Review Paper

A Review: Melt Pool Analysis for Selective Laser Melting with Continuous Wave and Pulse Width Modulated Lasers

Jiwhan Kim^{a,†}, Seungmuk Ji^{a,†}, Young-Shik Yun^{a,b}, and Jong-Souk Yeo^{a,b,*}

^a*School of Integrated Technology, Yonsei University, Incheon 21983, Korea*

^b*Yonsei Institute of Convergence Technology, Yonsei University, Incheon 21983, Korea*

Received September 21, 2018; revised October 10, 2018; accepted October 20, 2018

Abstract

Selective laser melting (SLM) is a promising additive manufacturing technique applied to various areas such as aerospace and biomedical industries. Because product characteristics can be controlled by SLM process parameters, several investigations have been conducted to clarify the relationship between process parameters and product characteristics. Melt pool, controlled by process parameters, is a suitable resource to determine the product profile accuracy and mechanical property. Two laser types, continuous wave (CW) and pulse width modulation (PWM), are typically used in SLM processes, and each has distinct advantages depending on the purpose of the process. While CW maintains its power constant, PWM presents a repeated pattern with a pulse width. Herein, the main differences in the process parameters between the two laser types and their effects on the melt pool formation during the SLM process are explained. The results demonstrate that CW and PWM are favorable for dense and fine structures, respectively.

Keywords: Selective laser melting, Melt pool dimension, Pulse width modulation, Continuous wave

I. Introduction

Additive manufacturing (AM) is a technology that allows the building of an object layer by layer. Current developments in AM technologies brought attention to its potential in manufacturing industries including automobile, aerospace, and medical market [1-3]. AM technologies allow to design complex objects and manufacture parts in shorter lead time [4]. AM technologies are classified by the International Organization for Standardization (ISO) and ASTM (ISO/ASTM 52900:2015), including powder bed fusion (PBF), directed energy deposition (DED), binder jetting, and sheet lamination [5].

Each AM type presents advantages and disadvantages. PBF is most commonly used for medical implants as PBF results in a fine surface finish and a small spot size, allowing the construction of accurate and complex objects [6, 7]. PBF uses a melting mechanism with a heat source including laser and electron beam. A layer of metal powder is placed on a base plate, and the laser beam scan is followed by a computer aided design (CAD). The process continues layer by layer until it reaches the top of the plane [3,8,9].

As previously mentioned, PBF being the leading AM technology for medical implants, specific types of PBFs, such as selective laser sintering (SLS) and electron beam melting (EBM), are the most widely used due to their simple operating methods [10-12]. However, SLS presents a significant challenge for the designing of an accurate model as SLS lacks in laser precision and powder size [13]. Recently, many investigations have been published to find an alternative to AM technology, and selective laser melting (SLM) is one of the promising candidates [9]. In particular, SLM is highlighted as an alternative for the EBM owing to EBM's high cost [14].

In the SLM process, a thin layer of powder is deposited for each layer and levelled on a substrate plate or the previous layer [14,15]. While the chamber is filled with an inert gas to prevent from oxidation during the process, a laser with sufficient energy to fully melt the powder fuses the metal particles selectively according to the CAD data [16].

Although SLM has a high potential to be utilized, it is necessary to optimize the process parameters, such as the laser type, laser power, scan speed, and hatch spacing, which determine the total input energy density consumed to melt the metal powder [17,18]. Among these parameters, the laser type only characterizes the laser energy transfer, whereas the other parameters only define the total amount of input energy. There are two laser types in laser-based

[†]These authors contributed equally to this work.

*Corresponding author

E-mail: jongsoukyeo@yonsei.ac.kr

additive manufacturing processes: continuous-wave (CW) and pulse-width-modulation (PWM). While CW lasers maintain a constant power value, PWM lasers emit at a certain energy for a specified duration with a duty cycle. Thus, when the average power is fixed, PWM lasers can deliver high peak power. Recently, the need for PWM lasers has increased in the additive manufacturing industry as the demand for microstructure printing capability has increased, although the majority being possessed by CW lasers [19]. However, compared to the numbers of studies on SLM process parameters, not many publications specify the difference between the SLM laser types.

Understanding the differences between the two laser types is important for industrial SLM systems to become commercially available. Since the running mechanisms of CW and PWM are different, as mentioned above, the two laser types have different thermal history during the manufacture, including temperature variation and cooling rate that are crucial to the material and mechanical characteristics [17,20]. Differences in the thermal history between the two laser types inevitably lead to changes in the melt pool dimensions, directly translated into the part accuracy. Moreover, different laser mechanisms result in additional process parameters for PWM. For this reason, this study focuses on reviewing how the process parameters of the two laser types affect the melt pool dimensions.

II. Selective laser melting parameters

As mentioned before, understanding the relationships between the SLM parameters is crucial to optimize the SLM process as the resulting data of SLM can be varied depending on the SLM parameters used. Because SLM is a complicated process with irregular phenomena, it is hard to collect all the data in a simple manner [21]. Although PWM shares the basic process parameters with CW, such as laser power and scan speed, it presents unique process parameters due to its different laser pulse mechanism. For this reason, the process parameters are reviewed separately for both laser types.

1. Continuous wave parameters

According to Aboulkhair et al., the SLM process parameters can be arranged in four categories as illustrated in Fig. 1: laser-related, scan-related, powder-related, and temperature-related [21]. Each parameter has a significant impact on the melt pool dimension. Yet the most studied and used process parameters are the scanning speed, hatch spacing, laser power, and layer thickness [21-23]. Using all the major process parameters, a concept known as volumetric energy density (VED) is employed to examine the physical quantities, such as the melt pool dimensions and microstructures [17,24].

The VED is the amount of energy stored in a unit

volume. The VED is expressed in Eq. (1):

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

where P is the laser power, v is the scanning speed, σ is the hatch spacing, and t is the layer thickness. Sometimes, σ also refers to the spot size of the laser rather than the hatch spacing, especially in the case of a single-line printing

Figure 1. Selective laser melting process parameter classified by Aboulkhair et al. (Reproduced under a creative commons license from ref. 21, Copyright © 2014 The Authors. Published by Elsevier B.V.)

Figure 2. (a) Relative densities of SLM samples measured at various laser energy density, (b), (c), and (d) are taken with optical images at the energy densities indicated in (a). (Reprinted with permission from ref. 26, copyright © Emerald Publishing Limited 2017).

experiment.

Many studies have been performed to understand how the VED affects the melt pool morphology and mechanical properties. Yadroitsev et al. used scanning speed and laser power as process parameters while Han et al. varied scanning speed and hatch spacing [25,26]. On the other hand, Xu et al. used all three parameters, the scanning speed, laser power, and hatch spacing, to investigate the decomposition behavior of the α' martensitic structures under the condition of high energy deposition [27]. Many investigations have been performed to verify the correlations between the process parameters and the relative density (RD). A high RD represents a low porosity, and a low RD represents a high porosity in the material that can cause future defects. Usually, a high aspect ratio of the laser power and scan speed, i.e., high energy density, can produce a high RD in the part due to the most stable formation of the melting line [28]. However, aforementioned researches regarding the VED agree that there is a range of VED values to achieve the maximum RD, as presented in Fig. 2.

As demonstrated in Figs. 2(b) and (d), insufficiently low and high VED values cause a low RD value, resulting in a weak bonding of metal particles and pore formations, respectively. The statement that unsuitable VED value causes defects agrees with the argument stated by Wei et al [29]. Although VED has a good correlation with RD, VED is recently considered as an inaccurate parameter to predict the melt pool dimensions in SLM. According to Bertoli et al., the melt pool dimensions from a same VED with different parameter combinations are not the same [23]. For this reason, investigations with alternate parameter combinations have been conducted. For example, the peak temperature from a Gaussian laser source is not correlated with the ratio P/v , but instead correlated with $P/\sqrt{v}$ [29]. Although VED cannot determine the specific melt pool geometric dimensions, it can still be useful when combining the four common process parameters and available to determine a broad guideline for parameter combinations [23].

The hatch spacing and layer thickness are factors that affect the porosity and the roughness of the printed part [21,30]. The larger the hatch spacing, the greater the porosity is, due to the decrease in intra-layer overlap of the laser beam [21]. Therefore, if the hatch spacing is large, the porosity can be reduced by choosing a sufficiently thin layer that produces a suitable power density to engender the intra-layer overlap under a given laser power and scan speed. The large layer thickness also tends to increase the porosity and the roughness [30]. If the layer is too thick, the Marangoni force and recoil pressure due to material evaporation lead to a high instability of the melt flow and melt splashing, resulting in a large porosity and roughness. Therefore, in order to minimize the porosity and roughness, it is necessary not only to adjust the process parameters to determine the sufficient VED, but also to

create a stable flow of melt pool by finding an appropriate balance between the hatch spacing and the layer thickness.

2. Pulsed wave modulation parameters

Although PWM shares common process parameters with CW, the process parameter of CW lasers cannot be directly transferred to that of PWM lasers owing to the difference in laser energy mechanisms [19]. PWM parameters are more complex and have more criteria to be considered. Square wave shaping of laser power is a common method to transfer the laser energy in PWM and it is convenient to understand the energy transfer mechanisms, as presented in Fig. 3 [19]. The pulse energy E can be expressed as [19]

$$E = \int_0^{t_{on}} P(t) dt \quad (2)$$

where $P(t)$ is the power function of time t and t_{on} is the duration of the pulse. The pulse repetition rate (PRR) can be defined as

$$PRR = \frac{1}{t_{on} + t_{off}} \quad (3)$$

where t_{off} is the time when the power = 0. Therefore, the average power (P_{avg}) can be described as

$$P_{avg} = E \times PRR \quad (4)$$

The duty cycle (δ) is another important factor in the PWM laser. It represents the time over the pulse period and can be calculated as

$$\delta = \frac{t_{on}}{t_{on} + t_{off}} \quad (5)$$

Figure 3. Schematic representation of (a) temporal and (b) spatial disposition of pulses (Reprinted with permission from ref. 19, copyright © Springer-Verlag London 2017).

As the pulse is repeated with a high frequency in SLM, an overlap between each pulse exists in PWM laser. The overlap can be divided in two terms: pulse overlap (O_p) and line overlap (O_l). The pulse overlap happens in the horizontal direction due to the scan speed and pulse width, and the line overlap occurs in vertical direction due to the hatch spacing. O_p and O_l can be expressed as

$$O_p = \frac{(d_s - d_p)}{d_s} \quad (6)$$

$$O_l = \frac{(d_s - d_h)}{d_s} \quad (7)$$

where d_s is the laser beam diameter, d_p is the distance between the central points, and d_h is the hatch spacing.

In other words, CW lasers can also be expressed as 100 % duty cycle and pulse overlap [19,31]. These differences between CW and PWM lasers result in different characteristics of energy saturation and cooling rates depending on the exposed positions.

(1) Pulse shaping

In practice, the laser power does not present a constant rectangular pulse shape due to an overshoot, even though the laser input has a rectangular shape [32]. For example, it results in 75 to 100 % of the peak power for the first 0.7–1.1 ms, then remains in a steady state for most of the pulse duration and loses power with rapid cooling in the end. The details of the overshoot are decided by the SLM process parameters. Using this characteristic, pulse shaping techniques can be characterized in two types as shown in Fig. 4: ramp-up and ramp-down [33]. As the name indicates, the ramp-up emits more power in the late pulse, and the ramp-down emits at the early pulse.

According to the investigations on pulse shape and weld pool dimension studied by Bransch et al, the ramp-down pulse shape results in smaller melt pool dimensions and less porosity [32]. The biggest difference between the ramp-up shape and ramp-down shape is the location of the maximum power density. The maximum power density of the ramp-up shape is located at the end of the pulse duration, where the crater is already formed and the effective absorptivity is the greatest. In contrast, the ramp-down has a maximum power density where the energy coupling is the poorest. For this reason, the ramp-up shape has a bigger melt pool dimension than the ramp-down shape.

Figure 4. Two types of pulse shaping: (a) ramp-up and (b) ramp-down.

The pulse output is not always equal to the pulse input. The peak power of the output pulse may vary depending on the pulse shape. Mumtaz and Hopkinson determined that the ramp-up shape has a lower peak power than the ramp-down shape and a rectangular shape [33]. The energy is induced by the gradual heating at the beginning of the pulse shape. For similar reasons, the ramp-up shape has a bigger RD due to the early melt pool generation. Another parameter to explain the difference in RD is the pulse width. With a higher t_{on} and a bigger pulse overlap, a higher RD and a higher dimensional error were measured [19]. The ramp-up has a longer pulse duration than the ramp-down because it takes time for the pulsed laser to create an initial spike [33]. Hence, the ramp-up shape has a bigger RD than ramp down shape.

(2) Overlap

The overlap is one of the main differences between PWM and CW in terms of the scanning mechanism. As mentioned in the following section, the overlap can be classified into pulse overlap and line overlap.

Each overlap mechanism is related with the hatch spacing and the scanning speed, as presented in Fig. 3(b). Therefore, the overlap percentage is one of the crucial factors to determine the build speed. If the scan speed is faster or the hatch spacing is larger, the overlap percentages decrease so that the build speed becomes faster. However, it causes smaller RD with the higher porosity as the interlayer bonding is weaker in small overlap percentages [21].

Compared to the line overlap that can be adapted in both CW and PWM lasers, the pulse overlap is a parameter that is only used for PWM lasers. The line overlap is simply determined by the hatch spacing while calculating the pulse overlap is relatively complicated. The pulse overlap is determined by the distance between the central point d_p related with the pulse frequency and the scanning speed. High pulse frequency and slow scanning speed cause short d_p , thus causing high pulse overlap percentages [19].

Although the factors determining the overlap percentages of the pulse overlap and line overlap are different, the overlap mechanisms are similar [21,34]. Li et al. investigated the effect of the overlap ratio on microstructures [34]. According to their investigation, the micro-crack is reduced as the overlap percentages increases. As the result is similar to that of the pulse overlap, It is assumed that the pulse overlap and line overlap are similar mechanism in terms of energy density.

The surface roughness (R_a) is a suitable parameter to detect a premature crack in accordance with overlap percentages. Mumtaz and Hopkinson used the repetition rate and scanning speed variations to investigate the correlations between the overlap and R_a [33]. R_a of the top surface is determined by the temperature gradients of the laser beam, and the solidified zone while R_a of the side is

affected by partially melted powder particles at the end of the melt pool.

Several studies have investigated that high laser spot overlap, low scan speed, and high repetition rates enabling to reduce top R_a [35,36]. However, a low scan speed and high repetition rate may cause balling, which is detrimental for the density and the surface roughness [33]. By adapting this statement to CW lasers, CW can create a denser result but with the possibility of dimensional errors by an excess of the accumulative energy. For this reason, PWM is more suitable for finer geometries than CW due to its controllability in pulse overlap percentages [19].

III. Melt pool dimension

As each laser type presents different advantages, the laser should be chosen depending on its purpose. The melt pool dimension is a significant factor that influences the line and profile accuracy of a laser-printed part. As CW and PWM present different process parameters, such as pulse shaping and overlap, the melt pool dimension for each case requires separate discussions. In this section, the researches on the correlation between the melt pool dimension and the processing parameters according to each laser type are reviewed.

1. CW melt pool dimension

CW lasers commonly use four parameters: laser power, scanning speed, hatch spacing, and layer thickness. As Eq. (1), the formula of VED, is exactly defined by these four laser processing parameters, it is useful to express the total input energy transferred into the metal powder via a CW laser. Although the VED is useful to explain the rough trend in the experiment, there are limitations to understand the melt pool formation. From Eq. (1), the energy density is proportional to the laser power and inversely proportional to the scan speed. The melt pool geometry can be expected to be proportional to the energy input.

Yadroitsev et al. designed an experiment to examine the availability of VED to analyze the correlation between the melt pool formation and processing parameters [28]. When the power was reduced, the energy was compensated by decreasing the scanning speed to fix the VED [28]. The width and depth of the melt pool increased as the energy input increased, as expected by Eq. (1). However, despite the same energy density, the melt pool formation was different depending on the examined laser process parameters. The higher laser power produced a stable melt pool for a wider range of scan speeds. As previously stated, this indicates that the VED cannot be an absolute factor to determine the melt pool dimensions.

For instance, in single line printing experiments, the melt pool is converted from a hemisphere- to a funnel-like shape as the power density increases, as presented in Fig. 5 [23,37]. The funnel-like shape of the melt pool, called

Figure 5. Cross-sectional melt pool profile of the single-track deposits produced on a 316 L stainless steel (a) conduction mode (lower energy inputs), (b) Keyhole mode (higher energy inputs) (Reprinted with permission from ref. 23, copyright © 2016 Elsevier Ltd.).

keyhole, is engendered by deep penetration of the heat transferred by conduction and convection inside the melt pool. The keyhole mode conduction results in vaporization of the metal and, in many cases, trapped pores in the melt pool [37]. Therefore, in order to reduce the porosity and improve the mechanical strength of the printed part, it is commonly preferable to avoid the keyhole mode conduction.

In addition to the process parameters mentioned above, another parameter affecting the melt pool dimension can be considered. M. Cloots et al. demonstrated that the profile of the laser beam also has an influence on the shape of the melt pool [38]. A vortex-lens was placed between the scanning head and the beam collimator to create a doughnut-like beam profile at the focal plane. Compared to the Gaussian beam profile generated by the conventional laser set-up, the doughnut-like beam profile suppressed the keyhole mode melt pool even at a low scan speed.

2. PWM melt pool dimension

Although PWM lasers present more process parameters than CW, the basic melt pool mechanisms can also be adapted to PWM. For example, in the PWM laser process, if the power is large or the scan speed is slow, a large melt pool is formed.

It is necessary to analyze studies of laser welding process as its dynamics of melt pool is similar to the SLM process and there are several researches conducted with PWM lasers. Akman et al. examined the effects of the peak pulse power and pulse duration on the weld pool formation during the laser welding process of TiAl_6V_4 [39]. They defined the weld pool dimension using four factors: the width of the heat affected zone (h_1), penetration depth of the weld pool (h_2), underfill defects (h_3), and width of the weld pool (h_4), as presented in Fig. 6(a).

The result demonstrated that the penetration depth and the width can be controlled by the pulse energy and pulse duration. The peak power, rather than the pulse duration,

Figure 6. Laser welding experiment for TiAl₆V₄ (a) definition of a weld pool dimension (b) peak power effect on the penetration depth (c) peak power effect on the heat affected zone and the weld pool width (Reproduced with permission from ref. 39, copyright © 2008 Elsevier B.V.).

Figure 7. Dimension error corresponding to various exposure time (Reproduced with permission from ref. 19, copyright © Springer-Verlag London 2017).

has a significant influence on the weld pool dimensions, as depicted in Fig. 7. When the peak power is lower than 2 kW, the weld pool dimensions expand linearly to the peak power. In particular, as illustrated in Fig. 7(c), the heat affected zone enlarges faster than the width of the weld pool. This is due to the heat transfer to the keyhole wall being larger than the laser beam direction. For a peak power higher than 2.5 kW, the penetration depth increases abruptly due to the enhancement in laser plasma absorption of the keyhole, as presented in Fig. 7(b). Because the long pulse duration increases interaction time between the laser and the material, it can expand the heat affected zone and the weld pool width, whereas it has a negligible effect on

the penetration depth. An insufficiently large peak power may cause vaporization and crater in the weld pool. In this case, increasing the pulse duration is an alternative way to increase the penetration depth with as few defects as possible.

While Akman et al. focused their research on peak power and melt pool dimensions, Akbari et al. focused on the PWM laser parameter relationship between the welding speed and the melt pool dimension [40]. According to the result, the width and the penetration depth increased as the laser welding speed decreased. Nevertheless, the authors mentioned that keyhole can be caused at lower welding speed due to a long interaction time.

Pulse overlapping is also an important factor that contributes to the melt pool dimensions of the parts printed via PWM laser. The factors that decide the overlapping area are pulse frequency, laser beam spot size, and scanning rates [41]. The overlapping area is proportional to the pulse frequency, and inversely proportional to the scan rate. Tzeng considered an overlap theory of the pulse energy to explain the correlations between the melt pool dimensions and the processing parameters, such as the scan speed, pulse duration, and average peak power density (APPD) [42]. The author observed that the increase in scanning speed associated with a decrease in the overlap caused a reduction in the melt pool depth and hemispherical shaping owing to the specific low energy. This hemispherical shaping can lead to improper welding. However, increasing the pulse duration results in a high specific energy, tends to maintain the keyhole mode formation of the melt pool with a deep depth, despite of the high scan speed, and increases the volume of melt pool. This trend is increased by the increase in APPD while the average power and scan rate are fixed.

Width modulated laser pulse generates different size and dynamics of melt pool and microstructures compared to CW lasers owing to the pulsed energy injection. There is a comparative study between PWM and CW lasers for direct laser metal deposition processes (DLMD) [43]. According to the study, PWM creates a beat-like motion of the melt pool according to the pulse duration and presents a rapid cooling rate. The melt pool of PWM presents a higher curvature than that of CW. As a result, the finer columnar dendrite structures with relatively high tilting angle were developed by PWM lasers owing to the curved solidification front and the rapid cooling rate. This study was conducted for DLMD; however, the results on melt pool dynamics and microstructure formations are expected to be applicable for SLM process owing to the similar mechanisms of PWM.

Although the pulse duration may be considered as a less defect-causing factor, it engenders dimensional errors. In Demir et al.'s study, the geometrical error has been increased when the exposure time increased [19]. The results are presented in Fig. 7, where e_{avg} , t_{on} , and O_p are the

average dimensional error, pulse duration, and pulse overlap, respectively. It can also be concluded that moving towards CW from PWM causes more dimensional errors.

IV. Conclusion

The SLM process parameters for both CW and PWM have been identified. The basic melt pool mechanism is similar in both laser types: the high energy input causes large melt pool dimensions. The concept of VED can approximately predict the melt pool dimensions; however, it cannot be an accurate criterion for melt pool dimensions. In particular, the heat conduction mechanism must be carefully considered to achieve the correct characterization of the melt pool dimensions. The review considered the main process parameters for CW and PWM lasers. As PWM presents different laser mechanisms compared to CW in terms of pulse shaping and overlapping, it presents more process parameters, such as pulse duration, repetition frequency, and peak power density. Moreover, the melt pool dimensions have to be considered with the respective process parameters. PWM is advantageous for fine structure printing due to its pulse control capability, whereas CW can provide lower porosity. It is important to determine the difference in process parameters and characteristics of the two laser types and choose the favorable laser type accordingly.

Acknowledgements

This research was financially supported by the Ministry of Trade, Industry and Energy (MOTIE), and Korea Institute for Advancement of Technology (KIAT) through the International Cooperative R & D program (N0002624 Development of metal additive manufacturing system with in-situ monitoring and powder recycling devices for biomedical applications), and was also supported by the MIST (Ministry of Science and ICT), Korea, under the "ICT Consilience Creative Program" (IITP-2018-2017-0-01015) supervised by the IITP (Institute for Information & Communications Technology Promotion).

References

- [1] M. Brandt, *Laser Additive Manufacturing: Materials, Design, Technologies, and Applications* (Woodhead Publishing, Swaston, Cambridge, UK, 2017), pp. 1-18.
- [2] B. Vandenbroucke and J. P. Kruth, *Rapid Prototyp. J.* 13, 196 (2007).
- [3] L. Thijs, K. Kempen, J. P. Kruth, and J. Van Humbeeck, *Acta Mater.* 61, 1809 (2013).
- [4] J. P. Kruth, M. C. Leu, and T. Nakagawa, *CIRP Annals* 47, 525 (1998).
- [5] D. Ding, Z. Pan, D. Cuiuri, and H. Li, *Int. J. Adv. Manuf. Tech.* 81, 465 (2015).
- [6] B. Dutta and F.H.S. Froes, *Titanium powder metallurgy Science, Technology and Applications* (Elsevier, 2015), pp. 447-468.
- [7] C. Song, A. Wang, Z. Wu, Z. Chen, Y. Yang, and D. Wang, *Mater. Des.* 117, 410 (2017).
- [8] D. Gu, W. Meiners, K. Wissenbach, and R. Poprawe, *Int. Mater. Rev.* 57, 133 (2012).
- [9] J. P. Kruth, L. Froyen, J. Van Vaerenbergh, P. Mercelis, M. Rombouts, and B. Lauwers, *J. Mater. Process. Technol.* 149, 616 (2004).
- [10] E. Gordon, *UKEssays.com*, 2013. Available from: <https://www.ukessays.com/essays/engineering/additive-manufacturing-medical-implants-1014.php?vref=1>
- [11] E. Farré-Guasch, J. Wolff, M. N. Helder, E. A. Schulten, T. Forouzanfar, and J. Klein-Nulend, *J. Oral Maxillofac. Surg.* 73, 2408 (2015).
- [12] J. M. Pinto, C. Arrieta, M. E. Andia, S. Uribe, J. Ramos-Grez, A. Vargas, P. Irarrazaval, and C. Tejos, *Med. Eng. Phys.* 37, 328 (2015).
- [13] M. Saffarzadeh, G. J. Gillispie, and P. Brown, *Rocky Mountain Bioengineering Symposium* (Denver, CO, USA, April 8-10, 2016), Vol. 1, 142.
- [14] P. K. Gokuldoss, S. Kolla, and J. Eckert, *Materials* 10, 672 (2017).
- [15] S. Sun, M. Brandt, and M. Easton, *Laser Additive Manufacturing: Materials, Design, Technologies, and Applications* (Woodhead Publishing, Swaston, Cambridge, UK, 2017), pp. 55-77.
- [16] B. Ferrar, L. Mullen, E. Jones, R. Stamp, and C. Sutcliffe, *J. Mater. Process. Technol.* 212, 355 (2012).
- [17] H. Shipley, D. McDonnell, M. Culleton, R. Lupoi, G. O'Donnell, and D. Trimble, *Int. J. Mach. Tool. Manu.* 128, 1 (2018).
- [18] L. Thijs, F. Verhaeghe, T. Craeghs, J. Van Humbeeck, and J. P. Kruth, *Acta Mater.* 58, 3303 (2010).
- [19] A. G. Demir, P. Colombo, and B. Previtali, *Int. J. Adv. Manuf. Tech.* 91, 2701 (2017).
- [20] L. Caprio, A.G. Demir, and B. Previtali, *J. Laser Appl.* 30, 032305 (2018).
- [21] N. T. Aboulkhair, N. M. Everitt, I. Ashcroft, and C. Tuck, *Addit. Manuf.* 1, 77 (2014).
- [22] E. Sallica-Leva, A. Jardini, and J. Fogagnolo, *J. Mech. Behav. Biomed. Mater.* 26, 98 (2013).
- [23] U. S. Bertoli, A. J. Wolfer, M. J. Matthews, J.-P. R. Delplanque, and J. M. Schoenung, *Mater. Des.* 113, 331 (2017).
- [24] L. Eidam, O. Boine-Frankenheim, and D. Winters, *Nucl. Instrum. Methods Phys. Res. A* 887, 102 (2018).
- [25] I. Yadroitsev, P. Krakhmalev, and I. Yadroitsava, *J. Alloys Compd.* 583, 404 (2014).
- [26] J. Han, J. Yang, H. Yu, J. Yin, M. Gao, Z. Wang, and X. Zeng, *Rapid Prototyp. J.* 23, 217 (2017).
- [27] W. Xu, M. Brandt, S. Sun, J. Elambasseril, Q. Liu, K. Latham, K. Xia, and M. Qian, *Acta Mater.* 85, 74 (2015).
- [28] I. Yadroitsev, P. Bertrand, and I. Smurov, *Appl. Surf. Sci.* 253, 8064 (2007).
- [29] K. Wei, M. Gao, Z. Wang, and X. Zeng, *Mater. Sci. Eng. A* 611, 212 (2014).
- [30] C. Qiu, C. Panwisawas, M. Ward, H. C. Basoalto, J. W. Brooks, and M.M. Attallah, *Acta Mater.* 96, 72 (2015).
- [31] T. Eagar and N. Tsai, *Weld. J.* 62, 346 (1983).
- [32] H. Bransch, D. Weckman, and H. Kerr, *Weld. J.* 73, 141.s (1994).
- [33] K. Mumtaz and N. Hopkinson, *Rapid Prototyp. J.* 16, 248 (2010).
- [34] R. Li, Y. Shi, Z. Wang, L. Wang, J. Liu, and W. Jiang, *Appl. Surf. Sci.* 256, 4350 (2010).
- [35] H. Niu and I. Chang, *Scr. Mater.* 1, 67 (1998).
- [36] P. Fischer, V. Romano, H.-P. Weber, N. Karapatis, E. Boillat, and R. Glardon, *Acta Mater.* 51, 1651 (2003).
- [37] H. Gong, H. Gu, K. Zeng, J. Dilip, D. Pal, B. Stucker, D. Christiansen, J. Beuth, and J.J. Lewandowski, *Solid freeform fabrication symposium*, (Austin, TX, USA, August 4-6, 2014), 1, 256-267.
- [38] M. Cloots, P.J. Uggowitzer, and K. Wegener, *Mater. Des.* 89, 770 (2016).
- [39] E. Akman, A. Demir, T. Canel, and T. Sinmazçelik, *J. Mater. Process. Technol.* 209, 3705 (2009).
- [40] M. Akbari, S. Saedodin, D. Toghrarie, R. Shoja-Razavi, and F. Kowsari, *Opt. Laser Technol.* 59, 52 (2014).
- [41] V. Kumar, *Surf. Coat. Tech.* 201, 3174 (2006).
- [42] Y. f. Tzeng, *J. Mater. Process. Technol.* 102, 40 (2000).
- [43] S. Li, H. Xiao, K. Liu, W. Xiao, Y. Li, X. Han, J. Mazumder, and L. Song, *Mater. Des.* 119, 351 (2017).