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Using a dual-laser system to create periodic coalescence in laser powder bed fusion

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Conventional laser-based powder bed fusion of metals (PBF-LB/M) currently faces technological challenges in scalability due to its low building rate and manufacturing throughput. One approach to address this issue is to parallelize multiple laser beams to increase processing flexibility. Recent research has studied, for instance, the improvements to mechanical properties of final products when using two or more laser beams in PBF-LB/M. However, some obstacles still need to be addressed involving the proximity of molten pools and their interaction mechanism. In particular, interactions between two close, parallel molten pools have not been fully understood yet. In this study, two lasers create two parallel-running molten pools with a small spatial offset in between. With different spatial offsets, experimental results reveal that besides the completely merged and completely separated regimes, there exists a new regime which yields periodic coalescence between the two molten pools. High-speed imaging shows two different mechanisms for the formation of such coalescence, what we denote as head-to-head and head-to-tail coalescence. By changing processing parameters including laser power and spatial offset, periodic structures with various wavelengths can be engineered using this dual-laser approach.

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1. Introduction

Additive manufacturing (AM), also referred to as 3D printing and rapid prototyping, is a process for producing 3D objects in a layer-by-layer fashion. Currently, metal AM is widely used in aerospace, automotive and many other industries due to its ability to manufacture products easily and economically [1]. Laser-based powder bed fusion of metals (PBF-LB/M) is one of the most popular methods for metal AM. In conventional PBF-LB/M, a Gaussian laser beam is used as the energy source to fuse regions of a powder bed to create the final product [2,3]. However, slow building rate and other technological challenges prevent PBF-LB/M from gaining greater market share [1].

There have been studies on how to address the current challenges in PBF-LB/M. For example, extensive research has been done to explore the potential benefits using multiple beams or a tailored laser beam [4,5]. Numerical simulations have also been developed to explain how novel energy distribution geometries, like an elliptical Gaussian beam, affect the resulting structures and mechanical properties [5,6]. In the field of laser welding, novel beam profiles generated through a diffractive optical element (DOE) have offered greater control of weld pool dimensions and improved surface roughness [7,8]. Also, to specifically address the slow building rate, recent research has focused on using multiple beams to improve the processing efficiency. Renishaw has introduced an AM machine with four independently controlled laser sources [9]. Hong et al. utilized this particular Renishaw machine to compare the product properties constructed from multiple-laser PBF-LB/M with those from single-laser PBF-LB/M [10]. Zhang et al. conducted similar experiments with a multiple-laser machine developed in-house [11]. Slodczyk et al. showed that square arrays of beams created using a DOE can increase melt rates while maintaining melt pool stability [12]. Sundqvist et al. also solved the analytical solution for the temperature field for a spatially and temporally modified beam, which can help to quickly predict the temperature profiles for multi-spot welding [13]. Furthermore, Tsai et al. built a three-spot PBF-LB/M system by integrating a DOE into the set-up. Shorter processing time as well as lower surface roughness of the final product were achieved [14].

It is clear that the key to facilitating wider adoption of PBF-LB/M is increasing manufacturing flexibility, and parallelizing mul-
tiple laser beam is one approach. In previous research on utilizing two laser beams, the molten pools created by the two beams are either completely separate [10,11] for higher building rate or completely merged together [12,15]. In the latter case, one beam serves as a preheating or reheating source to reduce temperature gradient and improve mechanical properties [16]. We believe there is a gap between the two cases, namely the little-understood transition between the fully-merged and fully-separated regimes. For example, there was no clear establishment of the resolution limit in the parallel beams. Also, although research has been conducted on the macrostructure and morphology produced by a single molten track [17,18], critical questions regarding the macrostructure resulting from parallel-running beams remain unsolved.

To understand the questions raised above, we use two identi-
cal, parallel-running laser beams as energy sources for PBF-LB/M. By placing two molten tracks close to each other, we investigate the molten pools’ interactions on the cusp of merging. By doing so, the resolution between the two molten tracks is established. At the same time, we come to understand how the molten tracks transition from being fully merged to fully separated as the distance between the two tracks increases.

In addition to the lateral spatial offset between the two molten pools, we include a temporal offset between the two lasers, which effectively produces an in-line spatial offset. The introduction of the temporal offset allows us to further investigate how two close pools interact with each other within this broader parameter space. We find a new regime where periodic structures are produced at certain spatial offsets at each of the different laser powers tested. Additionally, adjusting spatial offsets within this regime changes the wavelengths of the periodic structures.

2. Experimental system

Fig. 1 shows the set-up for the dual-laser experiments. In this set-up, two 1070 nm wavelength lasers with Gaussian-shaped beams operating in continuous-wave (CW) mode are used as the laser sources. The laser beams, after being narrowed by focusing telescopes, pass through 3D scanning systems consisting of beam expanders, 2D scanners and F-θ lenses. Each of the scanning sys-
tems has a scan field of 178 × 178 mm². By putting two scanners side-by-side, an overlapping scan area of 20 × 178 mm² is created. Both lasers and scanners are controlled by control cards installed in a PC. A pulse generator is used to control the firing time delay between the two lasers and thus creates a small spatial offset between the two laser beams. However, this pulse generator only affects when the lasers are switch on. Once the lasers are on, they continuously emit beams in CW mode.

To understand the molten pool dynamics, a high-speed camera is used to capture images at a frame rate of 50,000 FPS and an exposure time of 1.5 μs. The imaged area is illuminated with a high-speed light cannon synchronized with the camera. The camera has a 2 μm/pixel resolution thanks to a 10X microscope objective.

In the experiment, individual laser powers (P) of 60, 80 and 100 W are used. Scan speed (v) is held constant throughout the experiment at 150 mm/s. The nominal 1/e² diameter of the circular beam (w₀) is 100 μm. 325 mesh sized (D < 44 μm) 316 L stainless steel powder is manually deposited with a doctor blade on a 316 L stainless steel plate. The stainless steel plate has a thickness of 0.15 mm and a mirror-like surface. Layer thickness (h) of the powder bed is 100 μm for all experiments.

To better define the relative position between the two laser beams in this set-up, we introduce two parameters as shown in Fig. 2 (a). The two red circles represent the laser spots, which run parallel to each other along the arrow direction. The component of spot separation distance perpendicular to the laser scanning direction (i.e., the distance between the two melt tracks) is defined as the hatch spacing (dₘ). Hatch spacing is controlled by the initial position of the two laser beams. In our experiment, hatch spacings between 90 and 320 μm are tested. On the other hand, the component of spot separation distance parallel to the laser scanning direction is defined as the perpendicular offset (dₚ), which is controlled by the scan speed and the temporal offset between the firings of the two lasers. dₚ is calculated as

\[ d_p = \Delta t \times v, \]

where Δt is the temporal offset introduced by the pulse generator. For example, a 0 μm perpendicular offset indicates that the two lasers begin firing at the same time (Δt = 0). The specific parameters at each laser power are listed in Table 1.

The two red lines in Fig. 2 (b) represent the laser spot paths in the experiment. Each individual track consists of a main line
4.5 mm long and two ramps about 1.27 mm long and angled 11° from the main line. In the experiment, the two lasers first move closer until they reach the desired hatch spacing. Then these two lasers move parallel to one another for 4.5 mm before they move further apart. We include the two ramps in the laser track design to better examine the merge and separation threshold of the two molten pools.

Before the PBF-LB/M experiments, calibration of laser marking on the substrate is performed. Similar processing parameters and the same scanning patterns as those in the experiment are used to make sure the laser scan paths are straight, parallel to each other and with desired hatch spacing, as shown in Supplementary material (Figure A11). This calibration validates that the scan field is not distorted.

3. Results

3.1. Effects of hatch spacing

Fig. 3 is a confocal image showing how different hatch spacings affect the resulting molten tracks when the perpendicular offset is kept constant. The image is captured by an Olympus confocal microscope. Different colors represent various heights for the sample, ranging from purple at the height of the undisturbed substrate surface to yellow at a height of around 100 μm above the substrate surface. In this case, both lasers operate with a power of 80 W and move at a scan speed of 150 mm/s. The perpendicular offset is held at 120 μm while three different hatch spacings are used: 140, 180 and 270 μm. For all three experiments, the top line leads the bottom line by the perpendicular offset. Both lasers move from left to right in the images.

Generally, as hatch spacing increases, the two molten tracks transition from being fully merged to being fully separated with an intermediate stage in which periodic coalescence is observed. At \(d_h = 140\) μm, these two molten pools merge together and a single molten track is created. With \(d_h = 180\) μm, we observe periodic merging and separation between the two molten tracks with a wavelength \(\lambda \approx 550\) μm. Each coalesced section is angled from the top left to the bottom right, which will be explained in Section 4.1. With an even larger hatch spacing of \(d_h = 270\) μm, the two tracks become completely separated. We also noticed that the leading track (top) has a much higher profile compared to the lagging one (bottom) at a large hatch spacing, which is due to the denudation effects in the PBF-LB/M [19,20]. Denudation zones up to 400 μm in width was observed in literature [21], and our hatch spacings fall into that range. Therefore, less powder is left for the lagging track (bottom) and a lower-profile molten track is formed.

3.2. Effects of perpendicular offset

Fig. 4 shows the effect of various perpendicular offsets in the experiments. Both lasers operate with a power of 80 W and move at a scan speed of 150 mm/s. Hatch spacing is fixed at 160 μm while the perpendicular offsets are 15, 135 and 285 μm. Again, the top track runs first and both lasers move from left to right in the images.

Generally, with the hatch spacing kept constant, we observe three outcomes from the two molten tracks: merging, periodic coalescence and separation. When the perpendicular offset is small \((d_p = 15\) μm), the two molten tracks completely merge, and only a single track is produced. With a larger perpendicular offset \((d_p = 135\) μm), periodic coalescence with a wavelength of \(\lambda \approx 580\) μm is created. Further increasing the perpendicular offset
to \( d_p = 285 \) \( \mu \text{m} \) causes the two molten tracks to become completed separated. The lagging (bottom) molten track has a lower height compared to the leading (top) track, again due to the denudation effects.

3.3. Processing maps at various laser powers

To better understand how the two parameters, hatch spacing \( d_h \) and perpendicular offset \( d_p \), affect the outcomes at different laser powers \( P \), experiments with various \( d_p \) and \( d_h \) are performed at 60, 80, and 100 W laser powers. Fig. 5 shows three processing maps at the different power settings. To enhance the visual illustration, the phase diagrams are shaded in red, gray and blue to represent the merging, periodic coalescence and separation scenarios, respectively.

At 60 W laser power, we observe three phases: separation shaded in blue, merged shaded in red and periodic structures shaded in gray. Periodic coalescence only occurs when 120 \( \mu \text{m} \leq d_h \leq 140 \) \( \mu \text{m} \). Intuitively, separation happens at a larger \( d_h \), and merging occurs at a smaller \( d_h \). At \( d_h = 140 \) \( \mu \text{m} \), periodic coalescence can be observed when \( d_p \leq 330 \) \( \mu \text{m} \). Any larger perpendicular offset than this makes it more difficult for the two separated molten pools to coalesce. Therefore, two separated molten tracks are formed once \( d_p \) reaches a certain threshold, in this case at 330 \( \mu \text{m} \).

By contrast, at \( d_h = 120 \) \( \mu \text{m} \), periodic coalescence exists when 120 \( \mu \text{m} \leq d_p \leq 420 \) \( \mu \text{m} \) and only a single merged molten track is formed at all other \( d_p \). In other words, no separation scenario occurs at \( d_h = 120 \) \( \mu \text{m} \). At a small \( d_p \), two molten pools merge together and thus create a single molten track. More interestingly, at large \( d_p \), the first track is completely solidified before the second molten pool is created, and the small \( d_h \) forces the second molten pool to partially remelt and fuse with the first track. Such process of creating a single track at small \( d_h \) and large \( d_p \) is similar to the conventional single-beam PBF-LB/M process where a small hatch spacing ensures that the laser beam remelts the previous molten track in each iteration to construct a relatively uniform 2D surface [17]. Furthermore, even though both small and large hatch spacings produce a single molten track at \( d_h = 120 \) \( \mu \text{m} \), the specific morphologies of the resulting tracks are not identical. The single, merged molten pool at small \( d_p \) creates a molten track symmetrical with respect to the central line (see Supplementary material, \( d_p = 195 \) \( \mu \text{m} \)), while the two separated molten pools at large \( d_p \) result in a lower shoulder over the scan path of the second laser (see Supplementary material, \( d_p = 585 \) \( \mu \text{m} \)).

At 80 W laser power, similar observations are made. Periodic coalescence can be found when 120 \( \mu \text{m} \leq d_h \leq 190 \) \( \mu \text{m} \). Within this \( d_h \) range, periodic coalescence occurs at a larger \( d_p \) for smaller \( d_h \): 225 \( \mu \text{m} \leq d_p \leq 375 \) \( \mu \text{m} \) for \( d_h = 120 \) \( \mu \text{m} \) and 30 \( \mu \text{m} \leq d_p \leq 270 \) \( \mu \text{m} \) for \( d_h = 180 \) \( \mu \text{m} \). At the same time, similar to the 60 W case, only a single molten track can be produced at \( d_h = 120 \) \( \mu \text{m} \) outside of the periodic coalescence processing window, and the single track at a small \( d_p \) is different from the track at a large \( d_p \).

At 100 W laser power, periodic coalescence is found at 140 \( \mu \text{m} \leq d_h \leq 200 \) \( \mu \text{m} \). Complete merging happens with a
smaller $d_h$ and separation at a larger $d_h$. The range of perpendicular offsets that yield periodic structures still depends on the hatch spacing: 210 $\mu$m $\leq d_p \leq 420$ $\mu$m for $d_h = 140$ $\mu$m and 60 $\mu$m $\leq d_p \leq 90$ $\mu$m for $d_h = 200$ $\mu$m. As before, only a single track is produced outside of the periodic structure processing window at small hatch spacings, $d_h = 140$ $\mu$m in this case.

Looking through these three processing maps at different laser powers, we find that in general, both the perpendicular offset and hatch spacing have to increase with higher laser power in order to produce the periodic structures. This is because the size of the molten pool generally increases with a higher laser power if the scan speed is constant. Therefore, a longer hatch spacing and a larger perpendicular offset is required to avoid complete merging and to create periodic coalescence. We shall discuss the detailed mechanism for periodic coalescence later in Section 4.1.

3.4. Wavelength dependence on hatch spacing and perpendicular offset

We also look into the wavelength of the periodic structures for each individual laser power as shown in Fig. 6. The center-to-center distance between adjacent coalesced sections is measured and averaged, then plotted against the perpendicular offset in groups of different hatch spacing. The same color is used for the same hatch spacing across all powers. For example, blue represents a 140 $\mu$m hatch spacing in all 60, 80 and 100 W laser powers. The error bars show the standard deviations of the measured distances, and the light gray lines in each plot have a slope of unity to enhance the visualization.

Generally speaking, change in the hatch spacing does not affect the wavelength significantly across all three laser powers. For examples, with a 60 W laser power as shown in Fig. 6 (a), the averaged wavelengths of $d_p = 120$ $\mu$m and $d_p = 270$ $\mu$m are very close between 120 and 140 $\mu$m hatch spacings. Similar cases can be established at both 80 and 100 W laser powers. For example, at 80 W laser power and 180 $\mu$m $\leq d_p \leq 330$ $\mu$m in Fig. 6 (b), no significant discrepancies in wavelengths can be observed across hatch spacings of 120, 140, 160 and 180 $\mu$m.

Furthermore, we notice that the shapes of the wavelength versus perpendicular offset plots are similar across differing laser powers with a minimum wavelength around 400 $\mu$m. In particular, this minimum value does not change significantly at different laser powers or hatch spacings in the experiments. For example, at 60 W in Fig. 6 (a), the wavelength first drops from 586 $\mu$m to 344 $\mu$m over the interval 30 $\mu$m $\leq d_p \leq 180$ $\mu$m and then increases to 667 $\mu$m when $d_p$ reaches 420 $\mu$m. Similarly, at 80 W in Fig. 6 (b), the wavelength drops from 880 $\mu$m to 375 $\mu$m when $d_p$ reaches 195 $\mu$m. Then it increases linearly with respect to $d_p$, reaching 652 $\mu$m at $d_p = 360$ $\mu$m. This general trend also applies to the 100 W laser power case in Fig. 6 (c), but the trend is not as clear as that for the 60 and 80 W cases. This is because at higher laser powers, molten pools become strongly turbulent, making it difficult for tracks to coalesce with uniform periodicity. Nevertheless, one can still discern that the wavelength first drops before $d_p$ reaches 270 $\mu$m and then increase along with $d_p$.

We also observe that the variance in wavelengths is greater when the wavelength decreases with increasing $d_p$ than when they increase in tandem. This is particularly pronounced in the 80 and 100 W power cases, in which the standard deviation of wavelengths become significantly smaller once the wavelength start to increase with $d_p$. We believe this is because different mechanisms are behind the formation of these periodic structures, which we discuss next.

4. Discussion

4.1. Two coalescence scenarios

High-speed imaging reveals the detailed mechanism behind the periodic coalescence observed in the previous sections. Schematic diagrams to elucidate selected high-speed images are shown in Figs. 7 and 8, and the corresponding high-speed images are in Figs. (C.13) and (C.14). Video clips corresponding to Figs. 7 and 8 are included in the Supplementary materials. In each figure, images (a)–(c) show a sequence of schematic diagrams for molten pool dynamics at 0, 80 and 160 $\mu$s, respectively, where $t$ is set arbitrarily to 0 $\mu$s at the first image shown. The red dots represent the laser spots and the dark orange areas are the molten pools. Black arrows in the molten pools indicate the direction of fluid motion within. The light orange areas represent the solidified molten tracks. Subfigure (d) in each figure is a confocal image that shows the periodic structure resulting from the process depicted in (a)–(c).

In Fig. 7, we present a case that we refer as head-to-head (HtH) coalescence. Such coalescence occurs at a large hatch spacing and a small perpendicular offset, which means two laser beams are switched on with small temporal offset (refer to Eq. (1)). HtH scenario can be observed in Fig. 6 where wavelengths decrease with increasing perpendicular offset. As shown in (a), the two laser spots are at similar positions on the $y$ axis. Starting from an unmerged state, the two molten pools experience perturbations that
cause them to swell and merge together. However, since the two laser spots (and consequently the areas of heat addition) remain separated by the pre-defined hatch spacing as they travel along parallel paths, the merged molten pool cannot be sustained continuously over the full track. The laser spots will draw the liquid away from the center of the merged molten pool and eventually divide it again into individual molten pools, as shown in (b). The two separated molten pools then proceed along their original parallel paths until the cycle repeats, and the next coalescence happens. The previous coalescence solidifies to form one of the periodic merged sections in this HtH case, as shown in (c). A section of the resulting structure is shown in (d). Since the coalescence into a merged molten pool occurs at the same time for both molten tracks and in a symmetrical fashion, the tracks generally have the same profile right before the merged section, as indicated by the two red arrows in plot (d).

Next, we identify a different coalescence scenario as shown in Fig. 8, which we refer to as head-to-tail (HtH) coalescence. This case generally happens at a small hatch spacing and a large perpendicular offset, which corresponds to a rather large temporal offset introduced by the pulse generator. HtH coalescence as seen in Fig. 8 is representative of periodic coalescence that occurs at perpendicular offsets to the right of the minimum wavelength in Fig. 6, where wavelengths increase along with perpendicular offset. The original positions of the molten pools are shown in plot (a). Prior to coalescence, the leading beam is the “dominant” beam (i.e. the beam whose molten pool is larger) due to the denudation phenomenon described earlier. Then, similarly to the HtH scenario, the perturbations within the molten pools cause the pools to coalesce. However, unlike in the HTh scenario, merging occurs at different positions with respect to each of the molten pools: the tail region of the leading molten pool and the head region of the lagging one. After merging, part of the molten pool is drawn towards the leading laser spot while the majority of the liquid is retained near the center of the merged pool, as shown in plot (b). Ultimately the molten pool splits as a fraction is pinched off into a smaller, separated molten pool centered around the leading laser spot. Afterwards, the lagging laser beam draws one edge of the previously merged pool forward, shearing it into one of the rhomboid-shaped periodic structures seen in plot (d). As a result, the height of the individual tracks immediately after the coalesced section is different: the lagging laser leaves the merged pool surrounded by a greater share of the liquid than the leading laser, causing the track created by the lagging laser (arrow 1) to have a higher profile emerging from the coalesced section than that of the leading one (arrow 2).

Generally speaking, HtH coalescence is easier to predict and to control, as the status of being the dominant beam is repeatedly passed back and forth between the two lasers. Thus, HtH creates periodic structures that are more uniform, as evidenced by a smaller standard deviation of wavelength. By contrast, in HTh coalescence, the wavelength of the periodic structure depends on when the perturbations in the two pools become large enough to result in merging. Therefore, the standard deviation of the wavelength in the HTh scenario is significantly larger.

4.2. Scaling of molten pool sizes

To further analyze the periodicity among various parameters, we look closely at the size of the molten pools. As it is difficult to accurately reproduce and measure the molten pool sizes during the molten pool interactions in the experiments, we record a solitary, traveling molten pool at 60, 80 and 100 W laser powers with the high-speed camera. We then measure, frame-by-frame, the width of slices of the molten pool as it moves through the focal plane of the camera. This allows us to reconstruct the 2D molten pool geometries, as shown in Fig. 9. In summary, the 60 W laser power creates a molten pool about 200 μm long and 110 μm wide. 80 and 100 W laser powers create molten pools only slightly wider but significantly longer: about 260 μm long for 80 W and 300 μm long for 100 W.
It is noteworthy that the molten pool length increases linearly with the laser power, a finding that is consistent with previous literature [22,23]. For this particular setting, we have a nondimensional number for the ratio of the laser dwell time to the thermal diffusion time:

$$\tau = \frac{D}{ua},$$

(2)

where $D$ is the thermal diffusivity of stainless steel, $u$ the laser scan speed and $a$ the beam size. In our experimental set-up, $\tau = 0.2 < 1$, suggesting a shallow and elongated molten pool, which is typical for materials with low thermal conductivity like stainless steel.

At the same time, we have another non-dimensional number for the ratio of the laser deposited energy density to the melt enthalpy:

$$B = \frac{\Delta H}{23/4 \pi h_s},$$

(3)

where $h_s = \rho C T_m$ is the enthalpy of melting, in which $\rho$ is the density, $C$ the specific heat capacity and $T_m$ the melting temperature. Also, $\Delta H = AP^{3/4}/\sqrt{\pi D_u a^2}$ describes the absorbed energy density, where $A$ is the absorptivity and $P$ the laser power [24].

In our experiment, we have $\tau = 0.2$ for all parameter selections. $B$ is proportional to laser power $P$ and takes on a value of ~1.8 at 60 W, assuming $A = 0.6$ [25]. Over the range of parameters tested, the molten pool length changes nearly linearly with the parameter $B$ as identified in the paper by Rubenchik et al. [22]. For example, through Rubenchik’s proposed scaling law, the molten pool created at 120 W laser power should be 98% longer than the one created at 60 W laser power. Therefore, considering the difficulties of measuring the exact molten pool shape and size during coalescence, we can assume the same scaling law stands and that the length of the molten pool created is proportional to the laser beam energy.

4.3. Scaling of wavelength of periodic structures

Molten pool sizes, as measured by length and width, appear to be important parameters for periodic coalescence, as they are the natural choices of length scale for perpendicular offset and hatch spacing, respectively, between the two molten pools. Together, these four parameters determine whether periodic coalescence could happen. Once the periodic coalescence exists, however, the hatch spacing seems to no longer impact the wavelength: wavelengths at different hatch spacings fall into the same pattern when plotted against perpendicular offset as shown in Fig. 6. This is especially true in the HTT case, where wavelength and perpendicular offset correlate linearly with each other and are both measured along the same direction as molten pool length. Therefore, molten pool length is the natural choice as the length scale for normalizing wavelength and perpendicular offset:

$$\lambda(P) = \frac{\lambda(P)}{l(P)}$$

(4)

and

$$d_p(P) = \frac{d_p(P)}{l(P)},$$

(5)

where $\lambda(P)$ is the normalized wavelength of the periodic structures and $\lambda(p)$ is the original wavelength presented in Fig. 6. Similarly, $d_p(P)$ is the normalized perpendicular offset and $d_p(P)$ is the original perpendicular offset presented in Fig. 6. Additionally, $l(P)$ is the molten pool length collected from the single laser experiment as a function of laser power, as shown in Fig. 9.

One could first notice that for all three different power settings, the smallest $\lambda^*$ is found around $d_p^* = 0.9$. Here, it is important to recall that both wavelength and perpendicular offset in Fig. 10 are scaled with the molten pool length generated by a single laser. The total power input in our dual-beam experiment is twice that of a single laser, so, following from our discussion in Section 4.2, the combined pool could be twice as long as that from a single laser. Therefore, the actual transition point from $HHH$ to $HTT$ likely occurs when $d_p^* = 0.45 \times l(Dual Beam)$. In other words, if the perpendicular offset is less than about half as long as the molten pool created by the two lasers, a $HHH$ case occurs and the wavelength decreases when perpendicular offset increases; otherwise, $HTT$ occurs and the wavelength grows with longer perpendicular offset.

We also observe that $\lambda^*$ at all three laser powers follow roughly the same pattern when plotted against $d_p^*$. This is particularly clear when the $\lambda^*$ starts to rise with increasing $d_p^*$, as most of the $\lambda^*$ values are confined into

$$\lambda^* = 1 + 1 \times d_p^* \pm 0.5,$$

(6)

which can be explained by the HTT mechanism. In the HTT scenario, the wavelength consists of two parts: the length of the merged section and that of the separated section. For each individual laser power, the length of the merge section does not change significantly across varying perpendicular offsets. This length is consistently about the same as a single laser’s molten pool length. Consequently, the smallest $\lambda^*$ created from this method increases linearly with laser power. The smallest wavelength is the sum of the length of the merged section and the smallest perpendicular offset
needed to achieve the HTT scenario. Once in the HTT domain, the length of a separated section grows linearly with the perpendicular offset. For example, at 60 W when the single laser’s molten pool length is around 200 μm, the lengths of the merged sections is between 200 and 300 μm at various perpendicular offset as shown in Fig. D.15 (a). On the other hand, the lengths of the separated sections increases from below 150 μm to close to 400 μm in the HTT regime with perpendicular offset increasing from 180 to 420 μm. Therefore, the normalized wavelengths grow linearly with the normalized perpendicular offsets and is bounded by Eq. (6).

We recognize that this scaling method does not fully capture the dynamics of the HTH scenario. As discussed before, HTH creates coalescence with larger uncertainty due to the unpredictable nature of its merging mechanism. Although we can observe qualitatively that λ* decreases with increasing dₚ until dₚ ∼ 0.9 as shown in Fig. 10, it is challenging to devise a scaling method to describe wavelengths in the HTH regime as accurately as in the HTT regime.

It is noticed that this scaling relationship is not restricted to 150 mm/s scan speed only. We further conduct experiments using 80 W laser power and 300 mm/s scan speed, which is 100% higher than the scan speed in the aforementioned results (in Supplementary material). A similar relationship between the wavelength and perpendicular offset along various hatch spacings is observed, and the normalized wavelength at 300 mm/s presents the same pattern as the results at 150 mm/s when plotted against normalized perpendicular offset, as shown in Supplementary material.

4.4. Driving forces for periodic coalescence and separation

For both HTH and HTT scenarios, we believe the coalescence is driven by the inherent instabilities of the molten pools during the PBF-LB/M process. Large temperature gradients together with strong recoil pressure disturb the molten pool and introduce perturbations. While surface tension drives some periodic deformations in welding, including the humping phenomenon [26] and molten track breakups [27]—both due to Rayleigh instability—we believe this is not the main contributor to our observed periodic coalescence. Normally the Rayleigh instability requires the molten pool to have a large aspect ratio, thus creating a fully-developed liquid jet [26,28]. In our experiments, however, the molten pool is not long enough to be significantly impacted by the Rayleigh instability. Therefore, the recoil pressure together with the strong flow in the molten pool caused by a temperature-driven surface tension gradient initiate the coalescence.

At the same time, the periodic separation is believed to be the results of an insufficient amount of powder in front of each merged section. The coalesced molten pool absorbs a large amount of the powder in front of it, forcing the large molten pool to split into two tracks in the HTH case and creating a smaller, separated molten pool in the HTT case. However, more studies, both in the form of experiments and simulations, are necessary to fully understand this phenomenon.

5. Conclusion

In conclusion, we introduce two parameters, hatch spacing and perpendicular offset, to arrange two identical laser beams in PBF-LB/M experiments. We find that a distinct phase exists between the completely merged and completely separated phases. This transition phase yields periodic structures that would otherwise be difficult to manufacture with conventional PBF-LB/M using only a single laser beam. For a given laser power, periodic structure arises only within a specific envelope defined by hatch spacing and perpendicular offset. Generally, to obtain periodic structures, both the required hatch spacing and perpendicular offset increase with higher laser power. Looking further into wavelengths and formation mechanisms of periodic structures reveals that there are two scenarios: head-to-head coalescence and head-to-tail coalescence. The head-to-head case happens when the perpendicular offset is smaller than half the length of the molten pool generated by the two lasers; head-to-tail occurs when the perpendicular offset is greater. Generally, the wavelengths from the head-to-head scenario decrease with increasing perpendicular offset while the wavelengths increase linearly with increasing perpendicular offset in the head-to-tail case. Also, by using the molten pool lengths to normalize both perpendicular offset and wavelengths, we find that the wavelengths generated from different laser powers collapses into a single pattern when plotted against perpendicular offset.

In the future, we would like to further explore this processing method of manufacturing periodic structures using two laser beams. For example, longer molten pools generated from a higher scan speed and a higher laser power may be used to revalidate this conclusion. This dual-beam set-up could benefit general additive manufacturing in terms of a higher building rate and possible surface patterning when multiple lasers are used. Also, we would like to analyze how the microstructure might change within this new processing window. We believe, as this method creates different energy distributions and subsequent molten pools from those in the conventional methods, the resulting microstructure, including grain sizes and orientations and possible porosity distributions, will be different as well. In that case, this method may present a different approach to engineer specific microstructure and affect localized material properties.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Supplementary material

Supplementary material associated with this article can be found, in the online version, at 10.1016/j.actamat.2020.09.071.

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