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EFFECT OF PROCESS CONDITIONS ON TEMPERATURE DISTRIBUTION IN THE POWDER BED DURING LASER SINTERING OF POLYAMIDE-12

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ABSTRACT

A sintered part's mechanical properties are often variable dependent on the temperature at which it was sintered. Prior research has investigated how predefined process conditions (such as scan speed and laser power) in the 'Sinter' software affect built parts (Majewski & Hopkinson, 2011), however, little work focuses on other process conditions that can directly affect the temperature distribution in the bed relative to these parts. These conditions are not always controllable in the 'Sinter' software. By replacing the scanner at the top of the Sinterstation 2000 with a thermal imaging camera, an insight into the temperature distribution on the part bed was obtained. A temperature variance of up to 7°C was found across the bed, as well as a large temperature drop and recovery period on powder layer recoat. This paper explores the possible causes of this variation in the processing of DuraForm™ Polyamide-12 powder by monitoring and assessing build operations, enabled by replacing the front viewing window with a retro-fitted thermal imaging camera. The part bed was observed and various process conditions analyzed including powder recoat, part and feed heaters, and swing gate configuration. On powder recoat, the part bed exhibited a drop in temperature because the fresh layer of powder is at a lower temperature than the powder already present in the part bed. The part bed temperature drop lessens with raised feed bed temperatures however there are limitations. Thermal analysis of the part heater proved that the uneven part bed heat distribution was not linked to the temperature gradient of the part heater. Swing gates were found to minimise hot and cold spots but spend a substantial time oscillating on roller passing.

INTRODUCTION

Selective Laser Sintering (SLS) is an additive manufacturing (AM) process which is growing to be a promising manufacturing method for direct part production. The premise of building a complex component with relative ease from powdered material is an attractive idea, and one which has the potential to revolutionize the manufacturing industry.

Currently, SLS is more commonly associated with the production of prototype components and parts. Together with computer aided design/computer aided manufacture software, AM permits the creation of shaped 3D parts via layer-wise manufacture. There are drawbacks that are preventing SLS elevating from a prototyping tool to a mainstream manufacturing technology. Currently, the process struggles to produce repeatable dimensional and mechanical properties across the x, y and z axes of the build volume. With a reduction in deviation, forecasts could be made about the likely properties of subsequent parts and assurances made in regards to conformity to specified tolerances.

This paper considers factors that affect the temperature distribution on the part bed within the DTM Sinterstation 2000 SLS machine. This machine encompasses a circular build envelope with a usable build diameter of 235mm. On initial machine set up and at regular intervals, part and feed bed temperatures should be calibrated. This calibration seeks to find the correct bed temperatures to give optimum mechanical properties and dimensional control of parts that are manufactured. When bed temperatures are set too low, parts will curl which will cause the build to fail as protruding areas will catch the roller upon recoating. When bed temperatures are set too high, parts are prone to over-growth, have a poor surface finish and can be difficult to break out of the build volume. This is confirmed by Hardro et al. (1998) who sought to find an approach to determine the optimal process parameters in SLS. Despite setting part and feed bed temperatures correctly to prevent the aforementioned issues, the thermal distribution is still not uniform causing varying mechanical properties in relation to location on the part bed.

Tontowi and Childs (2001) established that a part's mechanical properties are dependent on the temperature at which it was sintered. The machine's part bed temperature was adjusted between 174ºC, 178ºC and 182ºC and the size and density of the parts produced was recorded. It was concluded that a lower powder bed temperature would produce a lower density sintered part. To maintain a high density part, at a default laser power, energy density has to vary to compensate for the fluctuating bed temperature; alternatively the powder bed should be controlled to within 4ºC. Tontowi and Childs (2001) do not offer any explanation for this variation. To investigate whether a similar variation is found in the Sinterstation 2000 used in this study, the scanner was replaced with a FLIR E40 thermal imaging camera. An example of the output produced can be seen in Figure 1. The image indicates that there is a 7°C temperature variation across the complete bed.

To understand the effect that temperature variation has on mechanical properties, modified BS-EN-ISO 527 test specimens, as shown in Figure 2, were produced.

The geometry is shortened to limit the deviation in production parameters across the part. This amended geometry also permits placement closer to the circumference of the circular extremities of the build platform (as shown in Figure 3).

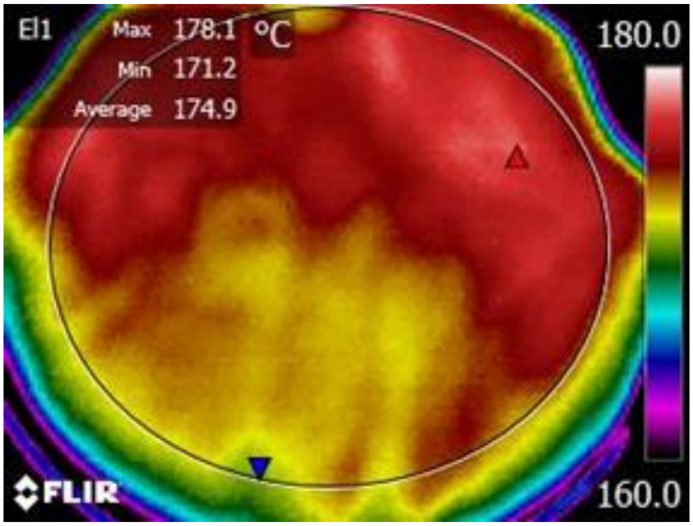

FIGURE 1: THERMAL IMAGE OF PART BED SHOWING OVERALL TEMPERATURE DISTRIBUTION

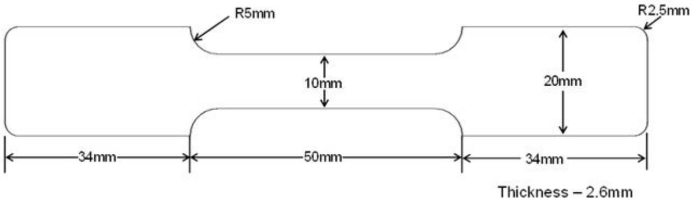

FIGURE 2: REVISED TENSILE TEST SPECIMEN GEOMETRY

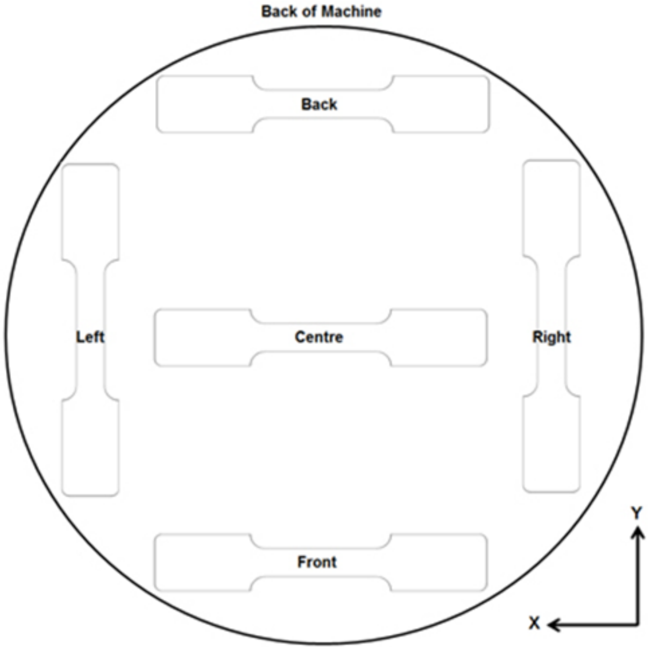

FIGURE 3: TENSILE TEST SPECIMEN LOCATION

The average ultimate tensile strength (UTS) was taken from specimens in each location on the platform, over six separate build operations; average results are shown in Table 1, with the 'Location' column corresponding to Figure 3.

Location	Average UTS (Mpa)
Front	46.87
Back	47.43
Left	48.78
Right	51.93
Centre	45.75

TABLE 1: AVERAGE UTS OF TENSILE TEST SPECIMENS FROM DIFFERENT BED LOCATIONS

The results show a variance in UTS of up to 6 MPa across the bed. The potential reasons for the temperature variations which are the primary cause of such varying mechanical properties are therefore investigated further within this paper.

EXPERIMENTAL METHODOLOGY

Apparatus

A FLIR E40 thermal imaging camera was used to determine the temperature distribution across the part bed. The toughened glass viewing window in the front of the Sinterstation 2000 was replaced with a steel-vermiculite-steel composite panel. A Zinc Selenide (ZnSe) lens was installed into the panel to facilitate viewing of the part bed. The thermal imaging camera was mounted to the front of the machine giving an image of the part bed as seen in Figure 4.

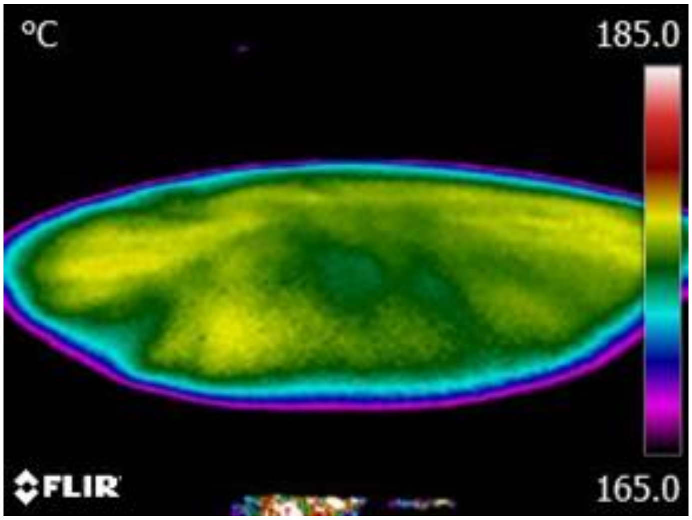

FIGURE 4: INITIAL VIEW OF PART BED ON INSTALLATION OF THERMAL IMAGING CAMERA

Procedure

The Sinterstation 2000 was heated up using the existing procedures currently in place for its operation. This involves two stages: heating up to initial warm-up set-points, and then heating up to the operational set-point. During the latter stage, powder layers of 0.12mm are spread across the surface of the part bed to a total depth of 17mm. To investigate the effects of process conditions on part bed temperature, the material feed beds were set to an operating surface temperature of 110°C and the part bed was set to 178°C. The part bed temperature was selected as it is just below the melting point of the material to be used (Gebhardt, 2007).

This experiment monitored the thermal profile of the part bed under numerous conditions common in the laser sintering process. The results were analysed in Flir Tools+ and logged in Microsoft Excel to assess and quantify the effects of these conditions on the part bed. The first condition was layer recoat; after each layer is sintered, a new layer of powder (0.12mm) is spread across the part bed. This powder is deposited from the feed beds which are at a lower temperature than the part bed. This, along with the cooling effect of the counter-rotating roller, has a negative impact on the temperature of the part bed.

Swing gates were first introduced in the Sinterstation 2500 model of the SLS family. The 3D Systems SLS reference guide describes them as "Pieces of metal in the process chamber that assist in preventing hot spots on the part bed by reflecting radiant energy from the part bed heater back onto the part bed" (3D Systems, 2002). The swing gates installed within the Sinterstation 2000 under study were retrofitted to the machine sometime after its commissioning. Thermal analysis was carried out to evaluate the effectiveness of these swing gates.

Recovery time is an important condition in laser sintering, more so in older machines where only one infrared temperature sensor is used. This sensor is utilized in the feedback control system to initiate scanning of the next layer once the desired temperature has been reached. Therefore, it is not only important that the bed reaches temperature as quickly as possible, but also at a uniform rate so that the sensor reading is true to the full part bed. Several factors were observed to affect both part bed temperature variation as well as recovery time including swing gates, roller temperature and feed bed temperature.

RESULTS AND DISCUSSION

Powder Recoat

When the laser has finished scanning, a new layer of powder is deposited on top. This causes cooling as the deposited powder is at a lower temperature. Using the thermal imaging camera, a good visualisation of the roller's cooling effect can be seen on the part bed. The temperature variation of the part bed changes significantly after the roller has passed, as shown in Figure 5 and Figure 6.

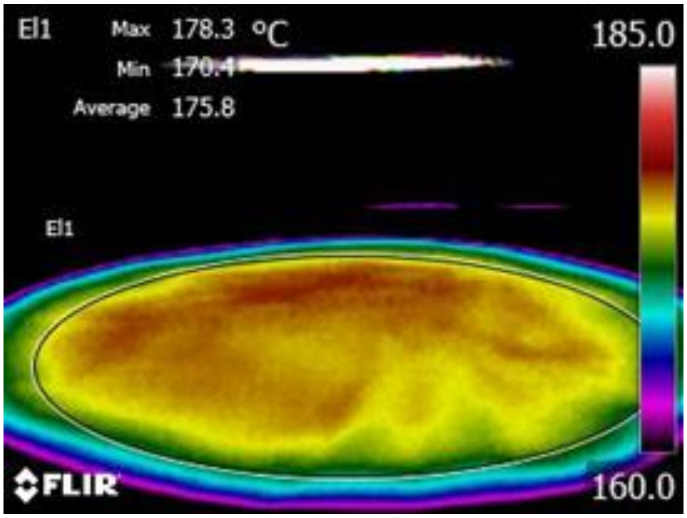

FIGURE 5: THERMAL DISTRIBUTION OF PART BED BEFORE RECOATING

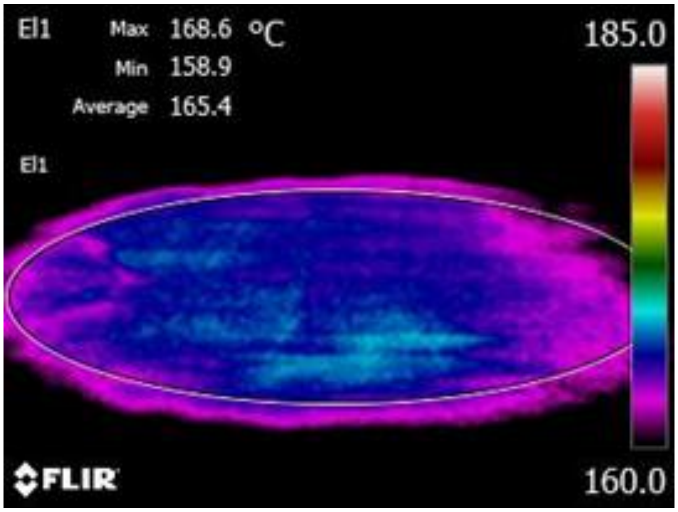

FIGURE 6: THERMAL DISTRIBUTION OF PART BED AFTER RECOATING

The average temperature drop is more than 10°C. To examine this further, the thermal imaging camera was used to determine the temperature of the roller. An example image taken of this is given in Figure 7.

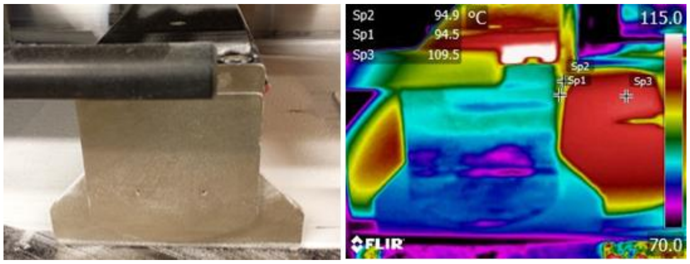

FIGURE 7: DIGITAL (LEFT) AND THERMAL (RIGHT) IMAGE OF ROLLER DURING RECOATING

The temperature of the roller was found to be 95°C and the temperature of the feed powder was 110°C. During sintering, the roller remains stationary at the end of the build chamber, which is distinctly cooler than the part and feed beds. As a result of this, when the roller recoats the part bed, heat transfer will occur from the feed powder to the cooler roller as well as from the current powder in the part bed to the fresh layer. The initial heat transfer from the feed powder to the roller has a negative effect on the sintering process. It is unavoidable unless the cooler surface is heated to the same temperature as the higher one in accordance with Kirchhoff's law of thermodynamics. The second heat transfer, from the current part bed powder at 178°C to the fresh layer at 110°C, is not as adversely impacting as the previous. As the newly deposited powder is at a lower temperature than required, any positive heat transfer is desirable. This comes from both the part heater above and the warmer powder below.

To improve the process, the feed bed temperature could be increased. This will not eliminate heat transfer but, as the roller is only in contact for 5 seconds, assuming the same rate of heat transfer, the powder will not have cooled as much when reaching the part bed.

Feed Bed Temperature

The Sinterstation 2000's 'Sinter' control software reads the feed bed temperature via thermocouples placed within each bed. The machine, in its current operational mode, has the feed bed temperature set to 83°C. To investigate how the temperature of the feed bed affects the part bed during recoating, an experiment was undertaken changing the feed bed temperature between 70°C, 80°C and 90°C (Figure 8).

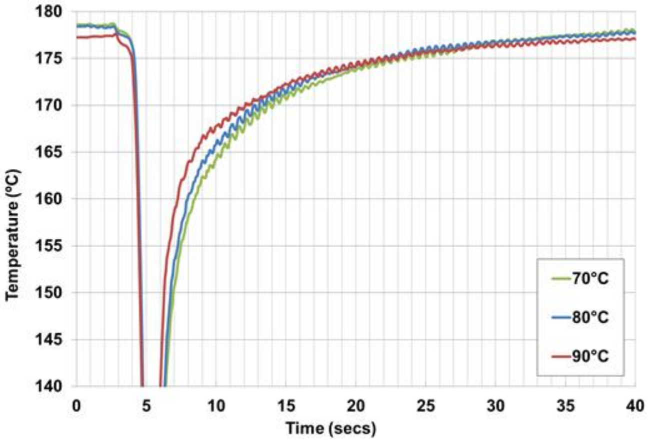

FIGURE 8: TEMPERATURE OF PART BED DURING RECOATING WITH VARIOUS FEED BED TEMPERATURES

It can be seen that with the feed beds set to the higher temperature of 90°C, the part bed recovers 4 seconds quicker than at 80°C. Therefore, a higher feed bed temperature is desirable, however there are limitations. According to the 3D Systems reference guide, clumping refers to “agglomerated powder on the powder bed surface accumulates in front of the roller as it moves across the part bed, and streaks appear behind the roller” (3D Systems, 2002). This is usually accompanied by melting or cracking in the feed beds. Melting was exhibited on the feed beds as soon as the temperature on the thermocouple exceeded 90°C.

Swing Gates

The machine was set up as described above, once with the retrofitted swing gates installed and once without. The resulting images, shown in Figure 9 and Figure 10, were taken just before the roller recoated the bed.

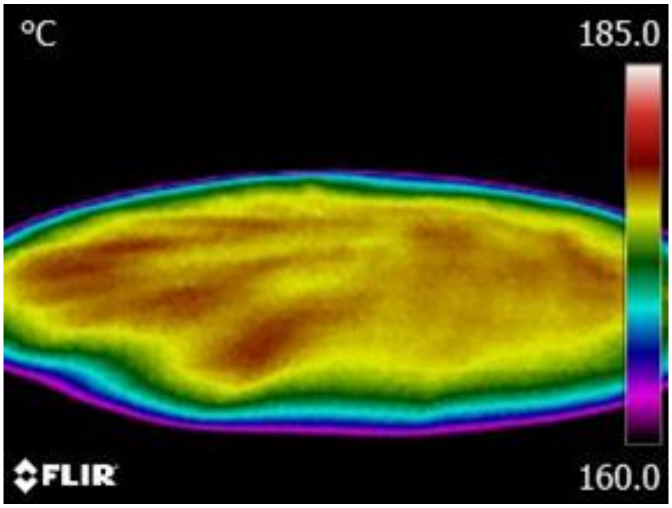

FIGURE 9: THERMAL IMAGE OF PART BED BEFORE POWDER RECOAT WITH SWING GATES INSTALLED

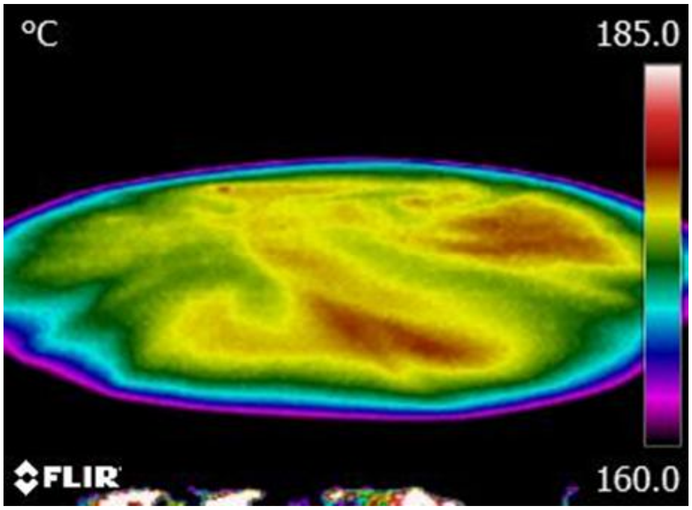

FIGURE 10: THERMAL IMAGE OF PART BED BEFORE POWDER RECOAT WITH NO SWING GATES INSTALLED

It should be noted that no parts are actually being sintered during this aspect of the analysis. This enables a comparable experiment and gives a true representation of the part bed temperature distribution. Areas that are sintered contain a lot more heat and as these areas move with each layer, it would be inappropriate to undertake the analysis when parts are being sintered.

Figure 9 and 10 show that the swing gates have a positive effect on the temperature of the part bed. When fitted, there is a noticeable reduction in hot and cold spots. During the sintering process, the swing gates are displaced when the roller passes to recoat the part bed. Drawing a horizontal line across the centre of the bed and recording the temperature during one recoat operation produces the graph shown in Figure 11.

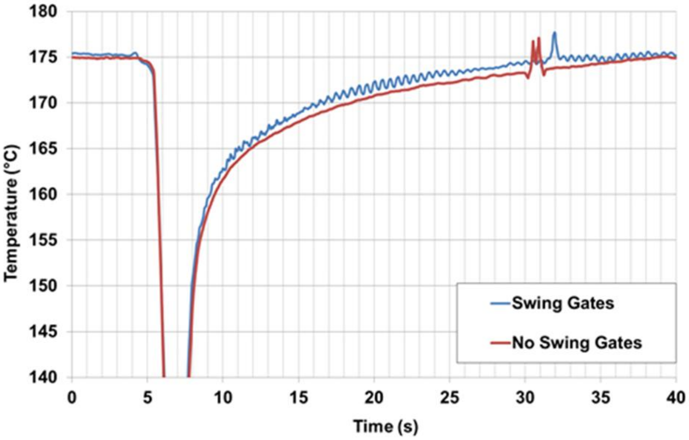

FIGURE 11: TEMPERATURE OF PART BED CENTRE LINE THROUGHOUT RECOATING PROCESS

The bed recovered faster with swing gates installed, however a smoother recovery was observed with none. These fluctuations are caused by the roller displacing the swing gates, varying the amount and location of heat reflected back on to the part bed.

Part Heater

The Sinterstation 2000 comes with coil stretched filaments that transfer heat mainly in the form of radiation, however due to the radiant efficiency of the heaters, some heat is transferred via convection. This involves the transfer of the heat energy via a moving fluid or gas; in this case Nitrogen, which is used to prevent combustion by inerting the sintering chamber environment. The rate of heat transfer, via convection, is dependent on many factors, including fluid density, the rate of fluid movement and temperature differential between the heating fluid and the substrate.

The manual stretching of the coil in the part bed heater could affect heat distribution to the part bed. Irregular stretching could lead to uneven heating of the coil heaters, which in turn could lead to the uneven heat distribution to the target substrate. Thermal analysis of the part bed heater, as shown in Figure 12, proved that the uneven heat distribution was not linked to the temperature gradient of the part bed.

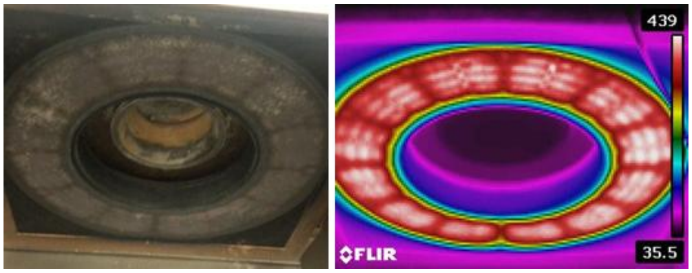

FIGURE 12: DIGITAL (LEFT) AND THERMAL (RIGHT) IMAGE OF PART BED HEATER

The part heater had an average temperature gradient of about 3°C. By studying the thermal image in Figure 12, any cooler areas caused by the part heater are more likely to exist at the bottom of the heater (i.e. towards the back of the SLS machine). Referring back to Figure 1, this corresponds to the section with a higher temperature variation. This further reiterates that the temperature gradient of the part bed is not linked to the part heater.

Other Factors

There are other factors that can affect part bed heat distribution; most noticeable is the effect of Nitrogen flow on the part bed temperature. Previous work by Yuan and Bourell (2013) investigated how the flow rate of Nitrogen influenced the surface temperature of the part bed. They studied this effect by observing results at different chamber flow rates. The Nitrogen supply was monitored at different rates from 0 to 2.5 m^3/hr at intervals of 5 m3/hr. They concluded that Nitrogen circulation showed potential based on computer modelling, but was found to be ineffective in reducing thermal gradients during testing. It was also found that down-drafting has a potential benefit on post-build factors such as thermal homogenization of the part bed and accelerated coolant of the part bed after the build is complete, however the effect on part bed surface temperature gradients was found to be minor.

Another factor that could be considered is part bed location in the machine. In the Sinterstation 2000, the part bed is set closer to the back of the machine than the front. This means that radiant energy is reflected back at a closer distance, a theory that agrees with the part bed temperature distribution seen in Figure 1.

Room temperature affects the temperature measuring system which probes the part bed. Although not directly affecting uniformity, from various experiments carried out during this research, it was noted that depending on the temperature in the room, the bed would settle at a variety of different temperatures. The probable cause is the reference temperature obtained for the infrared sensor located in the machine which is used to measure the part bed.

Wegner and Witt (2011) showed a decrease in maximum and average deviation as the build progressed. They showed that at z = 10mm, the average deviation was 11°C whereas at z = 37mm, this deviation had reduced to 6°C. A likely explanation for this is the continued heating of the chamber, eventually levelling out when all chamber components reach equilibrium.

CONCLUSION

Many process conditions have been identified that affect part bed temperature variation. Preceding analysis showed that this temperature distribution produced parts with varying part properties dependent on the location on the part bed.

The first process condition analyzed using the thermal imaging camera was powder recoating. A 10°C temperature drop across the powder bed was shown. This was caused by the lower temperature of the feed powder and recoating roller. Analysis continued by investigating how changing the feed powder temperature affected the recovery time. It was found that a higher temperature is desirable, however there are limitations of this temperature as powder may melt or clump. This would lead to sub-optimum recoating as unwelcome streaking and uneven powder distribution may be exhibited on the part bed.

Finally, the effect of swing gates on part bed temperature was investigated. By comparing thermal images of the part bed with and without the swing gates, a clear improvement to temperature uniformity was shown with the installation of the swing gates. When considering powder recoating, oscillations in part bed temperature are experienced when the swing gates were fitted. This was due to the movement of the swing gates as the roller passes. Despite these oscillations, the part bed recovered at a faster, more uniform rate with the swing gates installed.

A thermal image of the part heater did not correlate with the relevant cooler sections of the bed and therefore it was concluded that the part heater in the Sinterstation 2000 had none, or a minimal effect on part bed temperature distribution when used in its current practice for producing parts. Other process conditions that could affect part bed temperature are Nitrogen flow, bed location in the machine, room temperature and build duration.

Overall, this research has shown there are many process conditions that can affect the temperature of the part bed during the SLS process. In order to achieve consistent and repeatable mechanical properties within the part bed, a sophisticated control system is required. This system should control segments of the part heater to account for the disturbances discussed in this paper.

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