozzle configuration still becomes contaminated, leading to thermal instability. This problem can be solved by interrupting the manufacturing process and wiping the protective windows, which leads to a change in temperature inside the build chamber and, consequently, the appearance of defects. Another possible solution is to install a third nozzle assembly, located in the center of the side wall of the build chamber (Fig. 6). This solution prevents contaminated flow from entering the "clean" zone, thus allowing parts to be manufactured without interrupting the project. This solution can be further improved by adjusting the location and angle of the third nozzle, introducing a spoiler, or other methods.

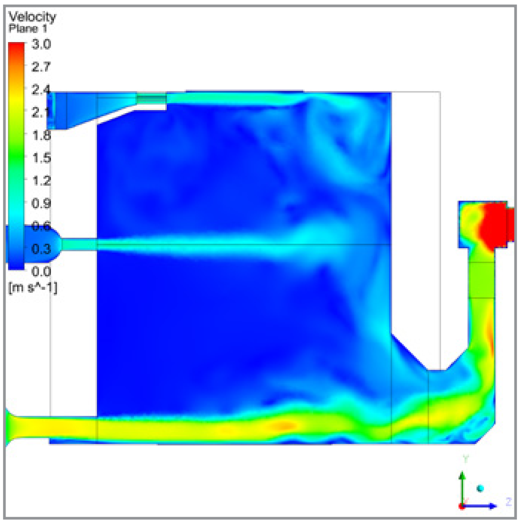


Figure 6: Velocity Field with a Third Nozzle

Technological Parameters of the Process

Process parameters include powder parameters (layer thickness, size distribution, etc.), laser radiation parameters (power, spot diameter, etc.), and scanning strategy parameters (hatch distance, speed, etc.). Parameters must be selected to ensure a stable melt pool during printing and, consequently, zero residual porosity. The search can be conducted experimentally (Fig. 7a) and/or numerically (Fig. 7b). Experimental search is a labor-intensive process, but it is a proven strategy that ensures high quality of the final product. Numerical modeling, even within the framework of multi-level modeling methodology and high computing power, requires significant computation time; however, it allows for a deeper understanding of the processes occurring during the interaction of radiation with metal powder [6, 7].

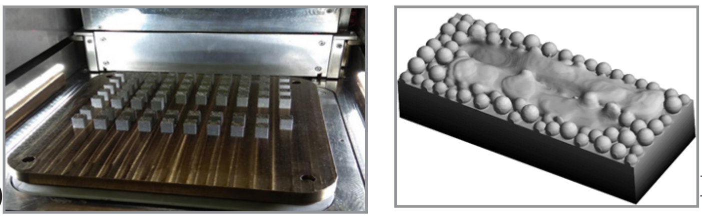
A)  B)

Figure 7: – a) Cube Production, b) Double-Pass Simulation

Another implicit parameter affecting print time and quality is the synchronization of the laser and scanner head control signals, which must be compatible with the dynamic behavior of the system components, i.e., the scanner-laser feedback and the specific interaction of laser radiation with the workpiece. For this purpose, the following dynamic characteristics are set: (1) laser delays – laser turn-on delay, laser turn-off delay; (2) scanner delays – jump delay (at the end of a jump), burn delay (at the end of a burn), and polygon delay (between two burn commands). Incorrect selection of these parameters leads to defects in the scanning path (remelting at the beginning or end of the burn section due to the low speed of the mirrors when the laser is on, incomplete (shortening) or excessive (extension) melting of a given section of the path (Fig. 8)). These parameters are usually selected experimentally.

Figure 8: Burnout Results for Different Dynamic Parameters

The melting pool characteristics can be affected by various parameters, such as changes in the oxygen content in the build chamber. Therefore, it is important to monitor the operating conditions of the installation. Various sensors are used for this purpose: growth table temperature, table position, pressure, flow rate, tank filling, and others.

Additional Quality Improvement Methods

Preliminary calibration of the system, designed to ensure the specified laser beam positioning accuracy, improves the geometric accuracy of manufactured parts [8]. A special reference object with a precisely known geometry and position on the work area is used for calibration. For example, a white square grid on a black background with a pitch of h. Existing cameras can be used for measurements, followed by subsequent processing. It is desirable that the residual error of measured deviations from ideal burn coordinates does not exceed 1/3 of the laser beam spot diameter. The calibration methodology typically includes image processing (Fig. 9), residual error assessment, and deviation compensation (if necessary). Experience shows that 2-3 calibration iterations are necessary to achieve the desired accuracy.

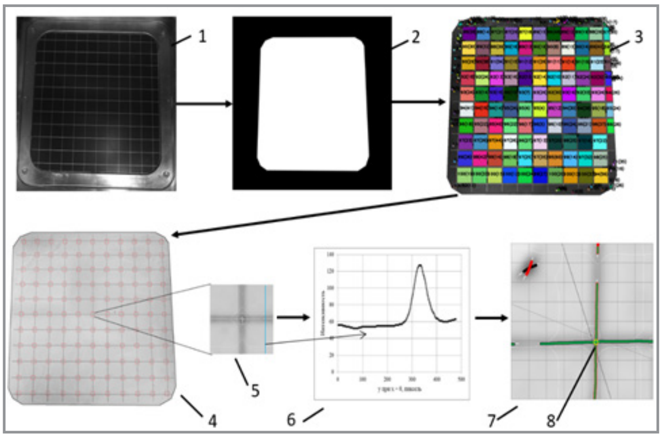


Figure 9: Image Processing Algorithm for Laser Channel Calibration

Using constant process parameters during the printing process is a widely used method for manufacturing parts. However, heat distribution within the chamber is uneven, leading to areas of overheating, which leads to intense fluctuations within the melt pool, material evaporation, and, consequently, deterioration in the quality of the final product. Using a real-time monitoring system will enable monitoring of the printing process and reduce the need for subsequent analysis, such as destroying the part to assess its properties or using expensive X-ray computed tomography (X-ray CT) measurements. This area of research is currently undergoing rapid development [9, 10]. Various sensors are used for monitoring, including acoustic sensors, photodiodes, pyrometers, and others. The primary parameters detected are the melt pool (Fig. 10), including area, length-to-width ratio, and temperature, since the impact of changes in these parameters can be seen in the melt pool's behavior. The next stage of development is the implementation of corrective actions to compensate for any undesirable effects.

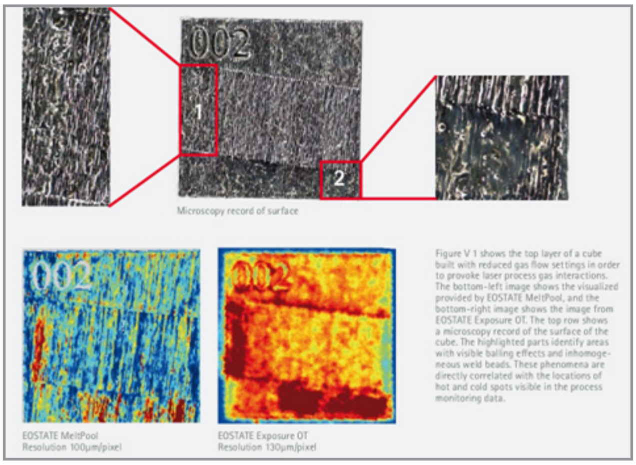


Figure 10: Example of Melt Pool Monitoring

Conclusion

SLM technology is being actively implemented in modern industry, enabling the creation of unique products while reducing the time and cycle time of the production process. When manufacturing products using SLM, it's crucial to achieve a high level of quality, which is ensured through the combined use of a monitoring system with subsequent printing process control, a machine status monitoring system, and real-time powder layer application control. Therefore, a comprehensive approach is essential to improving the quality of the final product manufactured using SLM technology.

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