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Short Communication

An overview of 3D structuring in microdomain[†]

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Abstract

In the emerging field of microrobotics and microelectromechanical systems, complex mechanical parts are gaining importance. On one hand, the overall size and shape of the product is becoming continuously smaller and more complex, and on the other the new product demand/offer is increasing manifold. To overcome this problem, we need a new organizational structure for product development and new technology. This paper highlights various processes, viz. microstereolithography of polymer resin, selective laser sintering of metallic powder as well as melting processes using lasers for rapid prototyping of three-dimensional parts in microdomain.

Keywords: Laser, microstereolithography, lamination, laser sintering, microcladding and microstructuring.

1. Introduction

With advancement in microrobotics and microelectronics/semiconductor technologies, the fields of micromachining and microelectromechanical systems (MEMS) have entered an era of practical applications. Examples of these fabrication technologies include bulk micromachining, micro EDM and micromoulding, etc. These methods have been used to produce many types of MEMS products such as minisensors/actuators and passive components, even packages and prototype devices. Besides, the products are becoming continuously smaller and the new product demand for/offer is increasing manifold. To overcome this problem, a new organizational structure is necessary for product development as well as for new technology. This led to the development of fabrication of microparts by beam technology. The basic idea is to produce or develop a part or a model more reliably with relatively uncomplicated but technically sound process. This technology offers a high potential to reduce the time lag for product development and thus reduces the cost of the end product. Until now, several techniques including laser stereolithography[1] have been successfully used for microfabrication of polymer resin-based two- or three- dimensional parts and rapid prototype products. Recently, two photon microstereolithography techniques have been applied to produce movable microstructures[2] with submicron resolution. Their main disadvantage is that they are two or more step processes for the fabrication of metallic parts. But the recently developed new technology of selective laser sintering/generating/laminating or ballistic particle manufacturing processes[3–10] offers the possibility of direct fabrication of metallic microparts and rapid prototype product in a single-step process. In all these processes, a correct amount of material is deposited/sintered/fused exactly when and where needed to grow the part gradually, where the part is built as a series of successive horizontal layers formed individually and bonded to the preceding layer. The last three processes actually have limitations on the feature size produced, due to minimum size of the molten droplet. But the selective laser sintering technique can bind the

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particles by melting together at the interfacial grain contact area only and thus producing still small feature size. In this paper we review a few of these fabrication techniques that produce complex structure in microdomain.

2. Fabrication technique

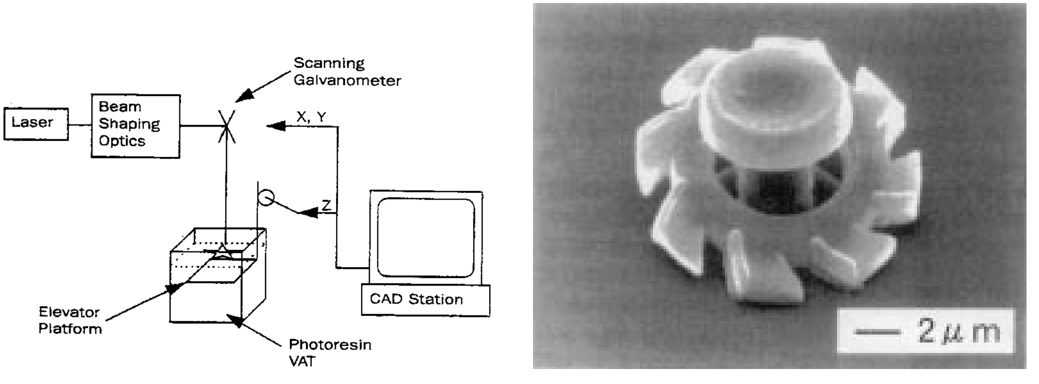
Basically four laser-based techniques, e.g. microstereolithography, lamination, selective laser sintering and microcladding techniques have been applied for generating complex 3D microparts of polymer, metal and metal–matrix composite, intended for rapid product development. In contrast to the techniques already summarized[3] for generating complex 3D structures ranging from micro- to macrodomains, we shall discuss here these techniques briefly with some new features for generating metallic/metal–matrix structures in microdomains.

2.1. *Laser stereolithography*

This method is based on laser photopolymerization (Fig.1a). A liquid polymer is selectively solidified by exposure to an UV laser (He-Cd or argon). The exposed laser beam's absorption is determined by Beer's law and the cure depth can be controlled to match the layer thickness. The initial layer is formed on an elevator platform which can be lowered precisely. This results in layer-by-layer fabrication of the 3D prototype product. The laser is usually directed by a scanning galvanometer or stationary beam. Typical slice thickness is of the order of 25 to 200 μm. Recently, a modified version of this technique has been extended to two-photon microstereolithography, which can produce 3D microstructure with submicron resolution.[2] Figure 1b shows a microturbine structure created with such a technique.

2.2. *Green tape laminated object manufacturing*

In this technique also a layering system is used, but each layer is created from a perforated sheet of material, instead of solid material. Usually, a CO_2 or Nd-YAG laser is used, which cuts the layer outlines which are bonded to the previous layer. The process has well been extended to ceramic, composite powders using a green tape sintering method. The technique is also gaining popularity in producing 3D structured micromachine parts.[4]

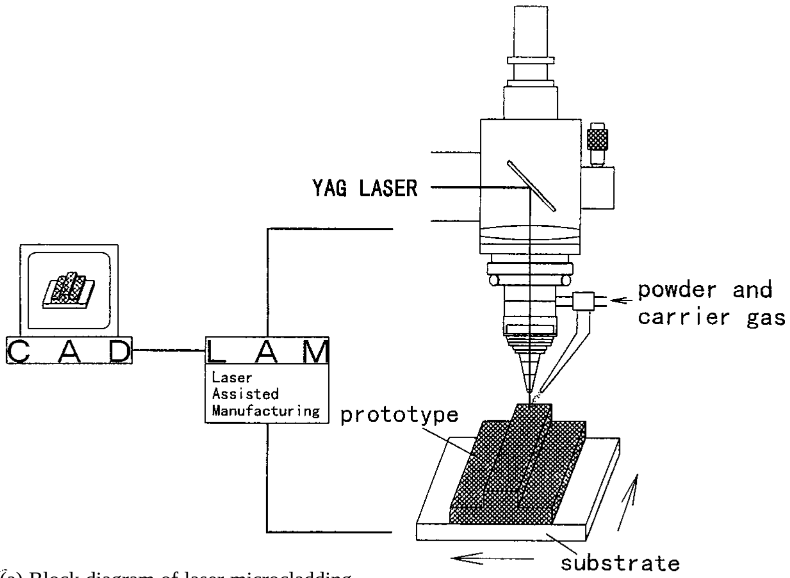


(a) (b)

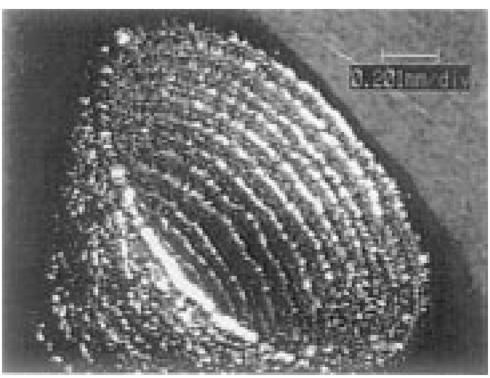
FIG.1. (a) Block diagram of laser stereolithography[9] and (b) microturbine[2]: diameter 14 μm.

2.3. *Laser microcladding*

Laser microcladding is a generic term of the conventional cladding process but applied in the microdomain. In this process, a molten pool of pasted or blown powder with a complex three-dimensional shape is formed on the substrate by laser beam interaction with powder material (Fig. 2a). The previous work recognised that this beam interaction time[5] ($t = D/V$; D: beam diameter; V: processing speed) plays a crucial role for the desired successful cladding and hence the generated structure. Fine structures can be created through layer-by-layer scanning in the horizontal as well as radial direction. Various substrates such as mild steel and stainless steel (304) can be used as base materials. Depending upon the type of the generated structure, it could also be detached from the substrate after necessary machining process, if required. A few test samples of the micro helical structures drawn with line scan process are shown in Fig. 2.



(a) Block diagram of laser microcladding.



(b) Bell structure.

(c) Helical microstructures.

FIG. 2. (a) Block diagram of laser microcladding and (b–c) a few 3D microstructures. Linewidth = 267–500 μm.

2.4. *Selective laser sintering*

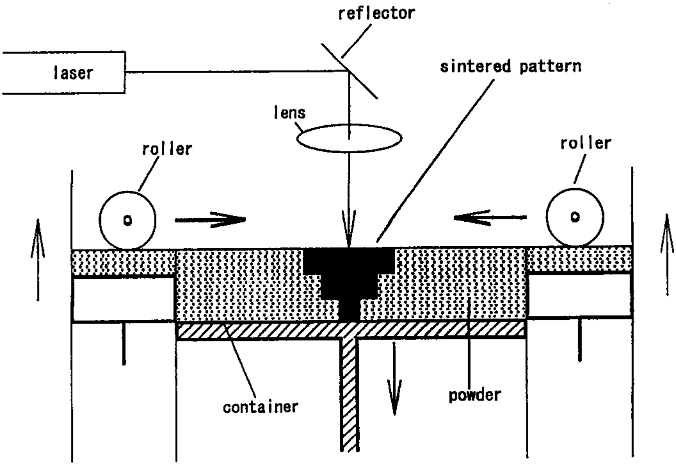
In the case of selective laser sintering process (Fig. 3a), generally there are two widely used techniques. These are described below.[6]

2.4.1. *Direct method: one component*

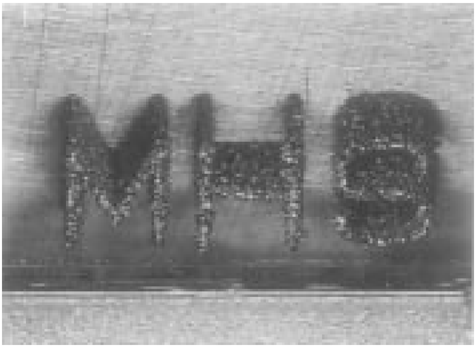
The first one is a direct method, the so-called single-component solid-state sintering in which the laser energy is tuned sufficiently enough to induce the temperature in the powder as close as possible to the melting point of the metal particles, without exceeding it, in order to avoid melt, so that binding occurs at the interfacial grain contact area. In this case, the principle of the sintering process with metal powder is based on the particle fusion[7] at temperatures below the melting point. During the sintering process, a neck forms between two adjacent powder particles. This reduces the surface area and increases the tendency for powder to aggregate. The driving force for this is the reduction of the free surface energy of the particle and the densification is proportional to this reduction. But for higher or complete melting processes, higher viscosity and surface tension effects cause the molten metal to form a spherical ball type structure, which is larger than the particle size. As the laser spot size is usually larger than the particle size, many particles melt together to form a bigger spherical droplet. The size of the spherical droplet depends upon the volume of the powder melted within the focal spot of the laser beam. With higher power and thicker powder layer, the molten material quantity and hence the spherical droplet become bigger. As the density of the spherical droplet is higher than the powder particle size, a cavity forms around the droplet. Due to the large size of the droplet, it connects with other droplets at certain points of the contour. Consequently, there may exist a porosity in the sintered structure. This process is workable only at slow speeds but is difficult to put to practical application. Figure 3b shows the logo structures for the one-component solid-state sintering, in which Ni powder was preferably used due to its various applications in the electronics industry. The average thickness of the wall structure in this case is about 221 μm.

2.4.2. *Two-component method*

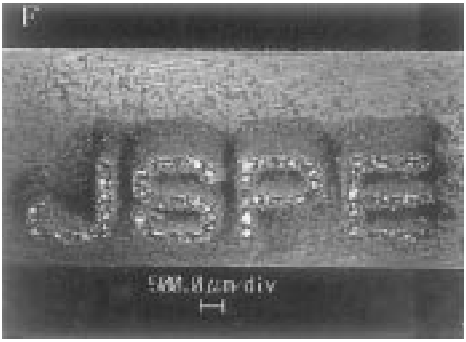
In order to minimize or eliminate post-processes and reduce time lag, the two-component method as described below is more realistic. However, this process becomes more effective with the mixture of two metal powders comprising a high melting point metal ($T2$) which is called the structural metal and a low melting point metal ($T1$) acting as a binder. In this case, the laser energy should be high enough to raise the powder temperature between the melting point of the two metals, i.e. $T1 < T < T2$, and to melt the binder metal and make it flow by driving forces such as liquid pressure, viscosity and capillary forces through the pores between the solid particles. This reduces the pores and causes the strength of the structure to remain intact. For better densification with reduced pores, the grain size of the binding metallic powder should be smaller than that of the structural material. This is because particles of bigger size have higher melting enthalpy due to their large mass and become less susceptible to melting and therefore wet well.[8] The particles of smaller size on the other hand lose their shape completely and form clusters. The large particles are thus wet by the small particles. If the grain sizes of the binding metal particles are substantially larger than the particles of the structural material, their partial melting may leave large pores, which may not be filled by the rearrangement. This could also happen due to low laser energy, which may result in residual porosity. Besides, if the laser energy is too high, excess liquid formation may produce compact distortion. Optimum laser energy and appropriate ratio of binding to the structural material are therefore very essential for obtaining good sintered structure.



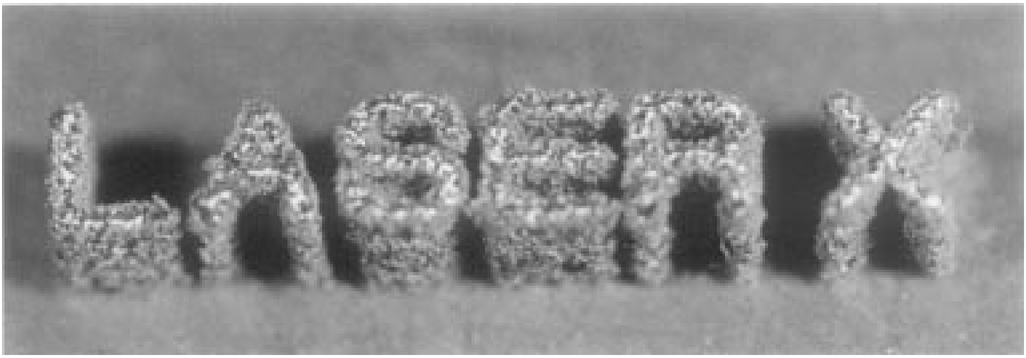
(a) Block diagram of selective laser sintering.



(b) MHS Ni-microstructure.



(c) JSPE composite microstructure.



(d) LASER X Cu-Sn microstructure.

FIG. 3. (a) Block diagram of selective laser sintering and (b–d) a few 3D microstructures. Linewidth = 221–460 μm.

However, for composite materials (i.e. ceramics and metal powders), ceramics exhibiting high melting point become structural material and alloying metal with low melting point acting as a binder. To achieve good wetting and efficient liquid phase sintering, the desirable contact angle is smaller than 45^o, so that the molten metal forms a thin layer on the ceramics particles and binds them together.[6]

Figure 3 illustrates two such examples of metal–metal (Fig. 3d) and metal–ceramic (Fig. 3c) combination for producing the microstructure part. One observes that the width of the line structure created is slightly higher than the one-component solid-state sintering case. This may be due to the melting effects in the liquid phase sintering process.

3. Conclusion

From this report we observe that in rapid prototype manufacturing in microdomain the impact of laser is just beginning. Most of these involve laser as a localized source for photopolymerization, lamination, selective laser sintering or microcladding techniques to produce a complex micropart of polymer/metal/composite material. It is also observed that though it has become possible to create ultrafine micro pattern with the photopolymerization technique, the line width of metallic structure with the laser is still limited by the particle size, molten droplet and surface tension effects. It is also believed that with the current advancement, the microfabrication technology shall come a step closer to the conventional LIGA process.

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