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Practical support structures for selective laser melting

M.X. Gan, C.H. Wong*

Singapore Centre for 3D Printing, School of Mechanical and Aerospace Engineering, Nanyang Technological University, 50 Nanyang Avenue, Singapore 639798, Singapore

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ABSTRACT

Support structure is an essential part in the selective laser melting process which are built especially in cases where reorientation does not eliminate overhanging features. These structures function as anchors, dissipate heat and prevent thermal warping of the parts. However, the materials used for the support structures are often discarded resulting in an increase in manufacturing time and costs. Therefore, this study explores three types of support structures to help design practical supports. As the levelness of each layer is critical in layered manufacturing process, experiments and finite element analysis were conducted to investigate the design effects on manufacturing thin plates and cuboids. The results revealed that the orientation and distribution of the support structures influence the levelness of the built part. Uniformly spaced vertical struts, of only 2.2% overhang-support contact area, enables fabrication of relatively levelled thin plates. Finite element analysis also showed that unequally spaced support structures changes the heat dissipation pattern in the thin plate which can lead to thermal distortions. The results also indicated that the angle between the support structures and the shrinkage direction of more than 90 ° prevents upward thermal warpages.

1. Introduction

Selective laser melting (SLM) is an additive manufacturing (AM) process. The general concept of AM is a group of manufacturing techniques that make use of successive addition of materials in a layerwise fashion creating a three-dimensional (3D) object. According to American Society of Testing and Materials (ASTM), AM, which is also commonly known as 3D printing (3DP), can be broadly categorised according to the pre-processed material format.

The raw material used in SLM process comes in powder form. As such, ASTM (Standard, 2012) categorizes SLM as a powder bed fusion technique. In an SLM process, the roller first deposits a layer of powder from the feed container onto the build cylinder. Excess powder falls into the overflow and is recycled as the roller moves across the build cylinder. An Ytterbium fibre laser with a wavelength of 1064 nm heats the powder to temperatures exceeding the melting point T_m to induce liquid phase fusion. The mirror scanner deflects the laser beam in the *x-y* axis to scan the cross-section corresponding to that layer. After scanning each layer, the build cylinder moves down by a layer thickness for subsequent deposition of powder material. The roller then deposits a new layer of powder in the build area and the process repeats. Particularly in SLM, Bremen et al. (2012) conveyed that the powder particles fully melt, thereby producing a relatively full dense part. Furthermore, the melting process takes place in the build chamber filled with an inert gas such as argon or nitrogen. The complete melting of powder in a layerwise fashion and controlled environment of the SLM process presents an alternative to existing manufacturing methods, especially for geometrically complex parts.

As SLM produces a solid part by fusion of successive layers of cross-sections, the process eases part fabrication of several applications for which in the past was challenging. For example, Wehmöller et al. (2005) successfully fabricated implants, which tend to require customization, through SLM. Furthermore, Hao et al. (2009) developed composites for load bearing implants to be printable through SLM process. In addition to customized parts, the difficulties encountered when manufacturing lattice structures now go only as far as the design stages with SLM (and other AM techniques). With the ability to produce delicate structures requiring no special tooling, Wong et al. (2007) and Emmelmann et al. (2011) showed that SLM is a very promising process for the field of heat transfer and light weight structures respectively. Not only that, Jia and Gu (2014) demonstrated that the high powered laser allows fabrication of materials with high T_m super alloys. Furthermore, the inert gas-filled build chamber makes it safe to process combustible

* Corresponding author.
E-mail address: chwong@ntu.edu.sg (C.H. Wong).

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metals such as pure aluminium and prevents oxidation, thereby ensuring high part quality.

Although SLM is a very attractive manufacturing process for its capability to produce good quality, customizable, and metallic functional end components, there are two drawbacks in the SLM process. Firstly, the powder bed density is not 100%. This implies that there are voids between the powder particles which allow some of the reflected photons to penetrate beyond the intended layer. Therefore, scanning at areas where the previous layer is a solid, depicted in section 1 of Fig. 1, ensures bonding between layers.

Additionally, Chivel and Smurov (2011) reported that scanning at overhanging areas where the previous layer is powder, as shown in section 2 of Fig. 1, results in melt sinking. Chivel and Smurov (2011) also discussed that the Rayleigh – Taylor instability in the gravity field causes the melt penetration into the powder bed. This is a possible explanation because metals have higher density and it is likely that the powder bed has insufficient strength to prevent the melt from sinking due to gravity pull. The heat from the melt pool then caused unintentional sintering of the powder particles, forming unsatisfactory downskin finishes. Furthermore, studies have shown that the thermal conductivity of a powder bed is approximately 100 times lower than a bulk solid (Rombouts et al., 2005). For example, at room temperature, bulk solid stainless steel 316L exhibits a thermal conductivity of 15 W/m K while the measured thermal conductivity for stainless steel 316L powder reads between 0.156 and 0.186 W/m k depending on the powder particle properties. This causes poor heat removal from the melt pool which subsequently affects the properties of the fabricated part. For instance, Mercelis and Kruth (2006) found that the different cooling rates between the top and bottom half of the same layer (section 3 of Fig. 1) can produce compressional or tensional force, raising the tendency for part warpage. Not only that, the thermal variation may introduce microstructural changes. Therefore, support structures are often required to aid heat dissipation especially at overhanging features. Furthermore, it was found that the SLM process is only capable of building unsupported overhanging features inclined up to a maximum of 45 ° and below which require support structures. (Thomas and Bibb, 2008).

Support structures, whose functions are anchors for initially floating objects (Jhabvala et al., 2012), melt pool heat dissipation, and thermal warping prevention (Vandenbroucke and Kruth, 2007), are added and adjusted before the model is sliced into layers during the file preparation process. Adding these structures to the initially separated objects ensures that they are at the correct position before they combine to form one complete part at later stages. Hussein et al. (2013) pointed out another common area that requires support structure is the overhanging feature where major deformation occurs. The support structure at these areas reduces melt dipping and improves heat dissipation from the melt pool. At the same time, the support structure holds down these areas to prevent thermal warpages. For instance, Cloots et al. (2013) and Hussein et al. (2013) investigated the use of lattice structures in place of conventional support structures. Comparable to the conventional support structure types, the results showed rather positive effects on manufacturability of overhangs. These structures built without surrounding walls also allowed retrieval of unused powder. However, lattice structures could be unsuitable in view of future large-scale AM. The amount of overhang-support contact points and structure complexity can hinder the part removal efficiency. For example, the limited space due to the cellular characteristic of a lattice structure can impair cutting tool accessibility. The use of lattice structures also wastes a considerable amount of material. Similarly, the conventional web and tube supports studied by Järvinen et al. (2014) also showed too much material usage and tough removal respectively. Although an increased density of the support structure improves part quality and resolves the melt dip issue as described previously, it is sometimes not desirable. As support structure is not part of the intended component built, the disposal of this extra structure at the end results in material wastages incurring higher expenditure for the production. To establish the design considerations for practical support structures, this paper explores various structure designs to investigate the effect on the final built part.

2. Methodology

2.1. Support structure designs

Three types of support structures, designed with the idea of easy removal and minimal material usage as shown in Figs. 2(a) to (c), will be referred to as inverted-Y (heareafter, simply known as 'IY'), 'Y', and Pin respectively.

A total of six samples for each design, whose dimensions are listed in Table 1, were built. In order to study the effect of these support structures on the manufacturability of a part, the six samples for each design were further divided into two groups of three samples each. In the first group, the support structures were built to support a cuboid, while the support structures in the second group were built to support a thin plate of similar cross-section.

Figs. 2(a) and (b) show the STereoLithography (STL) illustrations of a 16-unit 'IY' and 'Y' support structure model – each supporting a thin square plate respectively. The number of support structures were varied at 16, 25, and 36 in each group. The 'IY' support structures are placed such that the vertical struts are distributed equally within the supported geometry's area (Fig. 2(a)). As for the 'Y' design, the support structures are distributed within the supported geometry's area, in addition to the equally spaced vertical struts in contact with the substrate plate. Referring to Fig. 2(b), having four inclined struts branching out from each vertical strut, a single 'Y' support structure has four times more overhang-support contact points than a single 'IY' support structure. In addition, due to the arrangement described above, the inclined struts of the 'Y' support structures intersects, leading to unequal overhang-support contact spacing ($l_3 > l_4$). Furthermore, the centre row from point indicated y has twice the contact area as compared to other points. On the contrary, the equally spaced vertical struts produce equal overhang-support contact spacing, measured centre to centre ($l_3 = l_4$), for the 'IY' support structure.

Fig. 2(c) illustrates the Pin support structure, generated on overhangs of 5 mm width, supporting a cuboid. The centre to centre separation d of the pin support structure generated, as indicated in Fig. 2(c), was varied at 0.2, 0.4 and 0.6 mm (hereafter referred to as $d_{0.2}$, $d_{0.4}$, and $d_{0.6}$ respectively). The height of the pins ph and overhangs oh are 4 mm and 6 mm respectively. The thickness ot and downskin length dl of an overhang is 1 mm and 4 mm respectively.

In addition, the supported area was segmented into nine equal areas to facilitate support structure removal. Furthermore, maintaining minimal contacts between the overhangs and the build plate allow users to simply chisel built parts off eliminating the need for time-consuming wire cutting process.

2.2. Fabrication and measurement

The samples were built with a layer thickness of 50 μm in an argon gas-filled, Ytterbium fibre laser equipped SLM machine. Stainless steel 316L, with spherical morphology and particle size range of 10–45 μm as shown in Fig. 3, was used to build the samples.

Throughout the whole process, the substrate plate was held at a constant temperature of 473 K. Part removal from the build plate was carried out using an electrical discharge machining (EDM) wire