Selective Laser Sintering of Stainless Steel 314S HC processed using room temperature powder beds.

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Abstract

Metal powder bed pre-heating is a proposed route for the homogenisation of temperature gradients that can otherwise cause individual layer warping and cracking in direct metal Selective Laser Sintering (SLS). However, the high temperatures involved complicate a relatively simple process. This paper reports on the conditions for successful small scale SLS of binderless stainless steel 314S powders within the surrounds of a room temperature powder bed. Results show that a scan length around 15.0mm and a scan spacing around 0.275mm produce sintered layers showing no signs of warping. Experimentation also indicates that single layer shape effects warping but length of layer propagation does not.

Keywords

Rapid prototyping, Selective laser sintering, Processing, Part quality.

Introduction

A three dimensional direct metal part built by SLS contains many layers. Each layer is constructed by selectively sintering a metal powder bed, locally at elevated temperatures. The heat input is supplied by a laser beam which raster scans a pre-defined area (from a CAD model), heating and consolidating thin tracks of powder as it travels. The scan spacing determines the amount of overlap between adjacent lines (See Figure 1). Values of scan spacing are often small, typically ½, ¼ and $^1/_8$ of the beam diameter. This permits strong bonding which aids densification. After completion, the powder bed and sintered layer are lowered, allowing a fresh layer of powder to be spread into the build zone and the process repeats. Bonding must also occur between laminates as the new layer is sintered. This is achieved by appropriate selection of the layer thickness that allows heat to conduct sufficiently into the lower laminate. However, as the laser moves in a back and forth cyclic manner across the powder surface, each consolidated track can be heated several times before the laser passes. This scanning technique creates a unique temperature-time history causing thermal gradients to build up in the xy plane during single layer growth. Analogous to scan spacing, the build up of layers also allows thermal gradients to exist in the z plane. The existence of the thermal gradients permits differential shrinkage of the sintered layers during cooling, causing warping, layer cracking and inter laminae cracking [1 - 3].

There are a number of reported methods that have been investigated to prevent thermal distortions and cracking during metal sintering [4,5]. The most successful methods are: (1) powder bed pre-heating aimed at homogenising temperature distributions over entire laminates (~1000°C) and (2) by anchoring through sintering the first layer and any overhangs to

substrates placed within the powder bed. The substrates are usually sacrificial but could be designed as an integral part. All these techniques have proven successful though they complicate what should be a very simple process.

The research within this paper is (for us) a second step in understanding the process of metal powder solidification during SLS. This paper reports the conditions for creating single and multiple sintered layers with no powder pre-heating or conditioning and no additional support structures. Emphasis of the work is to establish a range of scanning routines that control the build up of thermal gradients during metal powder heating and cooling that will allow the creation of unwarped and uncracked layers.
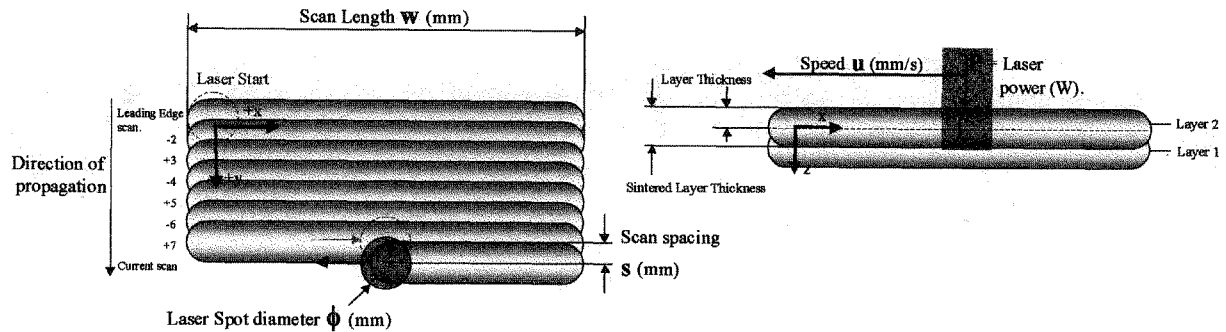

Figure 1: Clarification of scanning parameters.

Material

The material under investigation was a standard grade gas atomised stainless steel powder classified as 314S HC, an austenitic steel with a high carbon content (referred to as 314S). The material composition is given in Table 1. The powder was sieved into four batches having particle size distributions of $-300+150\mu m$, $-150+75\mu m$, $-75+38\mu m$ and $-38\mu m$. Each batch was used to examine whether thermal distortions are affected by changes in powder particle size.

Elements	(Fe)	(Ni)	(Cr)	(C)	(Si)
Weight %	Bal.	20.0	25.0	0.4	1.0

Table 1: Stainless steel 314S HC material composition.

SLS Machine and Environmental Control Equipment.

The Leeds high power SLS machine includes a 250W continuous wave CO_2 laser with a spot diameter adjustable between 1.0mm and 2.0mm at the focal length. Galvanometer controlled mirrors direct the laser beam onto a 70.0mm diameter build area which is housed within a $0.03m^3$ (L=460mm, H=260mm, D=250mm) process chamber (Figure 2) capable of sustaining a variety of atmospheric conditions including an absolute pressure of 10mbar.
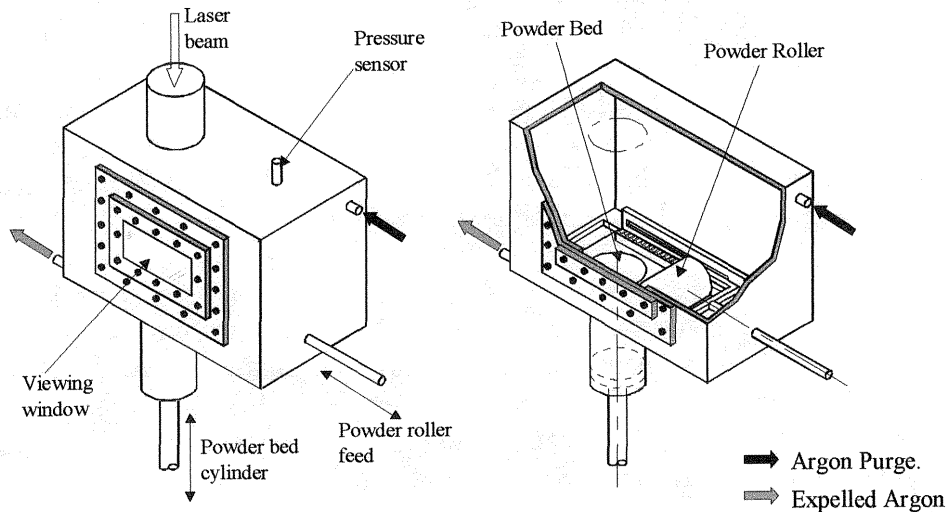
Figure 2: The process chamber.

For the work reported here, oxygen dilution within the chamber is achieved by a combination of evacuation followed by a continuous purge of argon (bottled argon at 99.9% purity). Effects of oxygen are detailed in a companion paper [6].

Experimental Procedure

The four batches of 314S were sintered in the conditions in Table 2. Single line and layer scans with scan lengths ranging from 5.0mm to 150.0mm were sintered within an argon atmosphere while observing for signs of warping and cracking. The number of scanned lines within a layer ranged from 1 to 200. Multiple layer sintering in the same conditions as the previous experiment then followed. Observations were recorded including how the layer thickness influenced warping and inter layer cracking, causing delamination.

The argon atmosphere (which still contained traces of oxygen) was achieved by evacuating the process chamber to a pressure of 50mbar followed by a pre-sinter purge of argon for 10 minutes at atmospheric pressure. During sintering the gas inside the chamber was held at 30mbar above atmospheric pressure.

Atmospheric Condition	Beam Diameter (mm)	Laser Power (W)	Scanning Speed (mm/s)	Scan Spacing (Fraction of beam diameter)
Argon	1.1	0 – 185 in steps of ~10	1 – 100 in steps of ~2	0.25,0.5,0.75

Table 2: Experimental conditions.

Results of single layer sintering

Single line scans varying in length from 5.0mm to 150.0mm were sintered while observing for signs of warping (See Figure 3). As has already been presented [6], single lines and layers could be obtained within an argon atmosphere above a (power/speed) energy density

range of 1.0 – 2.0 W/(mm/s). In such conditions, no warping was observed in single layer scans over powder batches of size –75 +38μm and larger. However, some warping was observed with the -38μm powder batch when sintering at high scanning speeds (>40mm/s). It was also found that higher energy densities caused the ends of sintered tracks to lift (all powder batches), a phenomenon that can be seen in figure 3. This effect is believed to be surface tension related rather than caused by temperature distortions.

During the build up of successive bonded tracks warping and stress cracking begins to occur. Two types of thermal distortion were observed: (1) in plane warping leading to arcing of the sintered tracks and (2) out of plane warping leading to dramatic elevations of the sintered layers. In plane warping takes place first and occurs within the first 2 – 10 scanned lines of a single layer though this is dependant on scan length (See Figures 4 and 5). As successive tracks cool differential shrinkage occurs causing the current hotter track to shrink and pull the cooler tracks towards it. As more tracks are produced the phenomenon escalates. The effects of the distortion causes stresses that lead to cracking. As the layer grows the resistance against in plane distortion increases and the arcing phenomenon eventually stops. However shrinkage still occurs and so stress equilibrium is achieved through out of plane warping (See Figures 4 and 5). Increases in layer length (number of lines) showed no visible changes in the magnitude of the distortion. However, the warping phenomenon was found to be periodic in nature causing a wave affect over the entire laminate as it grew (See Figure 5).

Reductions in scan length were found to dramatically reduce the amount of warping and stress cracking within a single laminate. A layer sintered with a scan length of 20.0mm showed no signs of warping but random cracking was still evident (See Figure 6). Further reductions in scan length to 15.0mm stopped both warping and cracking of sintered layers processed over powder batches of size –75 +38μm and larger, irrespective of both energy density, scan spacing and layer length. Single layer sintering using the -38μm powder batch was found to be limiting. Both warping and to a lesser degree cracking was observed when the scan spacing was small (>0.3 x beam diameter) and when the scanning speed was high (>40mm/s).

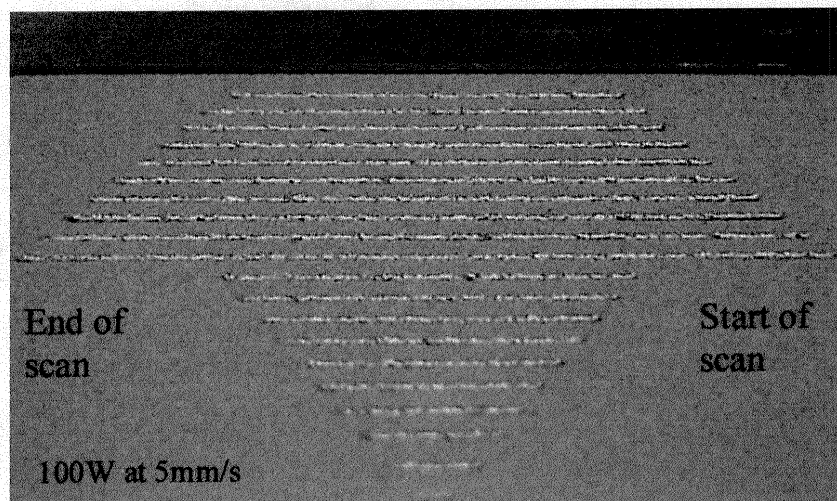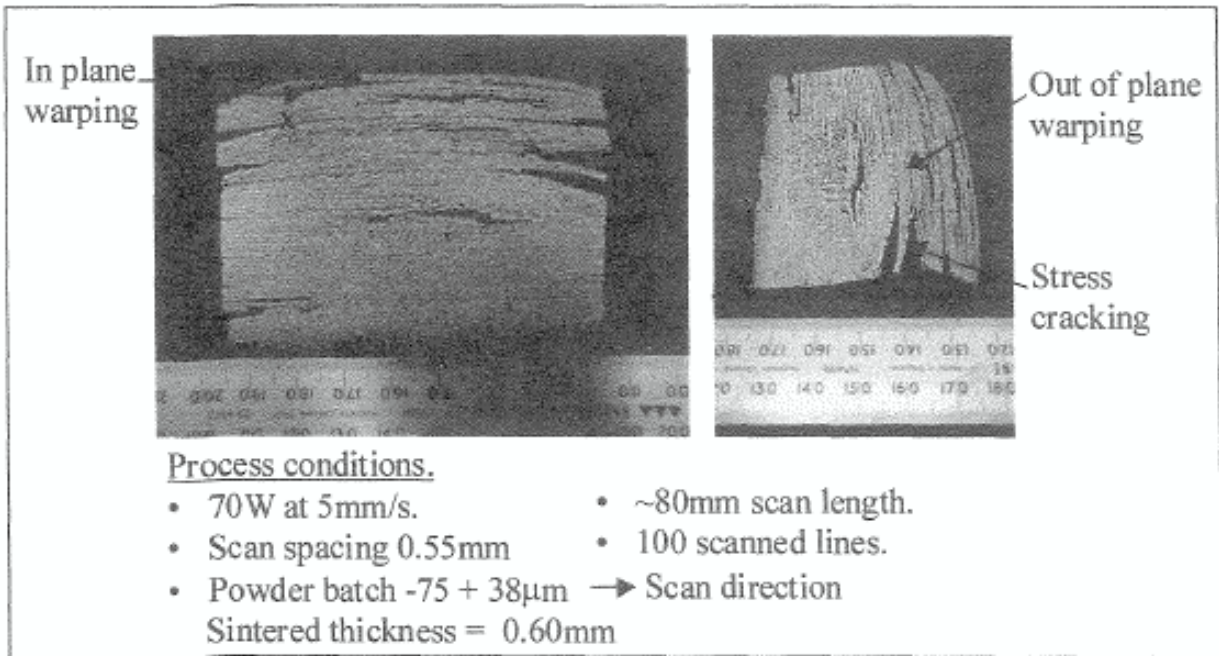Figure 3: Single line scans.

In plane warping

Out of plane warping

Stress cracking

Process conditions.
- 70W at 5mm/s.
- Scan spacing 0.55mm
- Powder batch -75 + 38μm
- Sintered thickness = 0.60mm
- ~80mm scan length.
- 100 scanned lines.
- → Scan direction

Figure 4: Single layer scan showing dramatic warping and cracking.

→ Scan direction

Process conditions.
- 70W at 5mm/s.
- Scan spacing 0.55mm
- Powder batch -75 + 38μm
- Sintered thickness = 0.65mm

120 scanned lines

Figure 5: Single layer scan showing warping and cracking.

Process conditions.
- 70W at 5mm/s.
- Scan spacing 0.55mm
- Powder batch -75 + 38μm

Sintered thickness = 0.63mm

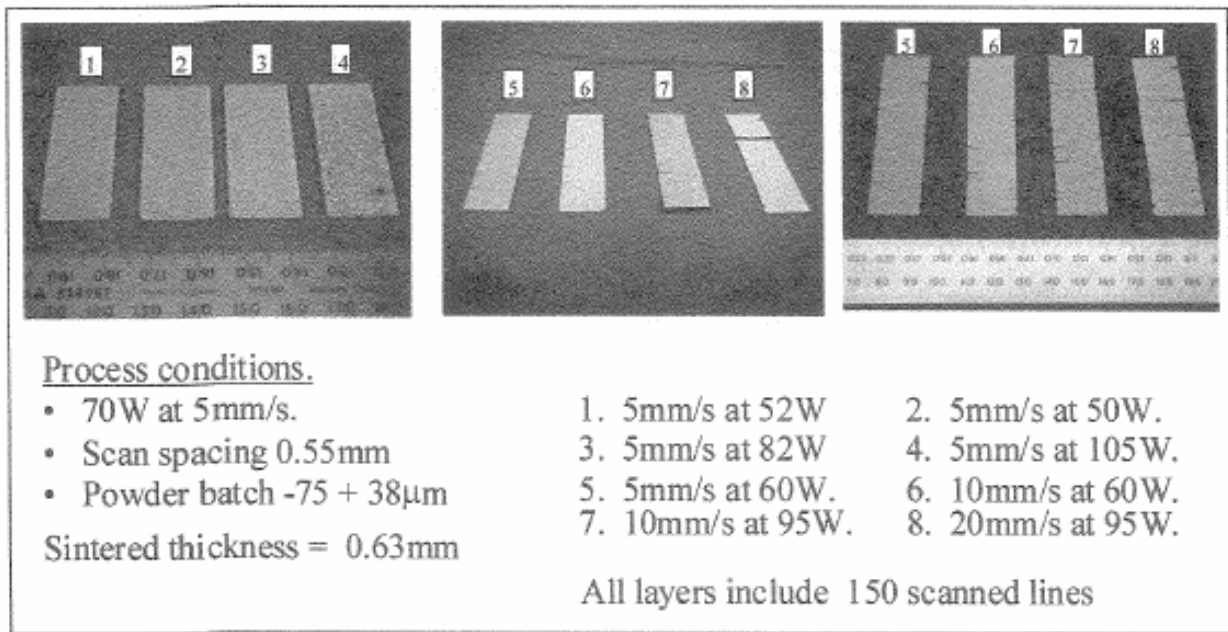|	
1. 5mm/s at 52W	2. 5mm/s at 50W.
3. 5mm/s at 82W	4. 5mm/s at 105W.
5. 5mm/s at 60W.	6. 10mm/s at 60W.
7. 10mm/s at 95W.	8. 20mm/s at 95W.

All layers include 150 scanned lines

Figure 6: Short scan length single layer scanning.

Changes of single layer shape

Effects of single layer shape were studied to observe how a variable scan length changes the magnitude of warping and cracking. Of the strategies implemented, circular and triangular scanning proved the most successful. It was found that varying the scan length of each track within a single laminate stopped out of plane warping and reduced in plane arcing (See Figure 7). During scanning of circular shapes, distortions were visibly reduced when scanning from the edge to the centre but grew in stature when raster scanning from the middle of the circle back to the edge.

Results of multiple layer sintering

Multi layer sintering was carried out over the range of scanning conditions where single layer sintering was successful. However, it was found that the progressive build up of layers when the scan length was 15.0mm allowed thermal distortions to occur causing delamination. Reducing the scan length further to 12.0mm was found to be more successful. Figure 8a shows a cube with 10.0mm sides consisting of 15 layers, each layer approximately 0.7mm thick (layer overlap was 0.4mm). The sintered density of the cube was ~55%, the density of the individual layers were slightly higher at 60%. Analogous to single layer triangular scanning, a multi layer pyramid was constructed by layering a series of laminates that reduced in surface area. Figure 8b shows a 25 layer pyramid with a base area 15 x 15mm showing no signs of warping or cracking, though layer displacement (stair step effect) can be seen but is a result of roller/sintered part interaction during the recoating process.
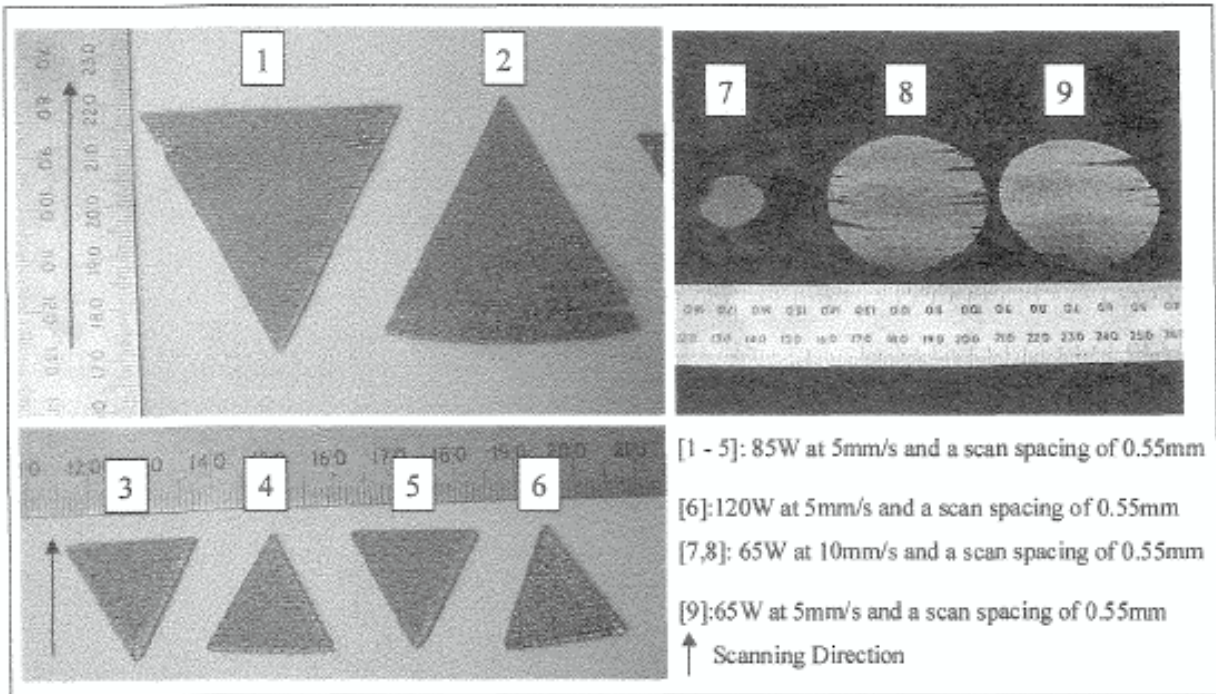
[1 - 5]: 85W at 5mm/s and a scan spacing of 0.55mm

[6]:120W at 5mm/s and a scan spacing of 0.55mm

[7,8]: 65W at 10mm/s and a scan spacing of 0.55mm

[9]:65W at 5mm/s and a scan spacing of 0.55mm

↑ Scanning Direction

Figure 7: Effects of single layer shape on layer warping and cracking..

(a)

(b)

Scanning Conditions.

• 100W at 5mm/s

• Powder batch -150+75 μm

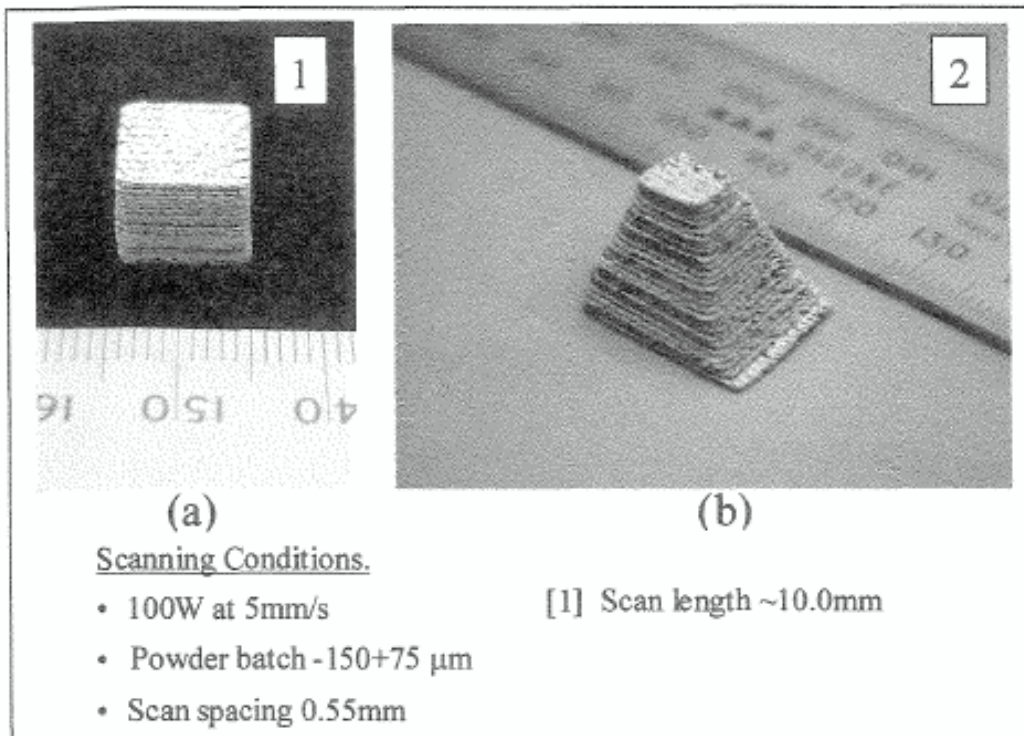• Scan spacing 0.55mm

[1] Scan length ~10.0mm

Figure 8: Examples of multiple layer sintering.

Discussion and Conclusion

Single and multiple layer SLS of a single metal alloy powder using a room temperature powder bed was found to be successful when the length of scan remained short. The thermal gradients that exist during sintering caused severe warping and stress cracking when the scan length is long. Single layers were successfully achieved with powder batches of $-75 + 38\mu m$ and larger and at energy densities greater than ~ 1.0 W/(mm/s), up to the limit of the machines laser power of 250W. In these conditions, unwarped and uncracked single layers could be achieved provided the scan length was kept below 15.0mm. This was possible because the heat input into the layer is concentrated over a small area and the temperature gradients are less dominant. Low speed scanning also reduced the chances of warping and was more beneficial in attaining better sintered densities.

The range of conditions for successful multiple layer sintering were similar to conditions for single layer sintering. However higher energy densities (>1.5 W/(mm/s)) were needed to improve on layer bonding. Under these conditions, unwarped and uncracked multiple layers showing no signs of delamination could be achieved provided the scan length was kept below 12.0mm.

During single line scanning no build up of thermally induced distortions was observed. This evidence, although not conclusive, indicates that the temperature gradient that exists between the upper and lower surface of a single line and possibly a single laminate can be assumed to be negligible.

Acknowledgements

REFERENCES.

[1] J. McWilliams et al, *Design of a High Temperature Process Chamber for the Selective Laser Sintering Process*, Solid Freeform Fabrication Symposium, University of Texas at Austin, 1992, [pp 110 – 117].

[2] C. Deckard et al, *Improved Energy Delivery for Selective Laser Sintering*, Solid Freeform Fabrication Symposium, University of Texas at Austin, 1995.

[3] G. B. Prabhu et al, Supersolidus Liquid Phase Selective Laser Sintering of Metals and Metal Melt Infiltration for Near Net Shape Fabrication of Components, Solid Freeform Fabrication Symposium, University of Texas at Austin, 1993, [pp 317 – 324].

[4] J. A. Benda, *Temperature Controlled Selective Laser Sintering*, Solid Free Form Fabrication Symposium, The University of Texas at Austin, 1994, [pp 277 – 284].

[5] W. T. Carter et al, Direct Laser Sintering of Metals, Solid FreeForm Fabrication Symposium, The University of Texas at Austin, 1993, [pp 51 – 59].

[6] C Hauser et al, *Atmospheric Control during Direct Selective Laser Sintering of Stainless Steel 314S powder*, This Conference, The University of Texas at Austin, 1999.