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Is the energy density a reliable parameter for materials synthesis by selective laser melting?

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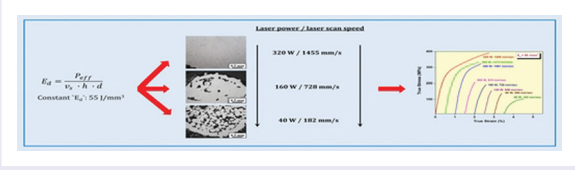
ABSTRACT
The effective fabrication of materials using selective laser melting depends on the process parameters. Here, we analyse the suitability of the energy density to represent the energy transferred to the powder bed, which is effectively used to melt the particles and to produce the bulk specimens. By properly varying laser power and speed in order to process the powder at constant energy density, we show that the equation currently used to calculate the energy density gives only an approximate estimation and that hatch parameters and material properties should be considered to correctly evaluate the energy density.



IMPACT STATEMENT
Al-12Si SLM samples were fabricated at constant energy density. The laser power and laser scan speed combination variation was used to demonstrate the significant changes needed with energy density equation.

ARTICLE HISTORY
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KEYWORDS
Selective laser melting; energy density; laser power; tensile properties

1. Introduction

Selective laser melting (SLM) is an additive manufacturing process that can produce parts with complex dimensions combined with fine microstructures, due to the high solidification rates realized during the process [1–4]. Materials fabrication using SLM requires a significant amount of research on developing the process parameters, which in turn depend on the physical and chemical properties of the metal/alloy to be processed and the interaction of the laser with the material [5–9]. There are several process parameters that can influence the fabrication process and that have to be carefully adjusted such as to produce parts without defects such as porosity, cracks, altered chemical composition by selective vaporization. [10,11]. However, most of the current research on the process optimization considers only the energy input or the energy density, which is given by

$$E_d = \frac{P_{\text{eff}}}{v_s \cdot h \cdot d}, \tag{1}$$

where E_d is the energy density or energy input (ED) in J/mm^3, P_{eff} is the effective laser power (W), v_s is the laser scan speed (mm/s), h is the hatch distance (mm) and d is the layer thickness of the powder bed (mm) [12]. This equation does not consider other important factors such as the hatch style, the direction of gas flow, the laser offsets at the corners, the laser diameter and its offset at the surface of the melt and so on. However, nowadays the hatch distance and the hatch style are also taken into account during the parameter optimization [13,14]. Nevertheless, the applicability of the Equation (1) is at stake, even though it has been widely used for optimizing the

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SLM parameters. The Equation (1) may not properly represent the effective energy transferred to melt the powder bed.

Accordingly, in this work we have investigated this aspect by studying the mechanical properties and the microstructure of the Al-12Si alloy synthesized by SLM. To test the applicability of Equation (1), laser power and speed have been properly varied in order to produce the specimens at constant energy density. Additional samples have then be synthesized at constant laser speed and varying laser power in order to highlight the importance of the individual parameters for the production of high-strength defect-free SLM parts.

2. Experimental details

The Al-12Si samples were fabricated using a SLM250 HL device (SLM solutions) equipped with Yb-YAG laser with a spot size of $\sim$80 µm. A layer thickness of 50 µm and a hatch distance of 110 µm with $\sim$20 µm overlap between the hatches was used for the experiments. A hatch style rotation of 73° has been employed for all the samples. The laser power and laser scan speeds were varied to have a constant energy density of 55 J/mm^3 in the first set of experiments, and in the other case the laser scan speed was kept constant at 1455 mm/s and the laser power was varied from 320 to 80 W. A detailed information about the fabrication of Al-12Si SLM specimens is reported elsewhere [15,16]. The density of the samples was measured by the Archimedes principle, and optical microscopy (OM) images along the cross section of the tensile bars [17–19] were taken using a Zeiss Axioskope 40. Room temperature tensile tests were carried out using an Instron 8562 device under quasistatic loading with a strain rate of 1×10^{-4} s^{-1} and the strain was measured using a Fiedler laser-extensometer. The tensile samples were built vertical to the substrate plate (standing against gravity). The exact dimension of the tensile rods +0.5 mm allowance was used to build the tensile samples. The as-built samples were then polished using polishing papers with grit 2500 and 4000, before testing in order to have a smooth surface. The tensile tests were carried out in the as-prepared condition without any external heat treatment. The samples were all built in one and the same build spread across the substrate plate [20–22].

3. Results and discussion

Figure 1(a) shows the room temperature tensile test results of Al-12Si specimens fabricated by SLM at a constant energy density of 55 J/mm^3 with a constant layer thickness and hatch distance. The two parameters laser power and laser scan speed were varied in order to have a constant energy density. It can be observed that the tensile curves are not identical even though the same energy density is supplied to the powder bed for the production of the tensile specimens. The yield strength, the ultimate tensile strength (UTS) and the ductility for Al-12Si samples fabricated with 320 W power and 1455 mm/s scan speed (i.e. optimized parameters) are $\sim$240, $\sim$385 MPa and $\sim$3%, respectively. The UTS and the ductility drop to $\sim$330 MPa and $\sim$1.75%, when the power is reduced to 280 W and the scan speed to 1273 mm/s. Similarly with gradual reduction of laser power and laser scan speed to 40 W and 182 mm/s, the tensile properties deteriorate and reach an UTS of mere $\sim$100 MPa and no appreciable ductility. These results show that the energy density cannot be used as a single parameter to effectively control the quality of the SLM specimens. The samples exhibit no ductility when the laser power is below 200 W and the scan speed is less than 1091 mm/s, except for the samples produced with a laser power of 40 W and a laser scan speed of 182 mm/s. These results show that either the laser power or the laser scan speed thus has to be independently adjusted to produce SLM parts with optimized mechanical properties. In order to clarify the influence of laser power/laser scan speed on the mechanical properties, Al-12Si samples were produced at both fixed scan speed by varying the laser power and fixed laser power by varying the laser scan speed.

Figure 1(b) shows the room temperature tensile test results of Al-12Si SLM specimens produced at constant laser scan speed by varying the laser power between 320 and 80 W (in steps of 40 W). It can be observed that with decreasing laser power, the tensile properties of the Al-12Si samples deteriorate. For instance, an UTS of $\sim$385 MPa is observed for the sample produced with a laser power of 320 W and the UTS decreases gradually to 355, 343, 275, 187, 128 and 60 MPa, when the laser power is reduced to 280, 240, 200, 160, 120 or 80 W, respectively. These findings reveal the strong influence of the laser power on the mechanical properties of the SLM processed parts. On the other hand, no significant changes were found for samples that were produced employing a constant laser power but a decreasing laser scan speed. Hence, this set of experiments will not be discussed here in further detail.

The deterioration of the mechanical properties of the Al-12Si samples either at constant energy density (by varying the laser power and laser scan speed) is also reflected in the microstructure of the different Al-12Si specimens. Figure 2 shows OM images of Al-12Si SLM samples produced at a constant energy density by varying the laser power and laser scan speed combination. It can be observed that the sample produced with 320 W

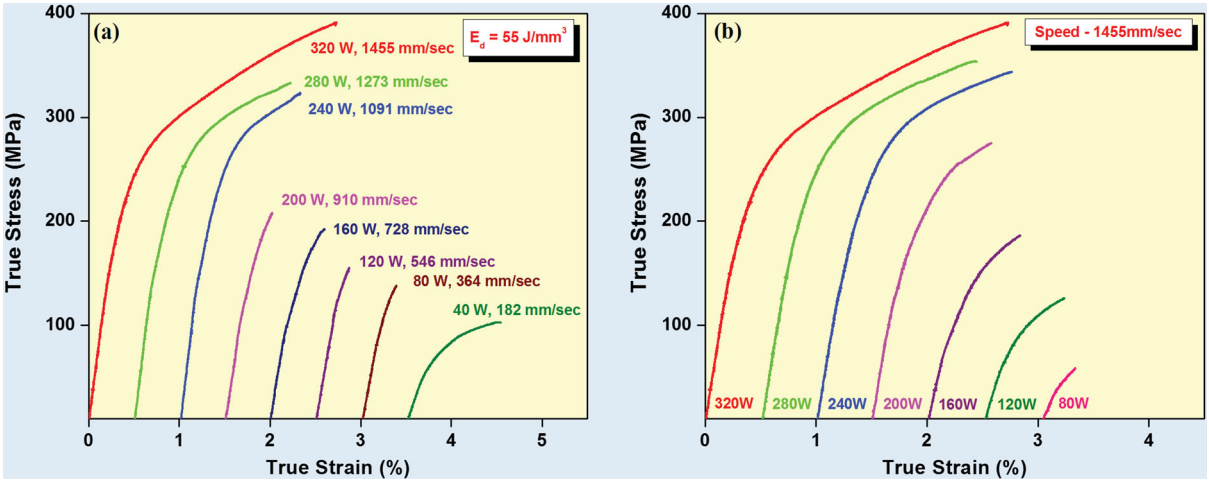

Figure 1. Room temperature tensile test results of Al-12Si SLM specimens fabricated (a) by varying the laser power and laser scan speed so as to keep the energy density constant at 55 J/mm^3 (b) by varying the laser power between 320 and 80 W (in steps of 40 W) at a constant laser scan speed of 1455 mm/s.

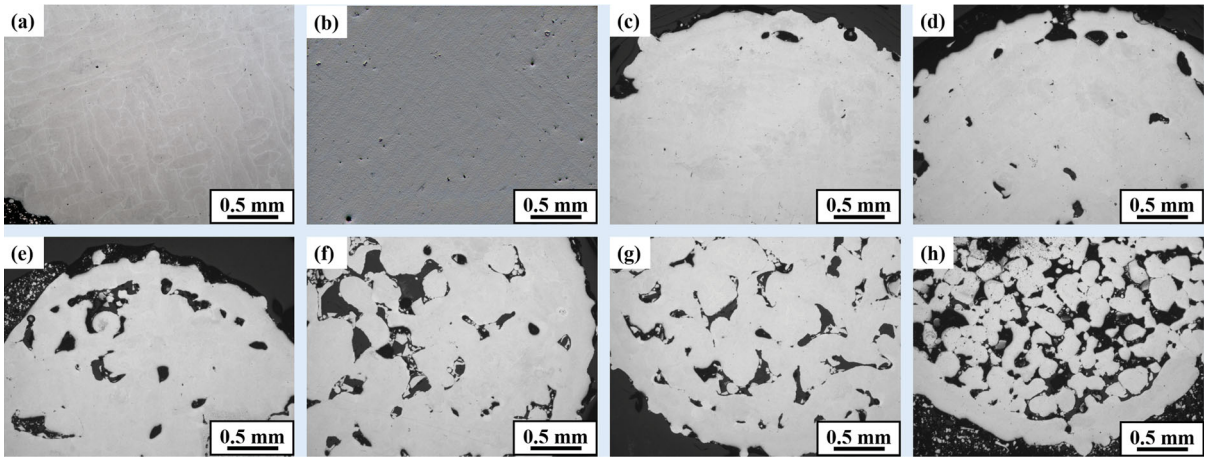

Figure 2. OM images of Al-12Si SLM samples obtained at a constant energy density of 55 J/mm^3 but with varying laser power and laser scan speed combinations of (a) 320 W, 1455 mm/s, (b) 280 W, 1273 mm/s, (c) 240 W, 1091 mm/s, (d) 200 W, 910 mm/s, (e) 160 W, 728 mm/s, (f) 120 W, 546 mm/s, (g) 80 W, 364 mm/s, and (h) 40 W and 182 mm/s, respectively.

laser power and 1455 mm/s laser scan speed (Figure 2(a)) does not show appreciable porosity but only traces of the hatch or the melting sequences are visible. One the other hand, the amount of porosity in the Al-12Si SLM samples increases with decreasing laser power and laser scan speed. The relative densities of these samples are depicted in Figure 3, where it can be observed that the relative density of the Al-12Si sample fabricated with a laser power of 320 W and a scan speed of 1455 mm/s reaches ~99.5% and the density decreases to 99% when a power of 280 W is employed. The relative density further drops to 98%, 93%, 81%, 75%, 72% and finally to 40% when the employed laser power is lowered to 240, 200, 160, 120, 80 or 40 W, respectively.

The pores observed in the Al-12Si samples are not spherical in shape, ruling out that they are 'metallurgical' pores caused by entrapment of gas (hydrogen) in the melt [23]. Since the pores are irregular in shape and mostly sized over 50 µm, this suggests the presence of keyhole pores [24,25] that form when there is a keyhole instability. There are several reasons that may cause the formation of keyhole instabilities such as high cooling rate, insufficient ED, improper laser offset at the power bed [26]. If the fast cooling rate had resulted in the formation of the keyhole instability, then all the samples should exhibit a similar effect. However, the samples fabricated with laser powers of 320 and 280 W do not show any traces of keyhole instability and hence this effect can be ruled out. This suggests that the keyhole instabilities observed in the samples fabricated with laser powers $\leq$ 240 W are due to improper melting of the powder bed, which means that the amount of energy supplied to the power bed

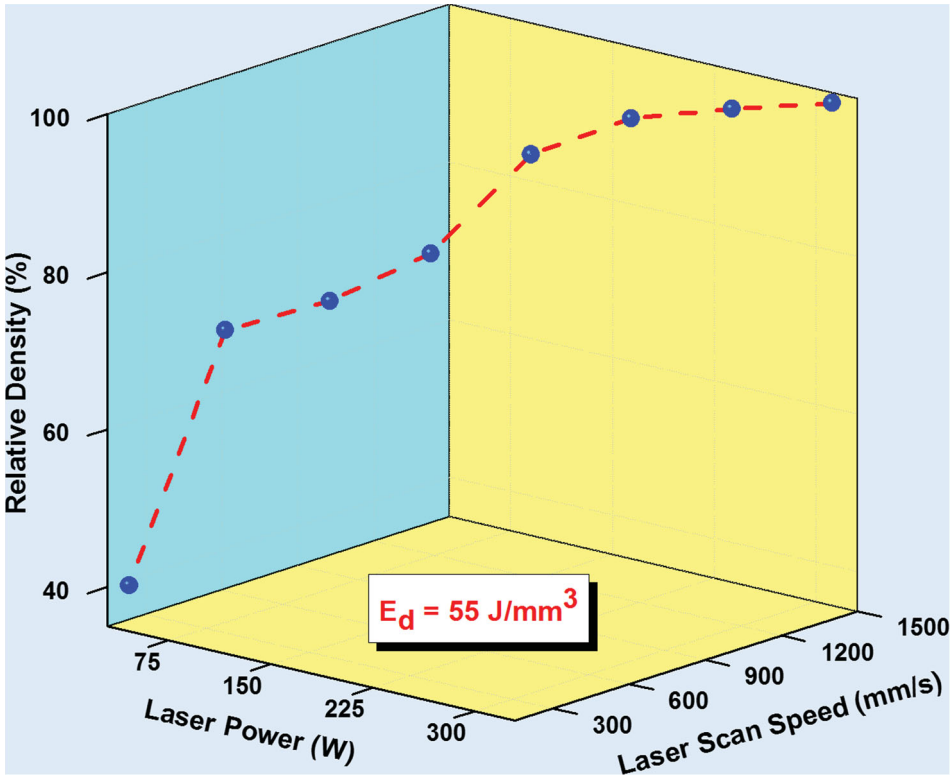

Figure 3. Relative density measured by the Archimedes principle for Al-12Si SLM samples obtained with a constant energy density of 55 J/mm^3 but with varying laser power and laser scan speed combinations.

is not sufficient to melt the powder bed completely. As a result, the powder particles at some places remain as powder particles (no melting takes place due to insufficient energy imparted) and they come off from the sample surface during subsequent polishing, causing the observed porosity in these sample. Some of the present results are in coherent with the results from Bertoli et al. [27], where decreasing laser power leads to balling. The present experimental results suggest that ED cannot be considered as the only criterion in the optimization of process parameters during the SLM process. Although the energy density remains constant, the combination of laser power and laser scan speed plays a significant role and, more importantly, the laser power has a dictating influence. This disproves the applicability of the Equation (1) for the evaluation of the energy effectively transferred to the powder bed during SLM processing and suggests that the energy density calculated through Equation (1) should be used carefully in the comparison with different materials, as it merely represents a rule of thumb. In fact, the SLM process parameters depend strongly on the properties of the metal/alloy and its interaction with the laser. In addition, the parameters do not include complex physical events such as Marangoni flow, melt instabilities, diffusion [27]. To use the concept of energy density effectively in the SLM parameter optimization process, it has to be modified extensively involving additional process parameters, such as hatch style, laser spot size and laser offsets, and materials properties, including thermal conductivity and reflectivity.

4. Summary

The applicability of the widely used energy density equation during the SLM process has been investigated for Al-12Si specimens. The Al-12Si SLM samples were prepared using different process parameters (1) at constant energy density by varying the laser power and laser speed combination and (2) at constant speed and varying laser speed. The results show that in either case with decrease in the laser power the tensile properties deteriorate because of the increasing amount of keyhole porosity. This suggests that the laser power is one of the most influencing process parameters to be considered and the ED equation can be merely used as a rule of thumb to calculate the energy transferred to the powder bed and to compare it with the ED used for other metal/alloy systems. In order to effectively employ the ED equation in the SLM parameter optimization process, an extensive modification of the equation has to be made involving the hatch parameters and the material properties.

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Disclosure statement

No potential conflict of interest was reported by the authors.

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