Residual Stress Distributions in Laser Powder Bed Fusion Steels Considering Displacive Phase Transformation

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Introduction

Additive Manufacturing (AM) is a promising method by which materials are built up layer-by-layer manufacturing method instead of the conventional subtractive machining method. Laser powder bed fusion (L-PBF) is one such method for metallic parts offering advantages such as high printing resolution and providing a near-net shaping manufacturing possibility. This opens up potential applications in the aerospace, transportation and biomedical sectors, where complex and customized components are needed.

However, the L-PBF technique still faces serious challenges, especially the entrainment of defects [1] and excessive residual stresses [2]. For as-built components, tensile residual stress is usually generated near the surface [3], which hinders its wide application in the industry by forming deformation, cracks and accelerating the fatigue crack initiation. This is because the great thermal gradient introduced by the laser and subsequent cooling shrinkage leads to a thermal contraction misfit between top layers and the underlying materials. Various techniques have been used to reduce the residual stress, including manufacturing parameter modification [4] and post-processing heat treatment [5]. Here the exploitation of the volumetric changes associated with the displacive phase transformations during the printing process is considered.

This strategy has been used previously to mitigate stresses due to welding. Moat et al. [6] investigated the stress relief during the welding/multipass-welding process in low transformation temperature materials. They found that the tensile strain on the top layer of welding, introduced by fast cooling, could be balanced by the martensitic volumetric transformation strain. For certain low transformation temperature steels, the formation of compressive residual stress on the top layers is possible, which could improve the fatigue properties.

L-PBF is similar to multipass welding in terms of the fast cooling rate and the layer by layer build method. In this paper, the influence of phase transformation on residual stress relief is investigated.

Methodology

For L-PBF manufactured maraging steel M300 (Fe-18Ni-10Co-5Mo), the martensitic phase transformation starts once the temperature is lower than ~143 °C, thus showing a plateau in the cooling diagram (temperature vs. time). While for ferritic steel 430L (Fe-16Cr-Mn), the austenite phase transfers to the ferrite phase during the cooling process, without displacive phase transformation. So, M300 and 430L were chosen in this paper to investigate the displacive phase transformation effect on residual stress and the relationship between phase transformation and printing parameters. Cylindrical samples (Φ20mm *18mm) were manufactured with the following L-PDF parameters: 180 W power, 30 µm layer thickness and 45 µm hatch distance. The scanning speeds were 1000 mm/s and 1400 mm/s, leading to different thermal strains.

In this paper, the residual stresses were measured by the contour method [7], conducted at the University of Manchester. The contour cuts the as-built sample into two halves by Electrical Discharge Machining (EDM) along the build direction, which is a destructive measurement. This method assumes that the measured surface is flat before cutting, and the curve of the surface is introduced by the deformation introduced by the residual stress relief. The profile of the surface is measured by a Nano-focus µscanner and then imported into Finite Element Analysis software (the open-source framework pyCM [7] was used in this paper). The original out-of-plane residual stresses are inferred by calculating the stress field introduced on returning the cut surface profile to a flat surface.

Result and Discussion

The residual stresses measured by the contour method for the additively manufactured samples are shown in Fig. 1.

As shown in Fig. 1 (b and (d, the L-PBF 430L samples have a residual stress distribution typical of L-PBF. Namely, a compressive residual stress in the centre, while tensile residual stress around the periphery, especially in the top and bottom regions. The residual stress distribution is influenced by scanning speed. Faster scanning speed results in higher tensile residual stress values in the top layers, but a smaller region, which explains the lower residual stress in the bulk region.

The L-PBF M300 samples on the other hand show a relatively complex residual stress distribution. Compressive and tensile residual stress regions appear alternately. For the top surface region, compressive residual stress was measured, which is in contrast to the 430L samples. However, fast scanning speed leads to smaller residual stress in M300, which is consistent with 430L, as can be seen from Fig. 1 (c and (e.

For the overall residual stress, M300 samples have smaller residual stress and show compressive residual stress on the top surface, which could be a better distribution than the 430L samples. That kind of residual stress relief and distribution optimization might be caused by the low-temperature transformation of M300.

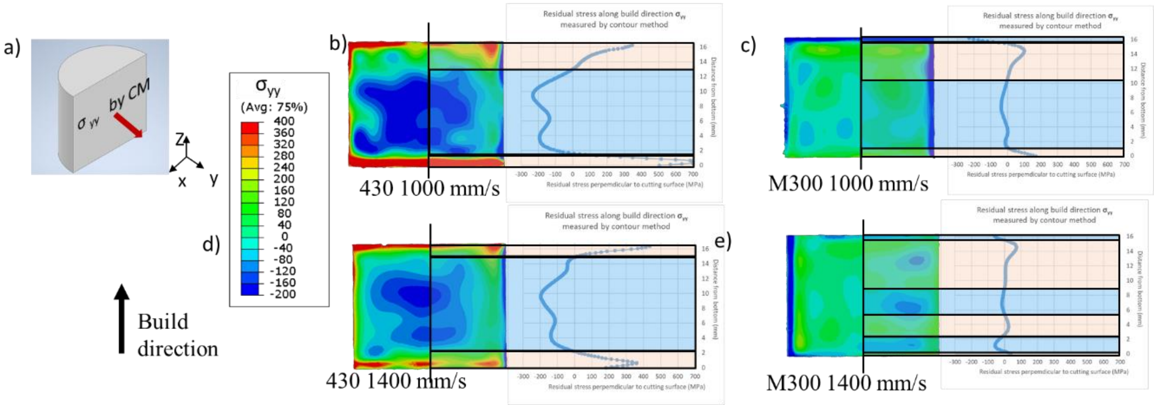

Figure 1 the residual stress, perpendicular to the build direction (σ_{yy}), distribution calculated by pyCM. a) Schematic of the residual stresses measured by the contour method; b) as-built 430L samples with scanning speed 1000 mm/s; c) as-built M300 samples with scanning speed 1000 mm/s; d) as-built 430L samples with scanning speed 1400 mm/s; e) as-built M300 samples with scanning speed 1400 mm/s.

Conclusions

1) For L-PBF 430 samples, there is tensile residual stress on the top and bottom regions and compressive residual stress in the middle region.
2) For L-PBF M300 samples, an alternative compressive and tensile residual stress is shown, with compressive residual stress on the top surface and tensile residual stress on the bottom area.
3) L-PBF M300 samples have smaller residual stress than 430L.

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