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EVALUATION OF LASER ENERGY DENSITY EFFECTS ON MECHANICAL PROPERTIES OF SELECTIVE LASER SINTERING COMPONENTS USING RAMAN SPECTROSCOPY

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Abstract: *This paper reports on an experimental study to use Raman spectroscopy to quantify and predict the mechanical properties of SLS manufactured components. Using a surface profiler, the degree of particle consolidation is measured in components manufactured using different laser energy densities. It is shown that the surface roughness of components decreases with increasing laser energy density. Raman spectroscopy is a powerful technique that is able to directly monitor particle consolidation of a sample by monitoring changes in absorbance and scattering effects from the surface. As the degree of particle consolidation is related to the mechanical strength as well as the surface topology, Raman spectroscopy measurements are able to accurately predict the tensile strength of a component.*

Key words: *selective laser sintering, process parameters, Raman spectroscopy, surface roughness, mechanical properties*

1. INTRODUCTION

Selective Laser Sintering (SLS) is an additive manufacturing technique that builds fully functional components layer-by-layer from particulate materials. Consolation of the powder is achieved through a laser selectively sintering areas of the powder bed. The degree of particle bonding is dependent on the laser energy density which can be affected by control variables such as laser power, scan speed, laser spot size and overlap of scan vectors. All of these parameters can alter the sintering process and the final component properties (Beal, Paggi et al. 2009). Due to the complexity of the sintering process it is not obvious how to optimise control variables to achieve desirable surface finish and mechanical properties.

Many studies have focused on developing strategies and parameters to manufacture SLS parts of the highest mechanical performance with good dimensional accuracy and repeatability. Caulfield et al. (Caulfield, McHugh et al. 2007) carried out an extensive study on the effect of energy density on the physical and mechanical properties of polyamide components. The tensile testing results revealed an increase in Young’s modulus and elongation at break with increasing energy density level.

Optimisation of a system through study of parameters and their effect on mechanical properties is a pragmatic approach to achieve desired goals. However, full understanding of mechanisms involved in complex processes such as particle consolidation needs in-depth analysis of the molecular changes in the material. Spectroscopy is one of the most powerful techniques available to provide specific information about vibrational bonds within a molecule. Raman spectroscopy has been successfully used in the analysis of a range of nylon structures (Hendra, Maddams et al. 1990). Hendra et al showed that Raman spectroscopy can differentiate between different types of nylon, ranging from nylon 3 to nylon 12, through analysis of peaks associated with the stretching and bending vibrational modes of CH2 chains.

Raman spectroscopy is also routinely used to study powder or compacted powder samples. It is widely observed that in addition to absorption in these samples multiple scattering processes occur that affect the observed Raman intensities. The optical properties of this type of diffuse reflectance measurements were first described by Kubelka and Munk (Kubelka and Munk 1931). The Raman intensity is related to the particle size of the powder and is generally accepted to decrease, for a set of samples having a constant absorption coefficient, with decreasing particle size (Waters 1994).

Surface roughness is an important parameter in manufactured SLS components that is directly related to particle consolidation and therefore mechanical properties. Through surface roughness measurement this article shows how Raman peak intensity is related to particle size and morphology. Furthermore, Raman spectroscopy is shown to be a powerful technique in the prediction of mechanical properties of SLS components using non-destructive measurements.

2. MATERIALS AND METHODS

2.1 Selective Laser Sintering - Parts Manufacture

Components were manufactured on a DTM Sinterstation using DuraForm polyamide powder provided by 3D Systems. The laser fill speed was kept constant at 1200 mm/s and samples constructed by varying the laser power from 3 W through to 8 W at 0.25 W intervals. In total 21, dogbone shaped test specimens with overall dimensions of 180 mm x 10 mm x 4 mm were manufactured using a laser fill scan spacing of 0.15 mm.

2.2. Raman Spectroscopy

Raman spectra were collected using a Bruker Sentinel Raman spectrometer fitted with a 785 nm, 500 mW laser. Raman spectra were recorded in the region of 75 cm^{-1} to 2100 cm^{-1} using an integration time of 30 seconds with 3 co-additions per spectrum. The spot size of laser was defocused to an approximate diameter of 2 mm in order to evaluate a large surface area.

2.3 Surface Topology

Surface topology measurements were made using a Taylor-Hobson Talyscan 150 using a contact FTSS probe in the deflection range of 418 µm with a resolution of 7.13 nm. The roughness parameter used, Sa, is a standard surface measurement calculated from the arithmetic mean of the deviations from the mean. TalyMap software was used to perform the analysis of the surface profile data.

2.4 Tensile Testing

Tensile test measurements were made using a Lloyd Instruments EZ20 with 10 KN load cell. The dogbone samples were tested at an extension rate of 2 mm/s.

3. RESULTS AND DISCUSSION

3.1 Surface Measurements

The degree of consolidation between particles can be directly measured by the surface topology of a component. Particle sintering interactions are dependent on the build parameters used in the SLS process and are reflected in the surface roughness of the component. This effect can clearly be seen in the 3D axonometric representations of three different SLS components in Figure 1. Each measurement map is made

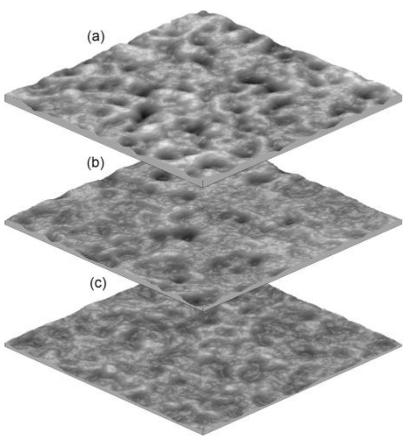

Fig .1. Continuous 3D Axonometric Representations of the Surface Profile of Components Manufactured at Laser Powers of (a) 3 W, (b) 4.5 W and (c) 8 W

by the surface profiler on 4 mm square area. At the lowest laser power level of 3 W, minimal neck growth and coalescence of particles has occurred. The initial particle size of powder is 58 µm and at this lowest laser power individual particles can still be identified. At the highest laser power level of 8 W the surface is much smoother, with less variation in surface height. This is due to the higher laser energy density causing better consolidation of the particles forming a denser, stronger component. The evolution of the consolidation process of the particles can be clearly seen through the measurement maps of the three components manufactured at different laser powers.

3.2 Raman Spectroscopy Measurements

As the peak intensity of Raman spectra is related to the scattering processes observed from the sample, it is possible to evaluate the topology of the surface through the intensity of spectral peaks. For each sample, Raman spectra were recorded along with surface roughness measurements. The peak height of the 1440 cm^{-1} peak associated with CH2 bending vibration was recorded for each measurement. Figure 2 shows linear regression analysis of the comparison between changes in surface roughness and the Raman peak intensity. It can be seen that a strong correlation between the sets of data can be observed giving a R^2 value of 0.989.

Figure 3 shows a graph of the Raman peak intensity against laser energy density. The peak intensity can be seen to decrease rapidly as the laser energy density is increased from 0.015 J/mm^2 to 0.03 J/mm^2. The changes to the laser power have a large effect on the sintering process within this region. Increases in energy density above 0.03 J/mm^2 have a reduced effect on the sintering process. This relationship is confirmed if the surface roughness is plotted against energy density which

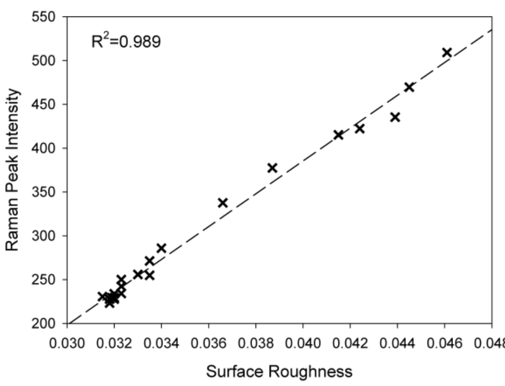

Fig. 2. Graph to Show Linear Relationship Between Raman Peak Intensity and Surface Roughness

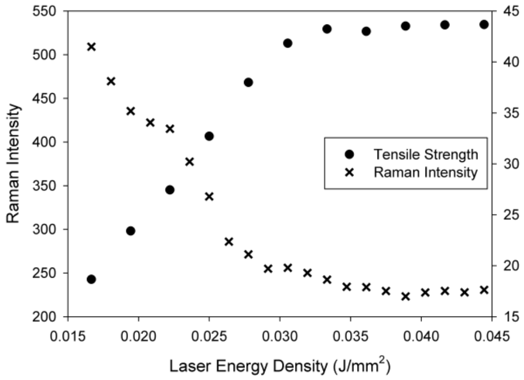

Fig. 3. Graph Showing Raman Intensity and Tensile Strength Versus Laser Energy Density

shows the exact same trend (not shown). This trend is reflected through accuracy of the regressional analysis shown in Figure 1 and the explanation for the clustering of points at low surface roughness.

3.3 Tensile Testing Measurements

The results of the tensile testing measurements are also shown in Figure 3. Tests were repeated in triplicate with the mean value displayed in the graph. It is a well reported fact that the tensile strength of SLS components improves with increasing laser energy density (Caulfield, McHugh et al. 2007), which is the observed trend shown in the graph. The interesting result is that the Raman peak intensity follows a similar trend with a decrease in peak intensity corresponding to an increase in tensile strength. Both curves show the same large changes at energy densities below 0.03 J/mm^2, with much smaller changes above this value. It is unclear at present whether the observed reduction is a machine effect or the kinetics involved in the complicated sintering process.

4. CONCLUSION

This study has shown that the surface roughness of an SLS component can be monitored using Raman spectroscopy. As the laser energy density affects both the surface finish and also the mechanical properties, changes in Raman peak intensity have also proven to be related to the mechanical properties. Therefore, Raman spectroscopy could be a powerful, non-destructive technique to predict mechanical properties of SLS components. Raman spectroscopy measurements are quick and non destructive and could also be used as a processing monitoring tool for quality assurance checks for SLS parts.

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