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<th>Methods of residual stress reduction for metal parts manufactured using selective laser melting (a review)</th>
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ABSTRACT: Residual stress is commonly associated with metallic parts produced from Selective Laser Melting (SLM) process in Additive Manufacturing (AM). Residual stress is often the limiting factor for employing metal parts fabricated using SLM process in final application. This paper presents a review of residual stress reduction strategies and methods used in SLM process, categorized as pre-processing, in-situ, and post-processing type. Methods used to relieve residual stresses in welded parts which may be applicable to AM produced parts are also discussed.

KEYWORDS: Selective Laser Melting, Additive Manufacturing, Residual Stress, Welding

INTRODUCTION

SLM is one of the AM techniques that is capable of producing end-usable metal parts with complex geometries. The ability to process metal powders in SLM is of great interest in many industries, such as aluminum (Buchbinder, Schleifenbaum et al. 2011) in aerospace, and stainless steel 17-4 (Kotila, Syvänen et al. 2007) in biomedical. However, not all types of materials are suitable to produce end-useable metal parts by SLM as different material suffer from different amount of residual stress (Mukherjee, Zuback et al. 2016). Residual stress is defined as stresses that remain in a structure even after the removal of externally applied loads, and is not necessary to maintain equilibrium between the body and the environment. Research has been done to reduce residual stress in SLM produced parts such as alpha-beta titanium alloy (Ti-6Al-4V) and Inconel 718 (Sticchi, Schnubel et al. 2015) to address the dimensional distortion and poor mechanical properties (Sagalevich 1974). When the residual stress exceeds the yield limit, plastic deformation can occur, causing premature failure below its operating load (Panontin and Hill 1996). Residual stress is often associated with the welding process. In both welding and SLM processes, steep temperature gradient develops due to rapid heating and slow heat conduction (Mercelis and Kruth 2006). To date, AM supports the manufacture of a wide range of materials. However, excessive residual stress is one of the limiting factors for the limited adoption of existing metal alloys in SLM (Frazier 2014). Studies have been done to investigate the “printability” of existing alloys based on common AM parameters (Mukherjee, Zuback et al. 2016) and methods to reduce residual stress is one important consideration.

REDUCTION OF RESIDUAL STRESS IN SLM

The methods to relieve welding residual stresses are classified by Berezhnyts'ka (Berezhnyts'ka 2001) into two categories: a) methods to prevent the formation of residual stress and b) methods to relieve residual stresses in finished parts. Preventing the formation of residual stress in SLM can be further branched out, into another two groups - pre-processing planning and in-situ prevention.
The methods of residual stress reduction presented here are classified as pre-processing planning, in-situ parameter settings, and post treatments.

**Pre-Processing Planning- Design of Support structures**

Support structures are required for some alloys in SLM to prevent dimensional distortion due to residual stress concentration, and thus keep the parts firmly attached onto the build platform throughout the SLM process (Lind, Hanninen et al. 2011). Metallic support structures improve heat transfer between the metal part and base plates (Cheng and Chou 2015), reducing the thermal gradient across the profile and reduces residual stress. Although support structures help to prevent dimensional distortion, they result in higher residual stress in the final build part (Mercelis and Kruth 2006). Although there are commercial software available for designing support structures, such as Magics by Materialise (Materialise 2018), they are mostly developed based on supports for weight of overhang features and not designed to cater to warping due to stress (Cheng and Chou 2015). Hence, further research is required to integrate the consideration of residual stress with the use of commercial software. Overhang features parallel to the powder bed surface require the most support (Vandenbroucke and Kruth 2007). Additional post processing machining required to remove the supports from the manufactured part might induce further residual stress into the part (Reddy, Kwang-Sup et al. 2008). The use of low melting point or soluble materials as support simplifies the post processing work required; however, it is currently not applicable to metallic SLM process. To reduce the time required for support structure removal, pulsed laser instead of continuous scan could be used for printing support structures (Jhabvala, Boillat et al. 2012), which reduces the density support structure produced (Morgan, Sutcliffe et al. 2004). Benchmarking was done to relate residual stress resulted warping with different types of overhang features (K.A. Mumtaz 2012), and attempts to optimize the amount of support structures were carried out (Cheng and Chou 2015).

**Pre-Processing Planning- Maintaining a Semi-Solid State during AM Process**

A possible method applicable to certain metallic alloys was inspired from a process developed for polymers. Given that rapid solidification as one of the causes of residual stress development in AM process, a novel method to reduce the rate of solidification was explored by making use of the different melting point and freezing point in supercooling polymers (Shi, Li et al. 2004). Nylon 12 and 13 have a unique property whereby the melting point is higher than the freezing temperature (Tontowi and Childs 2001). The powder bed is preheated and maintained at a temperature between its solidification and melting point, thus any regions exposed to the laser get melted but does not solidify completely. Holding the printed part in a semi-solid state throughout the process results in a reduced residual stress.

However, this method requires the material to exhibit two different temperatures required for melting and solidification, and the ability of the AM machine to preheat the powder bed to a temperature high enough to maintain the powder in a semi-solid state. EBM will be more suitable as compared to SLM in terms of powder bed preheat capability. In order to reduce residual stress using this concept on metallic alloy, a lower solidification and melting temperature is preferred which corresponds to the eutectic composition (Askeland and Wright 2013) saving the energy required (Campbell 2008). Eutectic Al-Si alloy was successfully manufactured by SLM without the use of support structures to redistribute the residual stress (Vora, Mumtaz et al. 2015).
However, alloys with eutectic composition have relatively low melting point (Callister 2003) and might not be suitable for high temperature applications.

Pre-Processing Planning - Material Property used

The choice of materials to be used in SLM affects the residual stress. In order to minimize residual stress, the material used should have a low volumetric coefficient of thermal expansion, minimal temperature gradient during the manufacturing process, low heat input per unit length (equates to lower input power and higher scanning speed), high flexural rigidity, high elastic modulus, high moment of inertia, and high density of alloy powder (Mukherjee, Zuback et al. 2016). The residual stress development in SLM materials is similar to that of a laminate composite made of different layers of materials with different elastic modulus. In SLM, the addition of each layer of molten material introduces a mismatch in material property with the preceding solidified layer. In laminate composites, residual stress can be reduced by optimizing the ratio of elastic modulus between each material layers (Hbaieb and McMeeking 2002). Functionally Graded Materials (FGM) with varying properties were patented in 1980s (Niino, Suzuki et al. 1988) and finite element model showed that FGM with varying composition can have reduced residual stress as compared to parts with uniform property when exposed to high fabrication temperature (Drake, Williamson et al. 1993). Formulation FGM by varying chemical composition in SLM is difficult. FGM in SLM could be produced by varying porosity (Li, Liu et al. 2010). FGM has been successfully attempted in SLM (Li, Liu et al. 2010, Niendorf, Leuders et al. 2014). There is a possibility to design a part by incorporating DFAM and FGM to fulfil the functional requirements of the part and reduce residual stress.

In-Situ Parameters - In-Situ Heat Treatment of SLM part

Heat treatment of each melted and solidified layer during SLM process was performed experimentally on SS316L. Rescanning each layers with 50% of the laser power used to fuse the powders (100W at 100%) helps to reduce the tensional residual stress by approximately 30% (Mercelis and Kruth 2006). However, using 100% of the laser power used in the heat treatment would cause re-melting of the layer, and the residual stress will not be reduced. For some cases, experimental results show that re-scanning of chrome molybdenum steel (JIS SCM440) with 100% laser power (50W on average) produced 55% reduction in residual stress (Shiomi, Osakada et al. 2004). These two results suggest that the optimum laser power could be used for in-situ heat treatment of each layer varies for different types of material.

In-Situ Parameters - Energy source power and scanning speed

The combination of energy source power and scanning speed determines the amount of energy concentrated per unit length onto the powder material. The ratio of energy source power to scanning speed equates to the amount of energy input per unit length and was used as a parameter of study in several literatures, for welding (Ravisankar, Velaga et al. 2014) and also for AM (Mukherjee, Manvatkar et al. 2017). A high energy input per unit length is crucial for highly reactive materials such as aluminum which tends to develop a layer of oxide, and requires a higher laser power and slower scanning speed to break down the oxide (Buchbinder, Schleifenbaum et al. 2011). However, using higher laser power and slower scanning speed to achieve high energy input per unit length causes an increase in residual stress (Qureshi 2004, Siddique 2005). Keeping the
power input constant, a higher scanning speed results in a lower residual stress in welding (Teng and Lin 1998, Qureshi 2004) as well as in AM for SS304L material (Ren and Dong 2012).

In-Situ Parameters - Scan Strategy

While welding sequence in welding process affects the residual stress in the welded part (Sattari-Far and Javadi 2008), scan strategy in AM affects the residual stress distribution in the AM part. Residual stress perpendicular to the scan direction was found to be higher than the residual stress parallel to the scan direction in stainless steel SS316L manufactured by SLM (Mercelis and Kruth 2006). However, another experimental result shows that the residual stress parallel to scan direction was larger than the stress perpendicular to it for the same material (Liu, Yang et al. 2016). A possible reason attributing to this contradicting result could be due to the scan direction relative to the dimension of the print. It was found that continuous scanning in a long path produces a higher residual stress in the same direction as compared to that produced by a shorter scan path (Mercelis and Kruth 2006). As such, instead of attributing residual stress magnitude to the direction of scan, it would be more appropriate to relate the stress magnitude to the combined effect of scan distance, direction and pattern instead. This combination of scan parameters are known as scan strategy. Studies have been done to develop and test new scanning strategies to reduce residual stress (Dai and Shaw 2002), and many SLM manufacturers have developed their own proprietary scan strategy.

Post Treatment - Cryogenic Treatment of Part

Other than using heat treatment, exposing the part to cryogenic temperature also helps in relieving residual stress. Unlike heat treatment, cryogenic treatment does not compromise on the material properties. Post cryogenic treated steel may have an improvement in its operational life and mechanical properties (Collins 1998, Kamody 1998). Not only was residual stress reduced, Inconel 718 subjected to cryogenic treatment have an improvement in strength, ductility and nano-hardness at room temperature. Cryogenic treatment was found to reduce successfully the surface residual stress on a welded aluminum alloy (Chen, Malone et al. 2000). Residual stress reduction can be enhanced with two cycles of cryogenic treatment of welded SS316 stainless steel (Wang, Wang et al. 2007). A single cryogenic treatment on Inconel 718 reduced 125 MPa of surface residual stress, from tensile to compressive type. The compressive stress was further reduced after a second round of treatment by 23 MPa (Li, Zhou et al. 2017).

SUMMARY

Methods of reducing residual stress of a part fabricated using SLM are presented, and categorized into 3 stages. Some methodologies require more resources, such as developing a new FGM. Some methodologies are dependent on the type of AM or the machine capability itself, such as in-situ treatment, source power, scan speed, proprietary scan strategies, and maintaining semi-solid state during the SLM process. Methods such as design of support structure, although assisted by existing software, require human judgment from experience or prediction by simulation to ensure a successful build. Hence, selecting a combination of suitable methods in the three stages presented is required to successfully produce end-usable parts.
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