

LASER RE-SCANNING STRATEGY IN SELECTIVE LASER MELTING FOR PART QUALITY ENHANCEMENT: A REVIEW

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ABSTRACT: The selective laser melting (SLM) process is a powder bed fusion additive manufacturing process that can produce near full-density parts for many high value applications in research and industry. Due to the use of laser, the laser re-scanning strategy (LRS) can be employed in SLM. LRS can be defined as the scanning strategy when any one of the part's layer have more than one passes of laser scan (instead of just one pass under normal scanning circumstances). The laser re-scan can be of any extent, e.g. point, contour, or area. This comprehensive review covers the applications of LRS to enhance bulk properties, improve surface quality, relieve residual stresses, minimize defects and improve part's accuracy. The challenges and future trends for LRS are also discussed.

KEYWORDS: Selective Laser Melting, Additive Manufacturing, Laser Re-scanning, Laser Re-melting, Powder Metallurgy

INTRODUCTION

Background

Additive manufacturing (AM or commonly known as 3D Printing) has gained much attention and popularity for its ability to rapidly build complex prototypes or even functional parts. AM offers many advantages over traditional manufacturing method, e.g. elimination of expensive molds and tooling, efficient usage of material, and ability to manufacture highly complex structure (Fatemi et al., 2017; Sing et al., 2017). For the purpose of direct digital manufacturing, one of the notable and popular AM process would be the selective laser melting (SLM) process. Aside from the general advantages most AM systems have, the SLM process is notable for its ability to produce near full-density parts, providing excellent mechanical properties comparable to wrought parts and superior to as-cast parts (Kruth, Froyen et al., 2004).

Despite SLM's advantages over traditional manufacturing method, near-full density is nowhere enough if full density part is required for high strength application (Yasa, Deckers & Kruth, 2011). Besides, part built with SLM has inherently poor surface finish which renders it from meeting desired service requirements (Calignano, 2018). Moreover, SLM's part building process has inherently short thermal cycles which can limit the flow of molten material, atomic diffusion process, types of microstructure, or even retain residual stress in the final part. Alternative laser

scanning strategy will be explored in this paper to improve the resultant SLM part, in particular, the LRS.

LRS is a broad term and can include many different scanning techniques under the term. Generally, LRS can be defined as the scanning strategy when any one of the part's layer have more than one passes of laser scan (instead of just one pass under normal scanning circumstances). The laser re-scan can be of any extent, e.g. point, contour, or area. It is good to take note that the laser scanning parameters can be different between the first laser scan and the subsequent laser re-scans in the same build layer, hence offering a whole lot of freedom for the SLM process. Figure 1 illustrates the area wide LRS to achieve re-melting of material in each and every layer (shown up to 3rd layer in the figure).

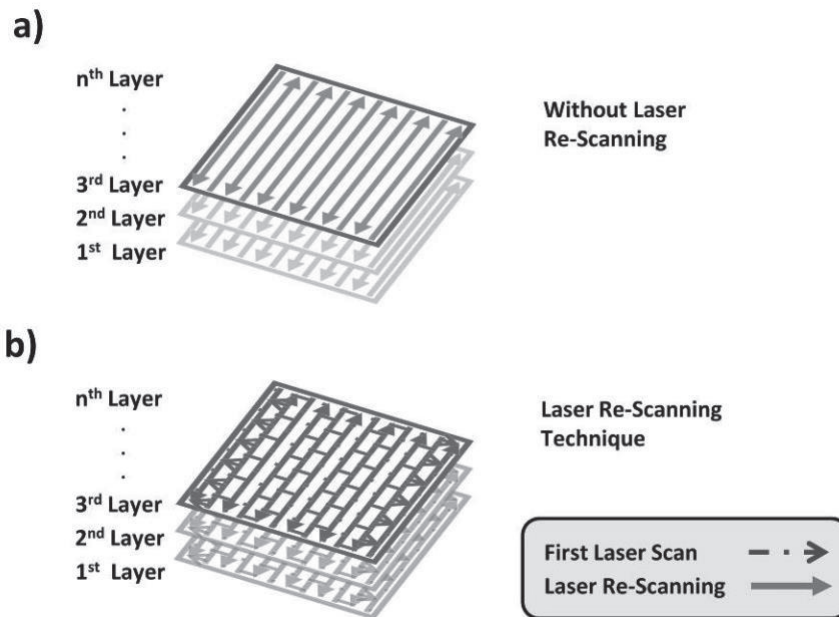


Figure 1. An Illustration of Laser Re-Scanning Technique to achieve Laser Re-Melting at each Layer (In Comparison with Conventional Laser Scanning Strategy).

One of the common use of the LRS in SLM is to achieve part modification via laser re-melting. Laser re-melting procedure is, in fact, not exclusive to SLM but has been studied and utilized in the past as a material modification technique. However, most of the non-SLM studies on re-melting procedure focus only on surface modification rather than bulk modification. For instances, improvement of wear resistance is observed after the laser surface re-melting of hyper-eutectic Al–20Si and Al–30Si cast alloys (Tomida et al., 2003). Moreover, the laser re-melting procedure was used to improve the quality of plasma sprayed coating (Wang et al., 2009). It was observed that the laser surface re-melting of plasma sprayed coating can reduce void formation, improve homogeneity, improve substrate to coating metallurgical bonding, improve surface quality, increase hardness and convert unwanted metastable state to stable state while retaining the nanostructure. Furthermore, the laser surface re-melting procedure was also applied on zirconia-

based bio-ceramic to improve surface wettability and bone-implant interface (Hao & Lawrence, 2006). Laser surface re-melting can also be used to improve the pit corrosion resistance of titanium sheet due to the microstructural changes caused by rapid solidification (Sun et al., 2003).

The laser re-scanning technique is not limited to just laser re-melting modification. It is certainly possible to incorporate different types of laser material modification or processing technology into the LRS, e.g. laser polishing, ablation, and heat treatment. This paper aims to discuss past studies and applications of LRS in the SLM process.

APPLICATION OF LASER RE-SCANNING STRATEGY IN SELECTIVE LASER MELTING

Bulk Properties

The LRS can be used to enhance core material properties of SLM manufactured part. A study by Yasa, Deckers & Kruth (2011) shows the possibility to improve the bulk density of SLM manufactured part by utilizing laser re-melting on every build layer. Moreover, the laser re-melting strategy promotes fine and uniform microstructure, leading to improvement in the part's hardness. The drawback of this method is that the improvement achieved is at the expense of longer build time. The undesirable edge effect was also observed in which more material is accumulated at the edge as compared to the center of every build layer.

Meanwhile, Yasa & Kruth (2011b) shows that SLM manufactured SS 316L part is able to achieve relative density as high as 99.96% via laser re-melting strategy. It was observed that pores formed between neighboring melt pool can be eliminated via this method. Further refinement of microstructure is also achieved by re-melting already melted and solidified material (after first pass of laser). Nevertheless, the undesirable edge effect is also reported in this study.

The work by Aboulkhair et al. (2014) uses a different strategy to reduce porosity in parts (AlSi10Mg) processed by SLM. Every layer of powder is first pre-sintered with half power followed by a re-scan that fully melts the layer at full power (100 W). Relative density as high as 99.8% is achieved with this strategy by minimizing keyhole pores and suppressing formation of hydrogen pores. Figure 2 shows the typical formation of hydrogen pore and keyhole pore in SLM produced part. Without LRS, similar relative density of SLM produced AlSi10Mg part can also be obtained but at a higher laser power, e.g. 99.4 % at 200 W (Thijs et al., 2013) and 99.8% at 900 W (Buchbinder et al., 2011).

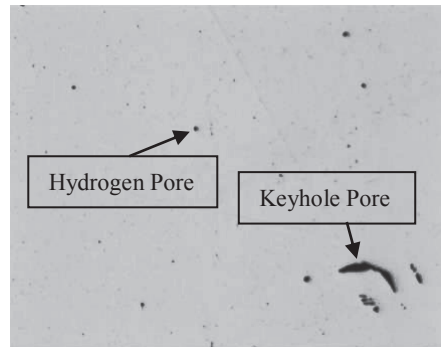


Figure 2. Typical X-Y Cross Section of SLM Produced Part under Optical Microscope showing Keyhole and Hydrogen Pore.

Surface Quality

To improve part's surface quality, laser surface re-melting can be used where only materials near the surface are re-melted. Unlike laser re-melting strategy, laser surface re-melting does not add much time to the part building process. Research by Yasa, Deckers & Kruth (2011) depicted that the usage of laser surface re-melting can significantly improve the part's surface roughness and achieve fully-dense outer shell, achieving better wear properties as well as thermal and electrical conductivity.

Moreover, Yasa & Kruth (2011a) also utilized laser surface re-melting where only the last layer is re-melted. The re-melted zone shows zero porosity and the top surface achieved average surface roughness (Ra) improvement from the original 12 μm down to 1.5 μm . Laser re-melting has also been used only on the contour of each layer to relieve stair case effect, but the improvement achieved is insignificant at only around 10-15% on Ra. A much better improvement of stair case effect at around 70% can be obtained if laser re-melting procedure is done on slanted surface after the part building process and powder removal process is completed.

Furthermore, the incorporation of laser surface polishing process into the selective laser sintering process (a process similar to SLM) has been described by Lamikiz et al. (2007) for metallic sintered parts. The results show clear Ra reductions for sintered SS 420 infiltrated with bronze, up to 80% reduction down to 1.2 μm Ra value. The resulting surface also improves in hardness, homogeneity, and achieve isotropic roughness which could improve part's fatigue life.

Relieving Residual Stress

The issue of thermal residual stress is common in SLM produced part (Salmi & Atzeni, 2017), mainly due to the inherently short and localized thermal cycle. These residual stress can cause warpage, delamination, fatigue life deterioration and worsen strength in the final part. Shiomi et al. (2004) shows that extremely large tensile stress remains in the top layer of the SLM produced part. To solve this problem, laser re-melting strategy has been used on each layer and the residual stress is successfully reduced by 55%. Meanwhile, Kruth, Deckers et al. (2012) shows that the pre-sintering and laser re-melting strategy at every layer does relieve some of the residual stress, but only have warpage angle reduction of 6% and 8 % respectively.

Other Notable Applications

The LRS has also been used for other interesting applications and shall be discussed in this section. For instances, the delamination of build part from the start plate is not uncommon and can render the whole build process useless. As such, laser re-melting of the first layer can be done to prevent this from happening (Hussein et al., 2013). Another notable application of LRS is the combination of selective laser erosion process (subtractive process) with SLM process (additive process) to form a hybrid manufacturing system (Yasa, Kruth & Deckers, 2011). The laser erosion process is based on the evaporation of material and can be used to improve the precision of SLM process. The study has shown that the hybrid manufacturing process is capable of producing inner and outer features in the range of 50 to 100 μm . Moreover, Krakhmalev et al. (2015) has shown the potential of in-situ heat treatment process in SLM such that the laser re-scans are for the purpose of laser heat treatment. Such LRS allows SLM to achieve complex geometry with desired properties, thereby reducing/eliminating the need of post process heat treatment. Last but not least, Jorge et al. (2015) demonstrated the usage of LRS in in-situ correction of fabrication defects. The study is conducted with an electron beam melting system but it is worth mentioning due to its similarities with SLM process. If combined with in-situ monitoring system, the affected area can simply be re-melted to correct the defect whenever one is detected.

FUTURE TREND

Despite the benefits offered by LRS, there are some drawbacks that is of concern. For instances, using LRS on every build layer will significantly increase the build time, hence should only be used when the quality enhancement obtained outweighs the cost of time. Moreover, the usage of laser re-melting strategy induces edge effect (Yasa, Deckers & Kruth, 2011), rendering the as-built final part not usable without post-processing. Furthermore, studies that can be categorized under LRS in SLM is very limited. To the best of author's knowledge, most LRS studies for SLM has been included in this review paper.

To truly unveil the potential of LRS, particularly when applied to every build layer (and area), the edge effect needs to be studied, understood, and eliminated. In addition, more studies can be conducted by incorporating different types of laser material modification or processing technology into LRS. The utilization of multi-laser system can also be explored to improve the current state of LRS.

CONCLUSION

The LRS has shown its potential in past studies and proven useful in the SLM process. The possibility to incorporate different types of laser material modification or processing technology into LRS makes it a robust technique. One common LRS is the incorporation of laser re-melting strategy on every layer to improve part's porosity, hardness and microstructural homogeneity. The drawback is the longer building process and the edge effect. Meanwhile, surface re-scanning strategy like laser surface re-melting and laser polishing allows the improvement of part's surface density and surface roughness. Moreover, LSR can be used to relieve residual tensile stress which is useful in improving part's fatigue life. The freedom of LRS also allows it to be used for applications such as prevention of delamination, hybrid manufacturing with laser erosion process, in-situ heat treatment, and in-situ defects correction.

ACKNOWLEDGEMENT

This research is supported by the National Research Foundation, Prime Minister's Office, Singapore under its Medium-Sized Centre funding scheme. S. Huang would like to acknowledge

Nanyang President's Graduate Scholarship from Nanyang Technological University for funding the Ph.D. studies.

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