Investigation on Multi-Layer Direct Metal Laser Sintering of 316L Stainless Steel Powder Beds

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ABSTRACT
Research and development of laser based sintering technology has occurred at a rapid pace since its invention in the 1980’s. A wide range of materials have been developed including polymers, metals and ceramics. The ultimate goal for this technology is to provide manufacturing industries with fast and flexible means of producing parts that are truly functional. Step by step this active research area is leading towards rapid manufacturing solutions which will be significantly different from the rather limited rapid prototyping solutions of today. In processing metallic materials, porosity is still a major problem although a number of notable solutions such as infiltration with low melting point alloys or direct fusing with binary powder mixtures have been proposed. Neither of these solutions allows one to build components without compromising part strength and functionality. A process route is required that will allow solid parts to be built from a single powder component without requiring time consuming downstream processes. The surface quality must be consistent with those attainable by modern machining techniques. To this end, the present work examines the feasibility of using low energy high peak power laser pulses from a Q-switched Nd:YAG laser to melt stainless steel powder fractions whilst examining the melt displacement and the effects of rapid vaporisation of the powder layer.

Keywords: Laser, sintering, metal, powder.

1 INTRODUCTION
Of the main rapid prototyping technologies (RPT), selective laser sintering (SLS) provides the widest range of build materials which include a variety of polymers and a number of metal based materials [1]. The accuracy of parts produced by SLS is no greater than that achieved with stereolithography, although the ability to produce functional parts directly from the SLS build chamber gives the SLS process considerable advantages over other RPT. A number of SLS methods have been used to increase the density of the fabricated component. Direct metal sintering relies on laser induced melting to couple powder particles together, significant thermal gradients exist using this route unless the powder bed temperatures are controlled to a value just short of the powder melt temperature. This approach reduces problematic temperature gradients and produces parts with minimum internal stresses. Porosity is still a problem which is normally reduced by post sintering infiltration.

Indirect sintering of metals relies on melting of the polymer coating on each metal particle, this “green” part can then be handled with subsequent de-binding, sintering and low melting point infiltration stages which are necessary to produce a solid high density part [2,3].

Binary phase sintering has been investigated by a number of workers [4,5,6]. This process involves the illumination of a composite powder mixture such that a particular phase of the powder is melted in preference to the other. Examples of binary mixtures include: Cu-Ni, Fe-Co, W-Mo. The low melting point components are employed to effect bonding within the mixture.

Objects built via the above routes are generally not suited for heavy duty functional parts since the majority of infiltrates and binary phase materials are low melting point metals with low mechanical strength. Parts produced thus have the strength and performance characteristics of their weakest composite phase. The production of fully functional parts requires processing routes that result in near 100% density from a single powder, i.e., stainless steel, tool steels, titanium etc. It is clear from the literature that there have been few attempts to condition the laser-material interaction such that laser induced non-thermal effects are generated to aid the melting and densification of powder beds in a single step.

The majority of laser based RPT utilise CO₂ gas lasers or in some cases solid-state Nd:YAG lasers. In commercial applications of SLS, a 50 W or 100 WCO₂ laser is used to thermally activate the powder bed. If melting occurs the process relies on surface tension driven melt displacement that distributes the molten volume and bonds nearest particles into a conglomerate that is near full density. Fusion based processes of this kind are very susceptible to unwanted thermal gradients which reduce the chance of wetting leading to balling phenomena and poor layer properties. In addition, Nd:YAG lasers have considerable advantages in terms of laser-powder coupling coefficients. On solid substrates this advantage is not so great, however, powder beds can be conditioned to offer excellent absorption of Nd:YAG laser radiation. This paper presents the results of a preliminary investigation on the interaction characteristics of nanosecond laser pulses and stainless steel powder beds.

2 EXPERIMENTAL ARRANGEMENT
An experimental SLS test facility was constructed which consisted of a Rofin Sinar 100W flash-lamp pumped Q-switched Nd:YAG laser with a frequency range of 0 to 60kHz. Typical pulse energies and pulse widths were in the range 10mJ and 100ns respectively. Line scanning was achieved using a RSG1014 galvanometer scanning head containing 2 thermally regulated S10 galvanometers giving a scanning speed range of 1-500 mm/s over an 80mm by 80mm area. The focal length of the imaging lens was 112mm giving a minimum spot size of 50μm.
Computer control of both laser parameters and scanning is accomplished using an IBM compatible PC running Rofin Sinar's Laserworkbench software under the OS2 operating system. This software not only allows scanning of many image types but also enables programming of scanning trajectory and the setting of all process variables from within a Pascal based programming language.

The build chamber consists of a build cylinder and powder delivery cylinder each 100 mm diameter powered by 2 linear stepping motors with minimum step size of 0.25 microns and maximum stepping rate of 380 steps per second. 316L Stainless powder with a mode size of 20µm is delivered to the build chamber by a 70 mm diameter counter rotating roller driven by a DC servo motor. The build chamber is computer controlled via a PC based SM30 3-axis stepper motor controller which simultaneously controls powder feeder, build platform and sweeper assembly. In house control software was used to link the laser system with the SLS build chamber thereby effecting full control over the experimental system. This preliminary investigation made no attempt to control powder bed temperatures in order to identify the benefits of the plasma initiated high pressure interaction.

2.1 Single Layer Powder Beds
Powder beds of 3mm thick were metered onto the build platform. After a suitable purging operation, the chamber was filled with Ar shroud gas (99.999%) in order to minimise oxidation effects. This is particularly important with Stainless Steel powders as the melt temperature of the chromium oxide is substantially higher than that of iron which causes problems when super heated pockets of molten iron are trapped within a "bag" of chromium oxide. Further heating of these oxide "bags" leads to catastrophic failure and explosive release of molten iron which dramatically reduces the controllability of the process.

System control software was used to fire the laser onto powder beds in order to sinter a matrix of pads with varying process parameters which included Q-switch frequency, laser spot size, scan speed, overlap % and average laser power. The experiments were repeated for different beam diameters which was achieved by moving the focal point of the optical system away from the surface of the bed.

2.2 Multiple Layer Powder Beds
The build chamber platform was sent to a position around 200m below the top surface. The build chamber was then filled with the stainless steel powder which was scraped flush with the surface and the chamber was then purged with argon gas.

The laser was fired at the powder to form the first layer. Software was written on the LaserWorkbench compiler to create ten pads of sintered material at differing parameters of Q-switch frequency. The optimum parameters for lamp current, scanning velocity were decided from the results of the single layer sintering experiments and were common to all of the ten pads. The value of the Q-switch frequency was varied for the ten samples to encompass values that were considered from the single layer sintering experiments to be of interest. The Q-switch frequency was the parameter that was changed since it is considered to be the critical factor affecting powder densification.

When this layer was complete, the inert chamber was removed to allow more powder to be placed over the first layer. The control software was used to lower the build chamber piston by 40µm. Powder was then gently deposited on to the previous layer using a powder sieve and levelling sweep. The chamber was purged once more and the exposure process was repeated until twenty layers had been processed. The samples were then mounted and analysed.

3 RESULTS
The results shown in Figure 1 represent a series of single layer pads produced with a range of operating parameters. One can see that neat square pads are produced with an area of 3x3mm. Figure 1 presents the optimum data set with a spot diameter of 300µm. More detailed discussions of single layer performance can be found in a previous publication [8].

Figure 1: 3x3mm single layer sintered pads produced with various operating parameters and an incident beam diameter of 300µm.

Figure 2 shows the good surface quality that can be achieved using optimised beam and processing parameters. In this case, the average laser power was 12W, Q-switched frequency of 60kHz, overlap 25% and scanning speed of 100mm/s. The success of single layer pad processing brought hope that multiple layer processing would result in high density parts that were free from porosity.

Figure 2: SEM image of the surface of a single layer sintered pad showing high surface density and little evidence of porosity. The scale bar represents 1mm in length.
Figure 3: Cross sections of pads produced using twenty layers of 80μm thick layers. Average power 12W, speed 100mm/s, overlap 25%, Q-switch frequency: a) 40kHz, b) 44kHz, c) 48kHz, d) 52kHz, e) 60kHz. Magnification x20.

With reference to Figure 3, it is interesting to note that the samples have all had near equal exposure and process parameters with the exception of Q-switch frequency. While there is a variation of some 20kHz between samples a) and e), marked differences between their physical characteristics are evident. As the Q-switch frequency is increased, the samples become thinner despite the equal build parameters such as layer height.

The powder densities available with short Nd:YAG laser pulses are high enough to cause even reflective materials to rapidly reach the vaporisation temperature. This vaporisation is such that immense pressures are induced which result in a shock wave as illustrated in Figure 4. The shock wave is responsible for the recoil forces which act in the opposite direction. When the energy intensity is high, such as is the case with a small beam diameter, the recoil pressure is greater resulting in blast removal of the powder. In Figure 3 the beam diameter has been set to 300μm such that blast waves are minimised. The effect of laser induced compression cannot explain the results of Figure 3 as the compressive effect will reduce with increasing frequency due to lower pulse energies.

Figure 4: Laser induced shock waves using Q-switched laser light.
The discrepancy between the actual density of the single layer samples in the XY plane and the density of the multiple layer sample in the Z plane can be explained to some extent by the experimental conditions. Because of the curling that occurred when the sintering was performed it was difficult to deposit an even layer of powder across the sample. Also, because the powder had to be applied manually, consistent layer thicknesses could not be guaranteed. The curling effect would also cause different parts of the sample to be at different focal positions and for the angle of incidence of the beam on to the powder to be different at the edges than in the centre.

All of these effects will play their part in increasing porosity. However, it is clear that in both the single and multi-layer cases higher Q-switched frequencies produced better surface quality and greater densities. The mechanisms at work in this study are the subject of further investigations. A theoretical study of pulsed laser powder interactions is underway to further understand the evolution of the melt film and its subsequent displacement. In addition, a wide range of experiments are being performed to examine the effect that particle size has on the compaction of the multi-layer powder beds.

4 CONCLUSIONS
The single and multiple layer sintering experiments demonstrated that using high frequency and high intensity Nd:YAG laser pulses for the selective layer sintering of metal powders could have a positive influence on the melt flow, densification and porosity of fused SS316L powder beds. The extent to which this occurs is dependent on the process variables such as frequency, beam diameter and laser power. A greater understanding of the interaction mechanisms is required in order to produce fully dense metallic components from powder substrates.

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6 REFERENCES