Thermal Stresses in Direct Metal Laser Sintering

Haiko Pohl[1], Abdolreza Simchi[1,2], Munther Issa[1,3] and Hugo Calefi Dias[1,4]

1. Fraunhofer Institute for Manufacturing and Advanced Materials IFAM, Bremen, Germany
2. Department of Materials Science and Engineering, Sharif University of Technology, Tehran, Iran
3. Department of Production Engineering, University of Bremen, Bremen, Germany
4. LabMat - Laboratório de Materiais, Universidade Federal de Santa Catarina, Florianópolis – SC, Brazil

Abstract

In Direct Metal Laser Sintering objects are created by sequential sintering loose metal powder particles by means of laser technology. When the laser sintering process involves temperature gradients, thermal stresses develop. Corresponding residual stresses induce warping of the densified structure leading to unacceptable tolerance losses. This paper examines the role of laser beam scan patterns on the resulting stresses and warpage of direct metal laser sintered plate-shaped specimens. The effects of a large variety of laser sintering parameters are described. It can be shown that the optimization of process conditions and material aspects results in a significant reduction of thermal stresses.

Introduction

Direct Metal Laser Sintering is one of a few Rapid Prototyping technologies which possesses the capability to produce metal parts and prototype tools directly from powders. The high laser power supplied by a cw CO_2 laser binds effectively metal powder particles together. Such laser sintered objects then exhibit high densities in the range of 95% theoretical density. Due to the high thermal energy which is required to promote all steps of material re-arrangement and densification during sintering within an extremely short period of time [1], thermal gradients exist in the densified structure. Thermal stresses and corresponding residual stresses induce warping and/or cracking of the object. Warping normally leads to tolerance losses but cracking results in a more detrimental loss of quality.

Various authors have discussed the role of thermal stresses in layered manufacturing, for example in Stereolithography by Jayanthi [2], and Ullet [3], in Selective Laser Sintering by Karapatis [4], and Dalgarno [5], in Shape Deposition Manufacturing by Chin [6], Klingbeil [7], and Nickel [8]. From all those contributions can be predicted that both material properties of the laser sintered system and process parameters such as power intensity, scan rate, thickness of layer etc., control the appearance of thermal stresses. In order to reduce the level of warpage in laser sintered objects, a detailed examination on the role of process parameters was performed. The variation of process parameters is described on two different powder systems, namely pure iron (Hoeganaes ASC 300) and a commercial steel-based powder DirectSteel 50-V1 (EOS GmbH, Germany).

Experimental

The powder systems were sintered layer by layer to the required shape using EOSINT M250*X*tended laser sintering machine. The machine consists of a powder handling system, a continuous wave CO_2 laser source with related optics and a process computer. When a part is to be built, the CAD file is sliced into a stack of thin layers. The powder is deposited on a steel platform using a doctor blade. The layer thickness can be varied from 0.05mm to 0.2mm. Then, the laser beam is scanned on the bed surface. The maximum output power is around 200W. The scan rate can be in the range of 50 to 175mm/s for the mentioned materials. The building process was performed under nitrogen atmosphere. The build plate temperature can be set to 80°C.

Two different material systems were used. Pure iron powder type ASC 100 (d_{90} = 45µm) from Hoeganaes was used to study the effects of process parameters on a one-component powder system. DirectSteel 50-V1 (d_{90} = 35µm) is a commercial steel-based powder from EOS GmbH for the direct part production or rapid tooling applications. The powder system consists of a low melting phase which promotes liquid phase sintering.

A steel sheet 1.1403 (1mm thickness) was fixed using screws onto the build plate. A test part with dimensions 60mm x 14mm (variable height) was then laser sintered on top of the steel sheet. The residual stresses in the laser sintered test part result in a deflected steel sheet. After removing the steel sheet from the build plate, the amount of deflection was measured pointwise along the axes on the backside of the steel sheet in x- and y-direction. The precision of the dial gauge was within 1/100 millimeter (Fig. 1).

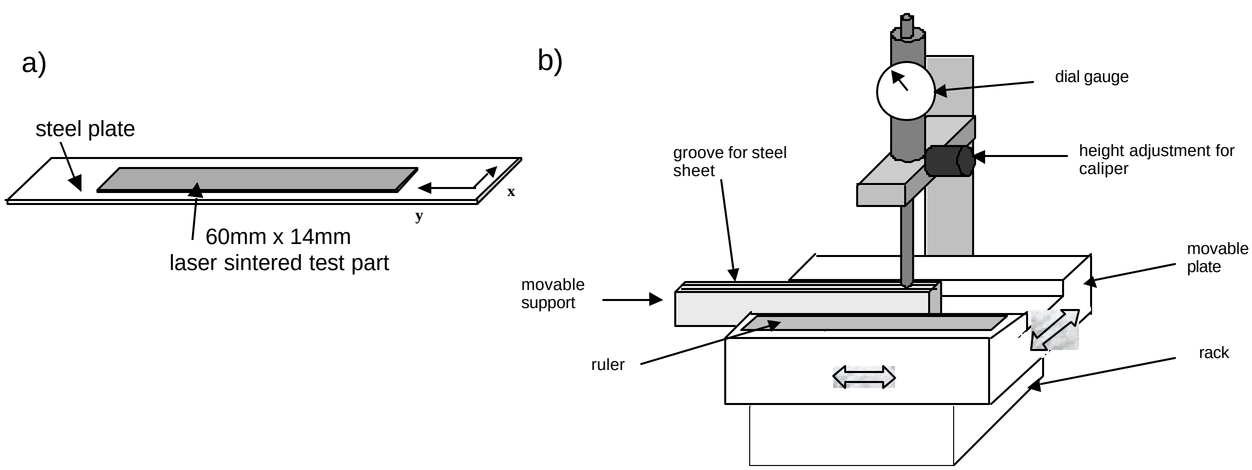

Figure 1: Steel sheet with laser sintered test part (a) and device for deflection measurement (b)

Laser power intensity, scan rate, hatch distance, layer thickness, and number of layers were varied to examine their influence on the amount of residual stresses. Additionally, several scanning patterns were applied. Here, the main target is the variation of the thermal gradient by using different laser scan lengths. An overview of the scanning patterns is given in figure 2.

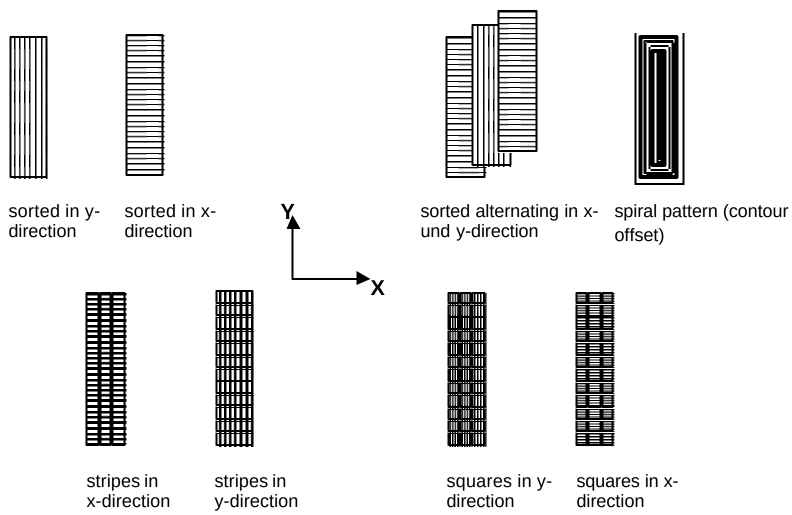

Figure 2: Scanning patterns used in Direct Metal Laser Sintering

The scanning pattern “Sorted” is a typical raster pattern with a short raster pattern in x-direction and a long raster pattern in y-direction. This type can be alternating from layer to layer, starting with a short raster pattern for the first layer. In the spiral pattern, first the laser scans the contour continuously in a single line scan. According to the hatch distance, the contour is offset towards the center of the part and repeated when a new single line scan follows. Scanning pattern “Stripes” is a combination of short and long raster patterns. Here, a short raster pattern determines the width of the stripes. Stripes can overlap each other. "Squares" normally are not attached to each other after scanning. The gap is then closed by a single line scan.

Deflection Measurements

Thermal stresses and corresponding residual stresses develop in the densified structure during laser sintering. The three dimensional stress state is characterized by their components in x-, y-, and z-direction. The deflection of the steel sheet is a result of the stress state in the densified structure. Measurements of the deflection can give a description of preferred process conditions in order to minimize warpage.

Generally, the steel sheet deflects in a bell shape. When the steel sheet is removed from the build plate, the edges bend up whereas the center remains in its original position. Figure 3 depicts the influence of the hatch distance on the deflection for the scanning pattern “Sorted”. Keeping all other process parameters constant, the reduction of the hatch distance clearly leads to an increase of deflection.

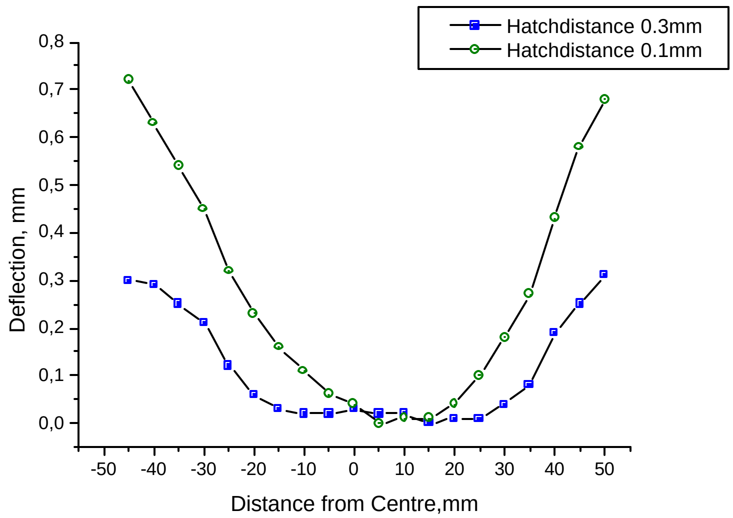

Figure 3: Effect of hatch distance on the deflection of a steel sheet with laser sintered test part, pure iron, sorted with long raster pattern, 50mm/s scan speed

Decreasing the hatch distance is equivalent to increasing the overlap between consecutive laser scan lines. Practically, a lower hatch distance results in a more localized heating of the powder bed by the laser source. In this case, temperature gradients must be more pronounced and bring about more thermal stresses compared with a more homogeneous heating.

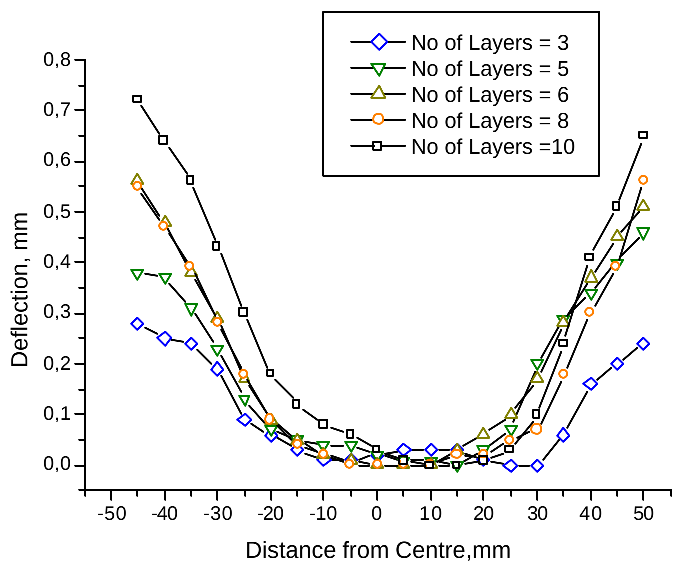

Figure 4: Effect of sample height on the deflection of a steel sheet, pure iron, sorted with long raster pattern, 50mm/s scan speed

Changing the number of layers was used to vary the height of the laser sintered test part. From figure 4 it can be noted that the amount of deflection in longitudinal direction increases with more layers. In contrast, the amount of deflection in transversal direction decreases with more layers. When new powder is spread onto the previous layer and densified by the laser beam, thermal stresses pile up. Neither annealing effects nor a saturation of this pile up was not found. However, the increasing deflection in longitudinal direction restricts the deflection in transversal direction.

The effect of material composition on the deflection of the steel sheet was examined by laser sintering two different powder systems. Figure 5 compares the results for pure iron and a commercial steel-based powder DirectSteel 50-V1. Although laser sintering of iron powder seems to result in less deflection compared with DirectSteel, it must be considered that iron is densified only up to 75% theoretical density (TD) but DirectSteel up to 95% TD. A higher degree of densification seems to promote the formation of residual stresses. Additionally, during laser sintering of DirectSteel material, a considerable amount of liquid phase should exist in order to generate liquid phase assisted sintering. During the solidification of the liquid and the accompanied volume shrinkage, further stresses may be induced into the adjacent densified structure.

In order to minimize thermal stresses, optimized process conditions should be chosen. However, some process parameters may be contradictory with one another. For example, in figure 6 the amount of deflection is compared between different types of scanning patterns using various scan speeds. While a high scan speed clearly leads to a significant reduction of residual stresses and, therefore, should be preferred, it also lowers the energy input and decreases the densification.

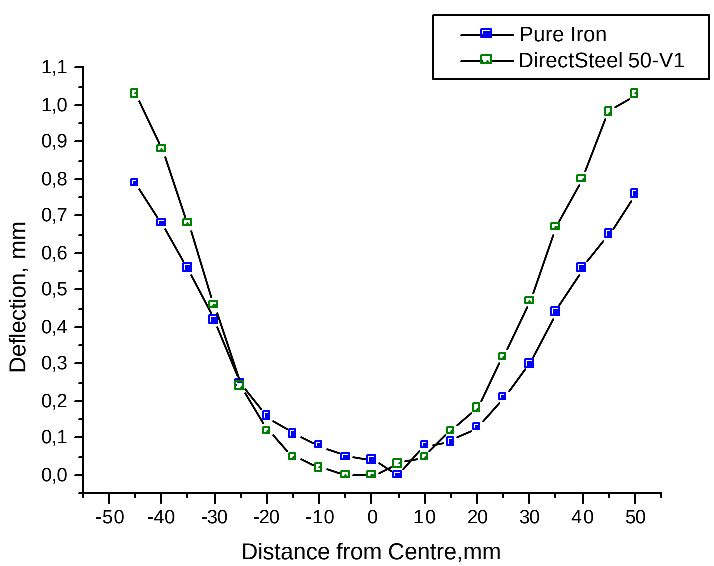

Figure 5: Effect of material composition on the deflection of a steel sheet, sorted with long raster pattern, 50mm/s scan speed

If the applications are such that high densities and corresponding good mechanical properties are required, a lower scan speed must be used. On the other hand, there is still a high potential to exploit as the differences in various scanning patterns are relatively high. The highest amount of deflection was detected for the spiral pattern. Due to the long scan vector length, temperature gradients are very high. The difference for low and high scan speeds is relatively small. Here, the spiral patterns seems to have a positive effect on a homogenized sample heating as soon as the outer contour scans are finished.

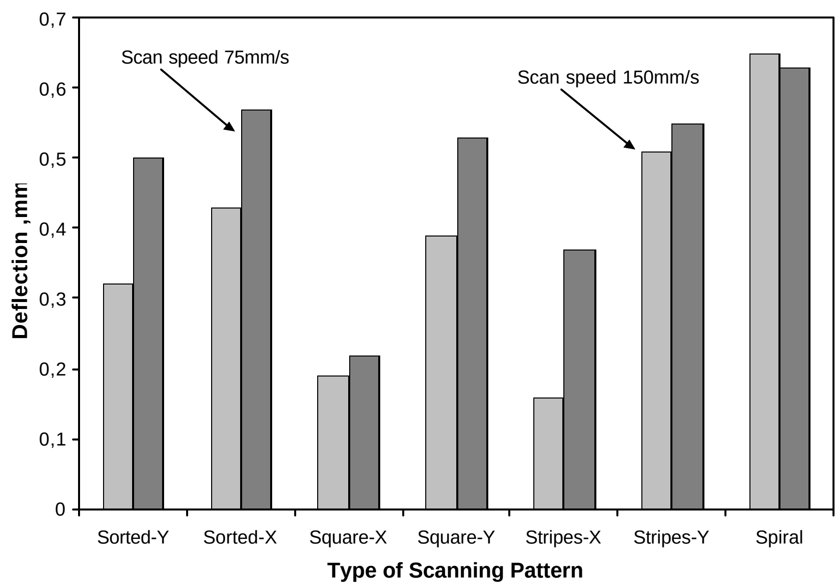

Figure 6: Effect of various scanning patterns on the deflection of a steel sheet at different scan speeds, pure iron (X = short raster pattern, Y = long raster pattern)

The lowest amount of deflections were detected for "square" and "stripes" type pattern with short vector lengths (x-direction). But the residual stresses increase significantly when a long vector length (y-direction) is applied for those types. The difference between short and long raster pattern for type "sorted" is quite small. In contrast to the stripes pattern, the preheating of the powder and substrate might not be well enough by just one progressing laser line. In stripes pattern, the preheated area is mostly determined by the width of the stripe. If the width of the stripes was set at an appropriate rate to the overall dimensions of the laser sintered structure, a significant reduction of residual stresses can be expected.

Conclusions

This study contributes deflection measurements in order to achieve assessments for thermal stresses and corresponding residual stresses in laser sintered test parts. From the results it can be noted that several factors including processing conditions and material aspects play an important role. To minimize residual stresses, a optimum process parameters should be chosen. However, some parameter sets which are essential to other properties such as density or strength of the laser sintered structure may be contrary to the goal of reduced stresses. It was found that such process conditions leading to a higher densification by increasing the energy input bring about a higher deflection and, thus, higher residual stresses. Whenever a slightly lower final density is acceptable, faster scan speeds, larger hatch distances, less layers with higher layer thickness are recommended.

For different scanning patterns, the lowest deflection was measured for scanning patterns type "Stripes" and "Squares". However, the improvement highly depends on the direction of the line scan. The deflection can be minimized if a short raster pattern is applied. For example, due to the width of the stripe, the laser beam more efficiently preheats the unsintered powder and the substrate material. This results in a more homogeneous temperature gradient and reduced thermal stresses.

Acknowledgements

One of the authors (A. Simchi) is indebted to the Alexander von Humboldt Foundation (AvH) for a research fellowship. This author also acknowledges Sharif University of Technology, Tehran, Iran for permission to reside in Germany as a visiting scientist at the Fraunhofer Institute IFAM.

References

[1] Simchi, A., Petzoldt, F. and Pohl, H.: Direct Metal Laser Sintering: Material Considerations and Mechanisms of Particle Bonding. *Int. J. Powder Metall.* Vol. 37, No. 2, 2001.

[2] Jayanthi, S. et al.: Proc. Solid Freeform Fabrication Symposium, 250-258, 1997.

[3] Ullett, J. et al.: Proc. Solid Freeform Fabrication Symposium, 242-249, 1994.

[4] Karapatis, N. et al.: Proc. Solid Freeform Fabrication Symposium, 79-87, 1998.

[5] Dalgarno, K. et al.: Proc. Solid Freeform Fabrication Symposium, 721-728, 1998.

[6] Chin, R. et al.: Proc. Solid Freeform Fabrication Symposium, 221-228, 1995.

[7] Klingbeil, N. et al.: Proc. Solid Freeform Fabrication Symposium, 125-132, 1997.

[8] Nickel, A. H., Barnett, D. M. and Prinz, F. B.: Thermal Stresses and Deposition Patterns in Layered Manufacturing. *Materials Science and Engineering*. Vol. 317, 2001.