THE ENHANCEMENT OF MICROMACHINING ABILITY OF SELECTIVE LASER MELTING BY SELECTIVE LASER EROSION

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Abstract

This paper presents an application of a process combining Selective Laser Melting (SLM) and Selective Laser Erosion (SLE) and discusses the improvement of SLM by SLE in terms of its micromachining capability. SLM is a layered manufacturing process for fabricating complex parts by fusing metal powders with the laser beam. Full melting of the powder gives the part almost full density and mechanical properties equivalent to the bulk material. However, the insufficient surface quality, which necessitates a finishing grinding or polishing step, is one of the short-comings of SLM and results in an inadequacy in fabricating tiny details. Because of the high roughness of built surfaces during SLM, there are often collisions between the roughness peaks the powder coater, which puts a new homogenous powder layer on the workpiece, with the peaks of the rough profile. Tiny structures can easily break as a result of these collisions and this limits the utilization of SLM in micromachining applications. In this paper, the problem is overcome by employing SLE which is a direct method to remove material in a layer-by-layer fashion. The removal of material with a pre-defined depth value after SLM prevents collisions between coater and workpiece and thus results in perfect tiny structures which cannot be produced by SLM only. This paper explains the combined SLM/SLE process in detail as well as the problems encountered during its application.

Introduction

Selective Laser Melting (SLM) is a layer-wise material addition technique that has wide applications such as for rapid prototyping, tooling, and manufacturing offering great advantages and opportunities compared to traditional material removal techniques. SLM has advantages over Selective Laser Sintering (SLS) in producing near full density objects with mechanical properties comparable to those of bulk materials without time-consuming infiltration process [1]. In contrast to conventional manufacturing methods, complex 3D shapes can be achieved without the need of lengthy tool path calculations and the powder material that is left over can be re-used after simple filtering process. On the other hand, because of large energy input of the laser beam and the complete melting of particles, problems like balling, residual stresses and deformations may occur. Moreover, the process accuracy, surface roughness and the possibility to machine geometrical features like overhanging surfaces and internal structures become very important issues. The micromachining capability of SLM is limited to the roughness and the layer thickness. The minimum layer thickness is reported to be limited by a value between 20 and 50 µm [2]. Regarding material aspect of the process, various ferrous [3]-[7] have been processed by SLM. Non-ferrous powder materials are also used in SLM for applications in the medical and aerospace sector [8]-[11].

The process uses very thin layers of metal powder on a building platform to fabricate complex parts by melting targeted geometries with the energy of a laser beam (Fig. 1). In each layer, the laser beam generates the outline of the part that is being built by melting the powder particles. Then the building platform is lowered by the thickness of one layer and coated with a new layer of material powder. In order to achieve a homogenous layer, a coater/wiper is used to spread the powder particles uniformly. Successive scanning and lowering of the building platform are carried out until the part is completed.

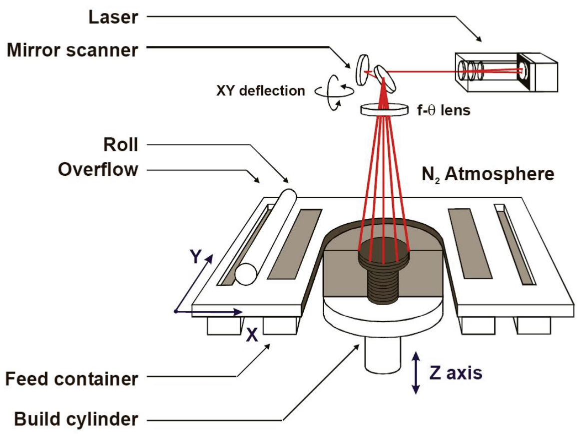


Fig. 1. The working principle of the SLM process [12]

In this paper, Selective Laser Erosion is utilized in order to enhance the micromachining capability of SLM. SLE is a direct method to remove material in a layer-wise manner due to the heat provided by the incident laser beam and can be employed to machine a wide range of materials, including most metals, glass, ceramics and plastics [13]-[15] but it is particularly suited for hard materials which cannot easily be machined by conventional manufacturing methods without sacrificing time and cost [16][17]. Additionally, the diameter of the laser beam can be reduced to as small as a dozen micrometers allowing very small internal radii and fine details to be produced by SLE and this results in high dimensional accuracy and repeatability giving SLE the capability of micromachining applications [18]. Even though the number of parameters involved in SLE is quite large and the relations between them are complicated and have not yet been investigated thoroughly, SLE process parameters can be determined to improve the SLM process by decreasing the layer thickness and removing roughness peaks formed during melting of powder material [18]

Problem Definition

During the SLM process, the thin parts break or are damaged when a new powder layer is deposited. Because of the bad surface finish of SLM process, the peaks of the last molten surface come into collision with the coater which lays a new powder layer. As a result of these collisions, the tiny parts break or are not manufactured successfully. Fig. 2 illustrates the problem. Five series of 3 pins with diameters respectively of 1, 0.7 and 0.5 mm have been built (from left to right). The two first pins of 0.5 mm (third and sixth pins in the row) are broken while the other 0.5 mm pins (ninth and twelfth) are highly distorted. Thus, it is not possible to manufacture pins with a diameter of 0.5 mm successfully by SLM.

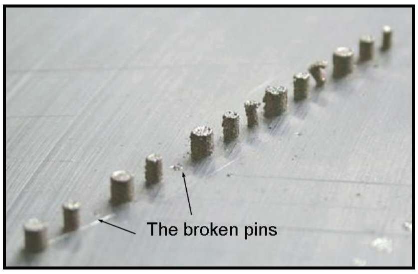


Fig. 2. The demonstration of the problem

The contact of the last built layer with the coater should be avoided or minimized by eroding a part of the last SLM built layer to remove the peaks by SLE process (Fig. 3). Thus, the solution to the problem can be named as the 'Combined Process'.

The experiments in this paper are performed by the combined process using stainless steel powder on the Concept Laser M3 Linear machine with a maximum average power of 100 W. The layer thickness selected in the experiments is 30 µm which is the possible minimum layer thickness. The other parameters used for SLE and SLM processes are given in the Table 1.

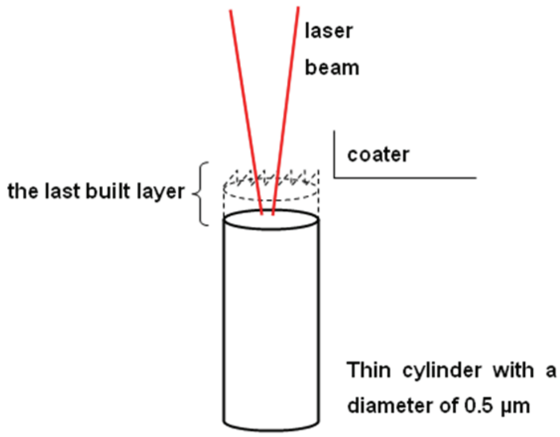


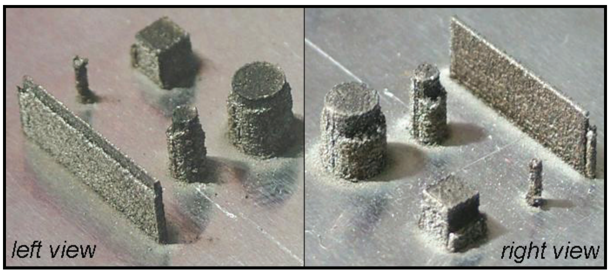
Fig. 3. Schematical illustration of the problem

Table 1: The parameters used in the experiments

	SLE	SLM
Power (W)	100	100
Pump Current (A)	36	36
Frequency (kHz)	30	0 (CW)
Scan Speed (mm/s)	400	400
Scan Spacing (µm)	50	105
Spot Size (µm)	170	170
Depth per layer (µm)	6	N/A

Experimental Results and Discussion

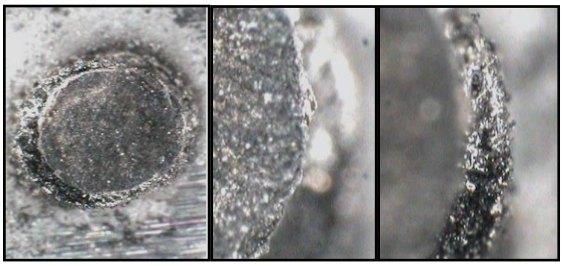
The first tests confirm that the combined process improves the ability of SLM to machine small objects. Fig. 4 shows a successfully built cylinder of 0.5 mm diameter and other objects that are built by combined machining without breakage. The surface quality and dimensional accuracy of the built objects are however not good: a 'bark' appears around the object, which has a different structure from the base object (Fig. 5). It is observed that the height of the bark is about 1 mm less than the object.



(a) (b)

Fig. 4. Wall with 0.5 mm thickness, with bark formation on one side (a), and no bark on the other side (b)

Different tests were conducted in order to investigate the factor that influence bark formation and the experiments showed that the part geometry (cylinder, wall or cube) and the position of the object on the work plane of the machine do not have any influence on the bark formation.



(a) (b) (c)

Fig. 5. Top view of the cylinder (a), including the bark (c) and the base object (b)

The formation of the bark is however dependent on the dimensions of the object. Fig. 4 shows a wall with a thickness of 0.5 mm, which has bark on only one side whereas Fig. 6 illustrates a wall with a thickness of 0.7 mm, which has bark formations on both sides.

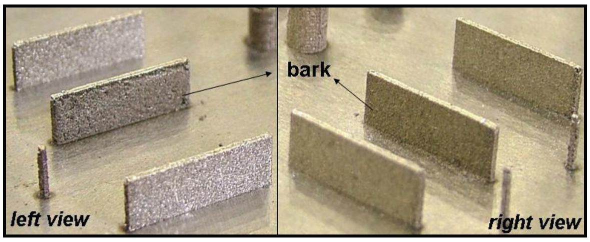


Fig. 6. Wall with 0.7 mm thickness, with bark on both sides

The scan tracks that the laser beam follows during SLE process are also investigated to study the bark formation.

Analysis of scan tracks

An analysis of the laser scan tracks is necessary to explain the formation of bark. The laser follows these tracks to melt the metal powder during the construction of the object. Fig. 7 illustrates the scan tracks for the case of a thin wall with a thickness of 0.5 mm. The full lines represent the scan tracks, while the dashed lines indicate the border of the wall. The figure depicts that the scan tracks of the wall with a thickness of 0.5 mm are not symmetrical. At the bottom side, the scan track is very close to the border. This side is actually where the bark is formed. On the other side, where no bark is existent, there is a larger spacing between the last scan track and the border (at the top).

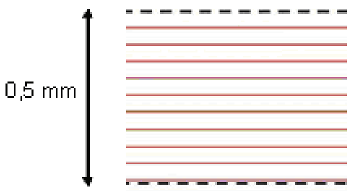


Fig. 7. Scan tracks of a wall with thickness 0.5 mm

The scan tracks of the 0.7 mm wall (Fig. 8) are also analysed. It is observed that they are symmetrical and very close to the border on both sides resulting in barks at both sides (Fig 3).

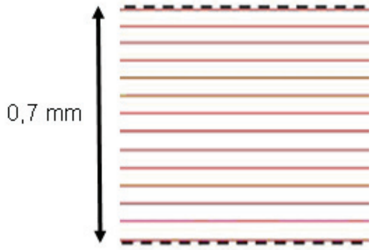


Fig. 8. Scan tracks of a wall with thickness 0.7 mm

This suggests that there is a strong relation between the distance from the closest scan track to the border and the formation of the bark.

The irregular form of the bark around the cylinder is also a result of the distance between the border and the scan track. Fig. 9 illustrates this irregular form of the bark which is close to an ellipse rather than a circular shape. At the sides of the cylinder, the bark formation is larger while at the top and the bottom there is less bark formation. The scan tracks of a cylinder with a diameter 0.5 mm are shown in Fig. 10. In the middle of the circle, at the sides, the length of the contour between the tracks is small as shown with a thick line in the figure. As a consequence, there is a large amount of erosion close to the border and a thick bark. At the top and the bottom of the circle, the length of the contour between the tracks is bigger, thus there is less erosion close to the border and less bark formation.

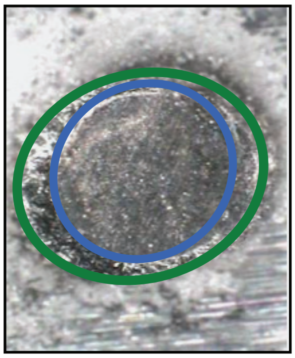


Fig. 9. Irregular form of the bark

The last phenomenon that can be explained by the analysis of the scan tracks is the existence of two vertical lines along the bark of cylinders shown in circles in Fig. 11 whereas Fig. 10 shows the scan tracks used to build such cylinder with 0.5 mm diameter. The vertical lines, visible on Fig. 11, are related to the scan track at the top (or bottom) of the circulated contour shown in Fig. 10 (see oval on top of Fig. 10). This track is very close to the border, so at the top (or bottom) of the circle bark is formed. On the left and on the right of that track, there is no erosion, thus no bark. The lack of bark on these positions in each layer leads to the two vertical lines in the bark.

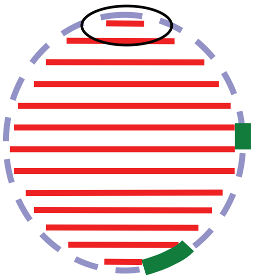


Fig. 10. The scan tracks of a cylinder with 0.5mm diameter

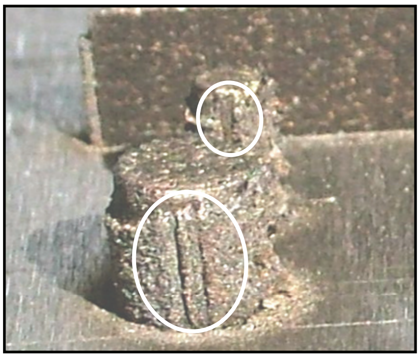


Fig. 11. Vertical lines in the bark of cylinders

The analysis of scan tracks concludes that the influence of the distance of the scan tracks to the border of the object on the bark formation is significant. In order to produce parts without bark formation, the scan tracks need to be analysed in detail and controlled.

Explanation of bark formation

The formation of bark is explained by the divergence of the laser beam (Fig. 12 a). When the scan track is close to the border of the object to be built, the laser partially scans the surrounding powder. During the erosion of the first layer, this layer is in focus and the intensity of the laser energy is very high due to the small focus diameter. The energy evaporates some of the surrounding powder while the vapour pressure blows the rest of the powder away.

During the second layer, some powder is evaporated by the laser beam and the vapour pressure blows some surrounding material powder away (Fig. 12 b). After some layers, the difference in height between the melted object and the powder that is not blown away is so big that this powder is not anymore in focus. Therefore, the energy intensity is not high enough to evaporate the powder but only melts it. Here begins the formation of the bark (Fig. 12 c). As observed during the tests, the formed bark is less high than the object. When the distance of the scan tracks to the borders is small, the laser beam scans a lot of loose powder, and a thick bark is formed whereas the laser beam only scans the melted object if the distance is bigger, resulting in no bark.

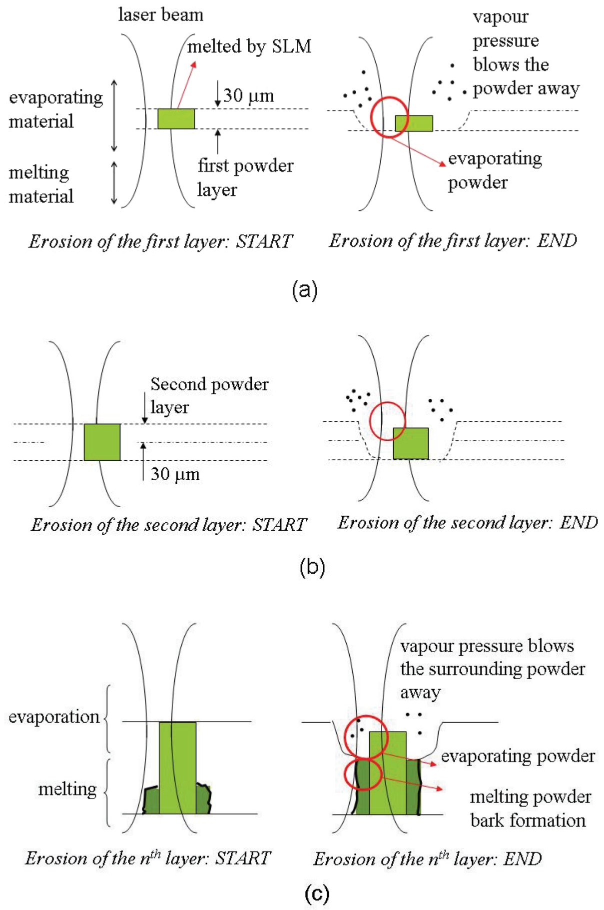


Fig. 12. Formation of bark

Solution

In order to prevent bark formation the scan tracks should be located far enough from the border. This prevents the melting of loose powder around and formation of bark. Fig. 13 shows the result of a test with a spacing of 100 µm between the scan tracks and the border. As expected, no bark is existent, but the small cylinder (0.5 mm) is not successfully completed. In order to achieve tiny objects, the scan tracks have to be close enough to the border of the object to scan the surface completely and erode the full area. Otherwise the coater has still the risk of colliding with the non-eroded material which results in broken or deformed small objects.

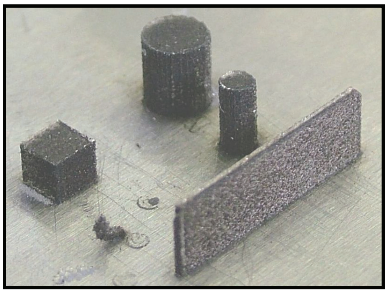


Fig. 13. No bark formation because of the scan spacing of 100 µm between scan tracks and border.

Conclusions

This paper discusses the opportunity to enhance the SLM process by SLE. After each layer is constructed by SLM, a part of the newly built layer is removed so that the collisions of the coater with the rough surface are avoided. The combined process helps to machine tiny details; even cylinders with a diameter of 0.5 mm are achievable. However, the bark formation appears as a problem in the combined process. The location and the scan spacing of the scan tracks has an enormous influence on the bark formation while the object geometry or position on the work plane do not affect the bark formation. The solution to this problem is to locate the scan tracks of SLE process far enough from the border of the object. In order to machine small details without barks, the distance of the scan tracks to the border of the object should be optimized.

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Keywords

Selective Laser Melting (SLM), combined process, Selective Laser Erosion (SLE), bark formation.

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