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On the limitations of Volumetric Energy Density as a design parameter for Selective Laser Melting

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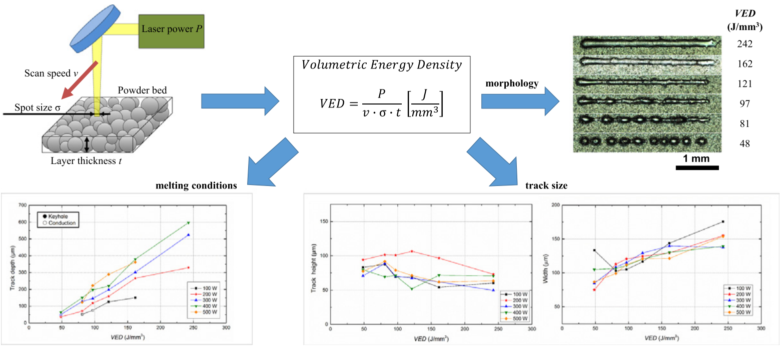
HIGHLIGHTS

- Volumetric Energy Density (*VED*) affects track shape, values lower than 100 J/mm^3 are insufficient to fully melt the alloy.
- Surprisingly, under some conditions, tracks deposited with sufficiently high *VED* values still had an undesirable morphology.
- *VED* fails to capture melt pool physics, hence it poorly predicts both melting condition and track morphology.

GRAPHICAL ABSTRACT



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ABSTRACT

Energy density is often used as a metric to compare components manufactured with Selective Laser Melting (SLM) under different sets of deposition parameters (e.g., laser power, scan speed, layer thickness, etc.). We present a brief review of the current literature on additive manufacturing of 316L stainless steel (SS) related to input parameter scaling relations. From previously published work we identified a range of Volumetric Energy Density (*VED*) values that should lead to deposition of fully dense parts. In order to corroborate these data, we designed a series of experiments to investigate the reliability of *VED* as a design parameter by comparing single tracks of 316L SS deposited with variable deposition parameters. Our results show the suitability of *VED* as a design parameter to describe SLM to be limited to a narrow band of applicability, which is attributed to the inability of this parameter to capture the complex physics of the melt pool. Caution should be exercised when using *VED* as a design parameter for SLM.

1. Introduction

The need for manufacturing of complex components that are difficult-to-impossible to fabricate through subtractive methods has increased interest in layer-by-layer manufacturing technologies given their freeform capability to process 3-dimensional parts with minimal

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Table 1
SLM parameters and energy density for fully dense 316L stainless steel.

Source	Laser power (W)	Scan speed (mm/s)	Laser beam size (μm)	Layer thickness (μm)	*VED* range for fully dense parts (J/mm^3)	Sample type
[27]	40–98	30–300	30	100	155.5	- Single tracks - Single layer ribbons - Cubic samples
[6]	50–150	30–400	70	35	245–1225	- Single tracks - Cubic samples
[14]	150–400	500–1800	54	0–200	92–155	- Single tracks - 3D pillars
[4]	180	Static pulses	70	50	105	- Cubic samples

material waste. Currently, Selective Laser Melting (SLM), a powder-bed-fusion based process, is arguably one of the most successful of these techniques. In SLM a high-power laser melts metal powders one layer at a time to produce final net-shaped components using a 3D computer-aided design (CAD) model as a guide.

Given the presence of a wide spectrum of custom-made and commercially available SLM systems, the manufacturing of parts is affected by a large number of different deposition parameters, at least 130 according to Yadroitsev [28]. The most commonly investigated parameters are laser power, scanning speed, scanning strategy, hatch distance and layer thickness. These parameters greatly affect the final quality of the material being produced and the literature abounds with correlation studies (both simulation and experimental) between some of these parameters and final properties [1,2,6,9,10,21,27,32]. However, drawing quantitative comparisons between parts fabricated under different conditions can prove challenging.

Achieving full density in final parts is, for instance, one of the most desired outcomes in additive manufacturing (AM) since the retention of even minimal amounts of residual porosity seriously degrades mechanical properties, which explains the extensive experimental results available in the literature related to density [19,24]. Researchers have often presented their results on final part porosity using an approach based on energy density, finding that in many cases when deposition occurs in a specific energy density range, final porosity can be minimized. For instance, Wang et al. [26] combined laser power P and scan speed v into linear energy density $\Phi = P / v$ (for a fixed laser beam size) to identify the process window for deposition of Inconel 625 and found that values of Φ in the range of 1–1.5 lead to the best melting conditions for the tested material. Similarly, Yadroitsev et al. [30] in their work on 904L stainless steel optimized the P/v ratio and correlated it with track shape (height, width and depth). In their analysis of single tracks made of maraging steel, Campanelli et al. [3] combined power, scan speed and laser beam diameter σ in the definition of surface energy density $E_d = P / v\sigma$ finding that an increase in energy density resulted in a melt pool that was both wider and deeper. A slightly different approach was then followed by Ciurana et al. [5] where Volumetric Energy Density (*VED*) was used as a summarizing physical quantity to characterize shape stability of CoCrMo single tracks. Ciurana's definition of *VED* is expressed in Eq. (1):

$$VED = \frac{P}{v\sigma t}\left[\frac{J}{mm^3}\right] \quad (1)$$

Defined as the ratio between laser power P and the product of scan speed v, laser beam diameter σ and powder bed layer thickness t, *VED* expresses the amount of energy delivered per unit volume of powder deposited in the bed. Ciurana found that a minimum *VED* value of 151 J/mm^3 was required for efficient melting of CoCrMo powder into continuous single tracks. Similarly, Gong et al. [9,10] applied volumetric energy density on the analysis of Ti-6Al-4V alloy, but in their work the value used for σ was the hatch distance between two adjacent lines. Gong's results showed a correlation between *VED* values and internal porosity in final parts, demonstrating that it is possible to minimize residual porosity when deposition takes place in a precise *VED* window. When the energy delivered to the powder bed is insufficient, in fact, the poor melting conditions will lead to the retention of a high number of macroscopic pores (from tens to hundreds of microns in size) in the final parts. These pores led to deleterious effects on mechanical properties such as tensile strength and fatigue resistance. When the energy density is instead too high, a deposition condition known as "keyhole mode" is reached: in this mode the melt pool is very deep and re-melting of multiple layers occurs. Due to the high energy density, metal boiling temperatures are reached and vaporization of the alloy takes place. In addition, intense inward Marangoni flow in the melt pool can occur, adding to the propensity for vapor driven gas bubbles to be trapped and increase part porosity [17].

In a recent study by Yap et al. [31], *VED* values used by different authors were compared with the theoretical energy requirements for melting the alloys studied. In most cases, the energy provided to the powder bed was approximately four times the amount theoretically required. Table 1 summarizes some *VED* values and their corresponding parameters from previous work on 316L SS found in the literature. *VED* values were either provided by the authors or calculated on the basis of Eq. (1). According to Table 1 it appears that for 316L, *VED* values in the range of 100–1000 J/mm^3 are high enough to allow the deposition of stable and continuous tracks that should lead to fully dense parts. Values higher than 1000 J/mm^3 lead to inefficient deposition and energy waste and could potentially enter the undesirable keyhole regime.

The same value of *VED* can be obtained using significantly different deposition parameters, yet no information can be currently found in the literature that provides a comparison between parts obtained with constant *VED* values but under different conditions. In view of the above discussion it is the objective of the present study to ascertain the validity of using *VED* as a design parameter for SLM deposition, especially to evaluate the lower threshold value (~100 J/mm^3) by depositing single tracks in proximity of this threshold and by comparing their morphology and melting conditions.

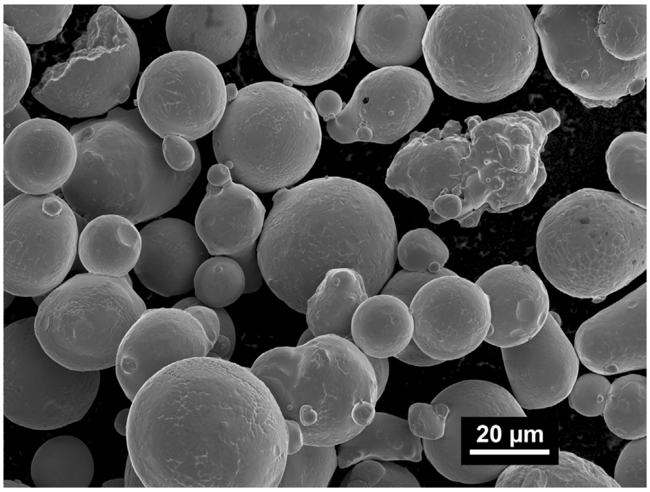

Fig. 1. The gas-atomized particles of 316L SS used in the present study have mostly spherical shape but also exhibit occasional agglomerates.