Characteristics of Single Layer Selective Laser Melted Tool Grade Cemented Tungsten Carbide

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Abstract

Cemented carbide tools, specifically tungsten carbide based alloys, have found a wide range of application fields including manufacturing, agriculture, and mining, among others. A need for customised tooling solutions using cemented carbide alloys have been identified. Additive manufacturing is chosen as a novel manufacturing process due to its superior material and process flexibility. The study investigates the melting behaviour observable during the SLM process using a tool grade cemented tungsten carbide powder. The laser power, scan velocity, and hatch spacing of the SLM process are varied and single powder layers are sintered accordingly. This is done to determine the varying influence these parameter combinations have on the melting behaviour of the material during sintering. For each set of parameter combinations the test samples were analysed using microscopic imaging. It is found that a combination of high laser power, high hatch spacing, and low scan speed yields the best results.

Keywords

Additive manufacturing, carbides, process windows

1 INTRODUCTION

The South African (SA) manufacturing industry faces specific challenges such as a relatively limited market - as compared to the European and US industries – as well as competition from Eastern sources (e.g. China's tooling industry) using low manufacturing input costs. In the SA context a rising need for customised industrial application solutions exists. Using customised tools could provide a competitive advantage allowing SA to compete on a global scale. Areas of customisation include tool geometry and material composition. Materials include carbon and alloy steels, stainless steels, cast iron, aluminium and titanium alloys, polymers, ceramics, tungsten carbide alloys, cermets, and other composites. Tools used in a wide range of industrial applications rely on the superior wear resistance and hardness of hardmetals, such as cemented carbides [1]. Cemented carbides consist of a carbide phase that provides excellent wear resistance and a binder phase that provides toughness and ductility. For specialist applications of cemented carbides, SA players need to exploit market niches where local conditions define a unique product. For example, Allen and Ball [2] determined that wear rates can vary by up to 20 orders of magnitude in agricultural applications. In power generation, ceramics and cemented carbides offer the ideal abrasive wear resistance required. These applications all require specific tooling solutions. SA players must be provided with rapid prototyping (RP) capability, using cemented carbide materials, to open up new possibilities. Specifically purposed tool design, as well as the ability to iteratively adapt the tool, is required. In additive manufacturing (AM) processes several variables influence the final part properties. In powder-based AM, these include the material, the process, and the energy source used to sinter the material [3]. Process related parameters include single layer thickness, scan velocity, hatch spacing, and scan strategy. An example scan strategy is the island scan strategy patented by Concept Laser GmbH that divides the scanned area into square sections (or islands) [4]. The scan sequence is randomised to determine in what order each island is scanned. Laser specific parameters include laser power, spot diameter, wavelength, and energy per laser pulse. Material specific parameters include type, particle size, particle distribution, particle shape, and percentage composition. To improve upon the resultant part properties using selective laser melting (SLM) and hardmetal powders, the laser power, scan speed, scan interval, powder mixture ratio, and particle shape and size influences must to be investigated [5]. To achieve favourable microstructural and mechanical properties, significant emphasis is required on the design strategy of powder materials as well as the laser control processes [6]. Thus a specifically tailored production strategy must be designed for a novel material. Investigation of single layer formation in a SLM process could establish a foundation for defining processing parameters for the powder material under investigation [7]. Kruth et al. [8] identified two crucial parameters influencing the dimensional control of the scan tracks: 1) scan speed and 2) laser power. Scan speed relates to track width, whereas laser power affects track thickness. Other parameters, found to also influence the formation of single layers, include layer thickness and hatch spacing, among others. Varying combinations of these parameters enables the formation of process windows, based on the observable melting activity. Process windows must be established experimentally for any novel material to avoid scan track instabilities (such as spheroidisation) and excessive part porosity [9]. Spheroidisation is the formation of isolated metal spheres having a diameter equal to the incident laser beam [3], [6], [10], [11]. The material is rapidly melted, and subsequently cooled, due to the rapid scan speed. Successful wetting of the underlying layer is hindered and the tendency to reduce the surface free energy dominates the molten material behaviour, thus forming these spheres. Gu and Shen [11] termed this 'shrinkage-induced balling' which they attributed to a significant capillary instability effect. The formation of these spheres hinders subsequent powder deposition and results in a decrease of the layer and final part density, as well as a reduction in the mechanical properties [3], [10], [11]. Several single layer experiments using an unconventional powder produced process windows identifying four melting states: 1) over melting, 2) moderate melting, 3) spheroidisation, and 4) insufficient melting [7], [12], [13]. The process windows are established through varying combinations of scan speed and laser power. Careful selection of both laser processing and powder deposition parameters are necessary to establish a suitable processing window and avoid spheroidisation [6]. This is required to maintain a moderate temperature field and avoid overheating of the powder material. A parameter relating laser power (P), scan speed (v), hatch spacing (h), and layer thickness (d) is the volumetric energy density (VED):

$$VED = \frac{P}{vhd} \quad (1)$$

High VED [$J.mm^{-3}$] values are required to initialise melting activity in the powder bed. This should be limited to slightly higher than the material's melting temperature. Lower hatch spacing increases the VED in the powder bed. Increasing the temperature beyond the melt point of the material results in evaporation of the powder [1], [2]. Rapid expansion of the evaporating particles creates an overpressure in the melted zone, resulting in material ejection from the powder bed. This occurrence leads to the formation of surface protrusions in single layer samples and could become prevalent where complete melting of the cemented carbide is desired.

The choice in energy source in laser melting is an important factor influencing the consolidation of powders. This relates to 1) the energy absorptivity of materials being dependent on the laser wavelength and 2) powder densification being dependent on the incident laser energy on the powder bed [6]. Furthermore, the laser contact time determines the amount of laser energy transmitted to the powder bed. Contact time in SLM is usually between 0.5 and 25ms. This is dependent on the spot diameter and the scan speed. Fully molten powder particles cannot be achieved unless high laser power levels are used, due to the short exposure time. A particular difficulty associated with SLM is scan track formation and the subsequent shrinkage behaviour observable. Individualised scan tracks promote uniform single layer formation. Part stability, the corresponding increased part density, and the associated mechanical properties are dependent on uniform single layers. Hatch spacing, scan speed, and laser power have been found to be the dominant factors affecting how well an individual scan track is formed [6], [14]–[17]. Specfically, hatch spacing relates to the amount of scan track overlap and determines the amount of energy dissipated into the substrate, previous scan tracks, and the raw powder [18], [19]. The incident energy reheats the previous layer and the substrate and conducts heat to the unmelted powder. The second scanned track appears lower than the first and the powder consolidation zone diminishes. The occurrence of this phenomenon relates to shrinkage phenomena. Shrinkage commonly occurs in conventional and novel sintering of cemented carbides [20]. Parts experience varying degrees of shrinkage, dependent on the nature and properties of the material used [1]. During SLM the material experiences thermal expansion upon heating of the powder bed. As the melted tracks cool and solidify, the particles rearrange and shrinkage occurs. The use of finer powder particles leads to faster onset of shrinkage. Catastrophic process failure by delamination was extensively studied by Yasa et al. [21] and noted to be a function of both shrinkage and the occurrence of elevated edges. The formation of elevated edges is explained as a consequence of surface tension. A scan track will assume a form minimising surface tension and maximising volume (i.e. a round cross section in a cylindrical shape). The first scan line is surrounded by unmelted powder with low thermal conductivity. As the melt pool changes, powder particles are drawn towards the melt volume, increasing the melt pool, and altering the solidification rate. This results in lower amounts of powder available for subsequent scan tracks. The result is lower adjacent scan tracks. Spheroidisation, and other defects, also result from the presence of oxide layers between powder particles and previously processed layers. Reduction of surface oxides is required to enable direct metal to metal interfaces [6]. This will encourage successful wetting in the SLM powder system. Oxidation is reduced or avoided by conducting AM processes in inert environments, such as argon gas. Even under extremely low partial pressure of oxygen, most metals form oxides at their respective melt temperatures. Li et al. [7] analysed W-Cu samples produced by SLM that showed lower part densities than for conventional PM. This is attributable to non-melting of the hard phase and limited liquid phase content under the investigated processing parameters. Part densities may be increased by a decrease in scan speed, using narrower hatch spacings, and material exposure at higher laser power [7], [13]. SLM is capable of producing high part densities; however the process develops residual stresses in the material, derived from the high thermal gradients induced in the material. Part distortion, cracking, and/or delamination are but a few defects that could result from excessive residual stresses [3], [6]. Many authors specifically focus on the effects of changing laser power, scan speed, and layer thickness in a SLS/SLM process and how it influences the achievable single track, single layer, and multi-layer sample properties [15], [16]. Others investigate different hatch spacing values and the associated effects on each of these different production phases [18], [19]. Similarly, several works are presented on SLS/SLM using different materials and what the effect is of different material characteristics on achievable properties in single scan tracks and layers, as well as multi-layered samples. Finally, authors have also focused on determining the specific formation mechanisms associated with, for example, residual stress and balling [17]. From this it is clear that the production of cemented carbide parts using SLM technology is feasible and of great interest. The melt behaviour and associated defect formation during processing, however, remains a topic that requires further research. This work investigates single layer formation of a tool grade cemented tungsten carbide material in a SLM system. The influence that varying levels of laser power, scan speed, and hatch spacing have on the single layer formation is the primary focus of this work.

2 EXPERIEMENTAL METHODOLOGY

2.1 Single layer sample production

The 16 test samples for this study are produced from WC-6.6wt.%Co with a M2 LaserCusing® SLM machine from Concept Laser GmbH according to the experimental design outlined in Table 1. The samples are 35x35mm squares. The geometry is used for simplicity and ease of analysis. Magics® software is used to prepare the Computer Aided Design (CAD) model and produce the 2D slice model data. The slice data are exported to the SLM machine which is then used to scan each layer, building the final 3D part. In this work only a single layer is scanned for each parameter set. A uniform powder layer is sieved onto the baseplate to a thickness of 150μm. The machine is sealed and the build chamber flooded with argon gas, thereby creating an inert environment. At oxygen levels below 0.9% the scanning process may commence. The machine is capable of processing multiple build parameters for multiple parts at once. As such, all 16 samples are created on the same build platform during a single experimental run.

2.2 Microscope anlaysis

The single layer test samples are analysed using an Olympus SZX7 Stereo-microscope System. The software used is Olympus Stream Essentials. Microscope images are captured at 1.25 and 3.20 times magnification. The observable differences in single layer formation, as a result of different production parameter sets, are studied by graphing the samples according to high-low, low-high, low-low, and high-high combinations of power and scan speed. This is done for each hatch spacing value which is either 0.075mm, 0.100mm, 0.125mm, and 0.150mm.

3 RESULTS AND DISCUSSION

3.1 Microscope analysis

The microscope analysis is broken down into four primary focus points: 1) protrusion formation on the sample surface, 2) shrinkage activity present (i.e. valley formation), 3) scan track formation, and 4) balling present in the scan tracks.

3.1.1 Protrusion formation

All 16 samples exhibit protrusion formation on the surface. The extent of the formation depends on the combination of laser power, scan speed, and hatch spacing. This can be explained by the near-excessive VED levels developed in the powder bed during processing. In this work, as the layer thickness is held constant and the laser power and scan speed have only two levels (high and low), hatch spacing is the primary factor explaining the differences in the observable phenomena for each sample. Samples produced having a high VED (corresponding to a low hatch spacing) experience increased material ejection on the sample surface during processing. SLM is characterised by rapid melting and subsequent solidification of the material. The ejected material is thus trapped on the surface of the sample by the solidifying material. An increase in hatch spacing decreases VED which corresponds to a reduction in protrusion formation. This is shown in Figure 1 which shows all 16 samples produced. The protrusions appear as dark spots on each sample surface.

3.1.2 Shrinkage

The single layer samples in this work exhibit localised shrinkage near the island edges as well as the sample contours. This is explained by the rescanning of the island edge when an adjacent island is scanned. The rescanned area undergoes a second cycle of thermal expansion, particle rearrangement, and subsequent shrinkage. The process continues as the scan tracks are re-melted and reaches a plateau once particle rearrangement is no longer necessary or possible. It should be noted that shrinkage does not appear uniformly across any of the sample surfaces. The width, length, amount of shrinkage, and placement varies with the associated process parameter values. In some samples, the observable shrinkage increases as scan speed and hatch spacing increases. The occurrence of shrinkage at localised regions has the undesired effect of encouraging porosity formation.

Uniform deposition of powdered material will create thicker layers in areas where shrinkage is pronounced. The incident laser energy doesn't penetrate the material far enough to fuse to the previously sintered layer, resulting in unmelted powder being trapped beneath the newly melted layer. Unmelted powder has a

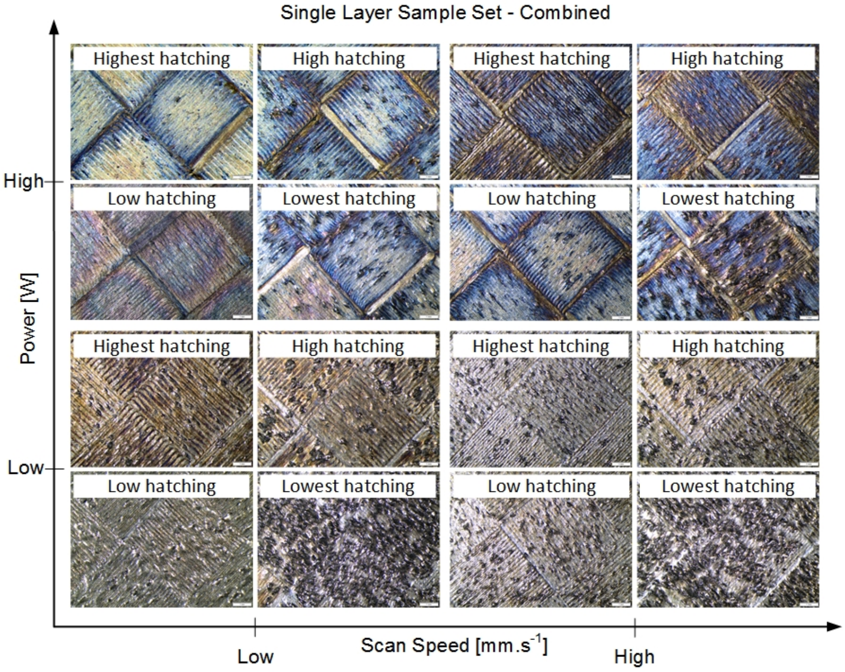

Figure 1 - Combined microscope images of single layer sample parameter sets, according to hatch spacing.

EXPERIMENT NAME	SCAN SPEED, v [mm/s]	LASER POWER, P [J/s]	HATCH SPACING, h [mm]	LAYER THICKNESS, d [mm]
E1	100	100	0,1	0,15
E2	200	100	0,1	0,15
E3	100	200	0,1	0,15
E4	200	200	0,1	0,15
E5	100	100	0,15	0,15
E6	200	100	0,15	0,15
E7	100	200	0,15	0,15
E8	200	200	0,15	0,15
E9	100	150	0,125	0,15
E10	150	100	0,125	0,15
E11	150	150	0,125	0,15
E12	100	100	0,125	0,15
E13	125	125	0,075	0,15
E14	175	175	0,075	0,15
E15	175	125	0,075	0,15
E16	125	175	0,075	0,15

Table 1 – Experimental design parameters and value combinations.

markedly lower density as opposed to the bulk material, which alters the mechanical properties of the built part. Furthermore, as unmelted powder is trapped between melted layers, unstable bonds are formed between these layers and delamination has a
higher probability of occurring. The single layer samples produced in this work exhibit localised tendencies to form elevated edges at both island and part contours.

3.1.3 Scan track formation

In this work it is observed that an increase in hatch spacing results in well-defined scan tracks. This follows since an increase in hatch spacing reduces the percentage overlap between adjacent scan tracks. Furthermore, it reduces the heat sink effect observable in single layer formation during SLM. Based on the experimental results observed here single layers with higher hatch spacing values yield favourable results. Samples with low hatch spacing exhibit obvious defects including pitting as a function of particle evaporation at low hatch spacing, balling as a result of low hatch spacing and moderate to high scan speed, and cracking as a result of low hatch spacing and high power.

3.1.4 Balling

Balling is visible in every sample, with the sample corresponding to P = 200W, v = 100mm.s^{-1}, and h = 0.150mm showing the least amount of balling. Balling is more prominent at high scan speed for both low and high laser power, corresponding to the definition of 'shrinkage-induced balling'. This shows that lower scan speeds yield more favourable results. It can also be seen that low hatch spacing yields higher levels of balling in the sintered samples. The binder material melts incongruently over a range of temperatures, exhibiting a larger degree of melt activity as the temperature increases above the solidus point. Excessive liquid formation is accompanied by a prolonged liquid lifetime (resulting from a higher energy input into the powder material), leading to considerably lower melt viscosity. A higher degree of superheat of the low melting phase results, enhancing the Marangoni effect. This forms a large amount of individual spheres with the associated diminishing surface energy. At lower hatch spacing values, the amount of thermal energy in the sample layer will be higher due to a larger concentration of laser energy per unit area, thus leading to the formation of individual balls. This suggests that high values for hatch spacing yield more favourable results. Combinations of high laser power resulted in less balling in the test samples produced in this work. Coupled with high hatch spacing, significantly better scan tracks showing less balling or defect formation is achievable. Parameter combinations with low laser power show a higher concentration of balling and/or protrusion formation. This suggests that parameter combinations of low scan speed, high hatch spacing, and high laser power will result in favourable single layer formation.

3.2 Process windows

The results in the previous sections are used to create process windows describing the expected observable single layer formation phenomena when selectively melting WC-6.6wt.% Co powder. Here, the process windows incorporate the effect of various hatch spacing values on the formation of single layers, shown in Figure 1. It is clear that a high laser power, low scan speed, and high hatch spacing combination leads to the best results. The resultant samples are characterised by low levels of protrusion formation, little to no balling, limited micro-cracking, and almost no shrinkage. This processing region is defined as the baseline parameter set to describe the observable phenomena in the remaining three regions. In comparison to the baseline, low-low (*P-v*) combinations for the remaining hatch spacing values are characterised by prominent protrusion formation and other surface defects. These defects include indistinguishable scan track formation, pitting, localised shrinkage, and a certain degree of balling. A similar observation can be made for low-high and high-high combinations of laser power and scan speed. When compared to the baseline process region, again it is clear that single layer formation is not as successful and surface defects are more pronounced. It is concluded that, for each combination (low-low, low-high, high-low, and high-high), as hatch spacing increases, the presence of surface defects decrease.

4 CONCLUSIONS

The following conclusions can be made from the results presented here:

1. Single layer samples were successfully produced using a SLM technology and tool grade cemented tungsten carbide powder.
2. Process windows were established to describe the expected melt activity observable for a given combination of laser power, scan speed, and hatch spacing.
3. Varying laser power, scan speed, and hatch spacing has a significant effect on single layer formation and results in different levels of surface defect formation.
4. The optimal processing region to produce single layers from a tool grade cemented tungsten carbide material corresponds to high laser power (*200W*), low scan speed (*100mm.s^{-1}*), and high hatch spacing (*0.15mm*). This corresponds to a *VED = 88.889 J.mm^{-3}*.

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