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Investigating the Melt-Pool Temperature Evolution in Laser-Powder Bed Fusion by Means of Infra-Red Light: A Review

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Abstract. Recent decades seen the success of Additive Manufacturing (AM) in many industrial applications including aerospace, biomedical, automotive, and tooling. In the manufacturing of metallic parts, AM technology has the ability to produce parts with complex geometries which are difficult or impossible to produce using the conventional fabrication methods, such as machining and casting. Another benefit of AM is the employment of metal and metal alloys which are difficult to machine. Alloys such as titanium, nickel-titanium, and stainless steel have a wide range of applications particularly in the aerospace and biomedical industry. Selective Laser Melting (SLM), also known as Laser Powder Bed Fusion (L-PBF) is a type of AM technology used for the 3D printing of metal and alloy parts. The major drawback in L-PBF technology is the anisotropic properties of the produced parts. From L-PBF, these anisotropies exist due to instant melting and re-solidification of the metal powder, the ultra-high cooling rates and the variant temperature levels across the build layers and within the single layer itself. This article explores the essential role of the melt-pool temperature and temperature gradients that occur during the L-PBF process and their effects on the additively manufactured part's properties.

Introduction

Additive Manufacturing (AM) can be defined according to the American Society for Testing and Materials (ASTM) as: "The process of joining materials to make parts or objects from 3D model data, usually layer upon layer, as opposed to subtractive manufacturing methodologies" [1]. The process can be classified into seven technologies: powder bed fusion (the focus of this article), direct energy deposition, extrusion, sheet lamination material jetting, binder jetting and Vat polymerization. AM technology is significantly growing in the last years and decades and showing an efficient competition with other traditional manufacturing methods [2-7]. Parts with complex geometry can be produced by using this technique. Moreover, AM parts can be made of metals like titanium, cobalt, inconel and other alloys which are difficult to machine by lathe and milling machines. Additive manufacturing is essential and reliable for the manufacturing of obsolete spare parts as it works on a (Create-Make) principle in which the part is designed by using a CAD software and loaded on the 3D printer without the need for moulding or machining. In addition, the technique saves the design and modification time and cost. Nevertheless, AM parts exhibit relatively low density compared to cast parts in addition to the high surface roughness which can reach up to 40 microns compared to 1 to 5 microns produced by machining (lathe and milling). The variation in the mechanical, chemical, and physical properties of AM parts are not shortened only in parts produced on different machines but also can be obtained across parts produced by using the same 3D printer and maybe in the same singular part itself when comparing these properties along the build direction. These properties include hardness, elastic modulus, wear resistance, chemical phase composition, grain size, colouration, and surface roughness. The most significant reasons behind this problem are the initial metal powder specifications, the build chamber size, inert gas type and circulation and the heat build-up during the build process. The latter reason is mainly caused by the thermal energy being added to the AM part during the powder fusion in each layer by the laser beam which results in the latter (top) layers achieving higher temperatures than the earlier (bottom) layers.

Some applications may include aerospace industry require consistent mechanical and physical properties, i.e., the surface profile is important for aerodynamic and drag forces performance. In biomedical applications, a bioimplant surface can be designed to promote bone growth or in some cases bacterial growth which can cause tissue damage and limits the employment of AM technology [8]. For these reasons, it is necessary to carry out a subsequent mechanical or laser polishing processes in order to enhance the surface conditions as a requirement for some applications [2, 9, 10].

As a thermal process, L-PBF uses laser beam to melt the metal powder in selective position in each consecutive layer. The molten material reaches very high elevated temperature levels and can be much higher than the required melting temperature. The high temperature levels can represent serious problems during the melting of specific metal and alloys. Nitinol (NiTi) for example is used in a very wide range of applications due to its unique properties which depend on its chemical composition. Nitinol parts can exhibit shape memory or super-elastic behaviour based on the nickel content. Small change in the balance of the two elements of the alloy, can alter the phase composition and its behaviour under working conditions like temperature and/or mechanical loading. This change in the chemical composition between the un-fused metal powder and the AM part is very likely to happen as some metals are easy to vaporise compared to others. In this case the nickel vaporises faster than titanium.

In laser processing in general, the input thermal energy and process control are carried out by setting the laser beam power and the residence time which is a factor of the scanning speed, the beam spot size, and the scanning off set (hatch spacing). There is often no direct measure or control on the processing temperature. The achieved melt-pool temperature is based on these factors and many other parameters like the metal type, absorption of the laser irradiation, the laser type and wavelength. In L-PBF, accurate, real time measurement of the melt-pool temperature is difficult due to the extremely high laser scanning speed in addition to the plasma, spatter or fume clouds which can obscure the zone of interest. Several researchers have investigated the melt-pool temperature by setting thermal cameras [11] or infra-red (IR) pyrometers [5, 7, 12] which record the reflected light from the melt-pool and result in massive amounts of data being recorded. This is often as millivolts (mV) which is directly proportional to the melt-pool temperature. The pyrometer option is most commonly used on 3D metal printers due to the relatively easy access to the melt-pool area compared to thermal cameras. The latter require more space and specific angles of access which is not always achievable.

The Effect of the Input Parameters on the Melt-Pool Temperature

This scenario was investigated by Obeidi et al. [7] during the melting of 3×3×4 mm nitinol (NiTi) testing cubes. The researcher reported that the melt-pool temperature showed clear direct correlation with the input processing parameters and the resulting input volumetric energy density (VED), see Figure 1 (a)(left). In (L-PBF), (VED) can be calculated by using the following equation:

$$\text{VED} = \frac{\text{Laser Power (W)}}{\text{Laser Scanning Speed}\left(\frac{\text{mm}}{\text{sec}}\right)\times\text{Hatch Spacing (mm)}\times\text{Buil Layer Thickness (mm)}}$$

As can be seen, the scale used in this figure was normalised with reference to the maximum value in (mV). Heigel et al. [12] reported that the excessive high (VED) values, i.e. high laser power and/or low scanning speed level can reach high elevated melt-pool temperature leading to over-melting, vaporisation of material, gas pockets trapping and an increase in AM part porosity can be resulted. In contrast, reduced (VED) values and the resulting low melt-pool temperatures can lead to lack of melting and trapped, un-melted powder particles which is also the reason for the reduced density and mechanical properties.

(a)

(b)

(c)

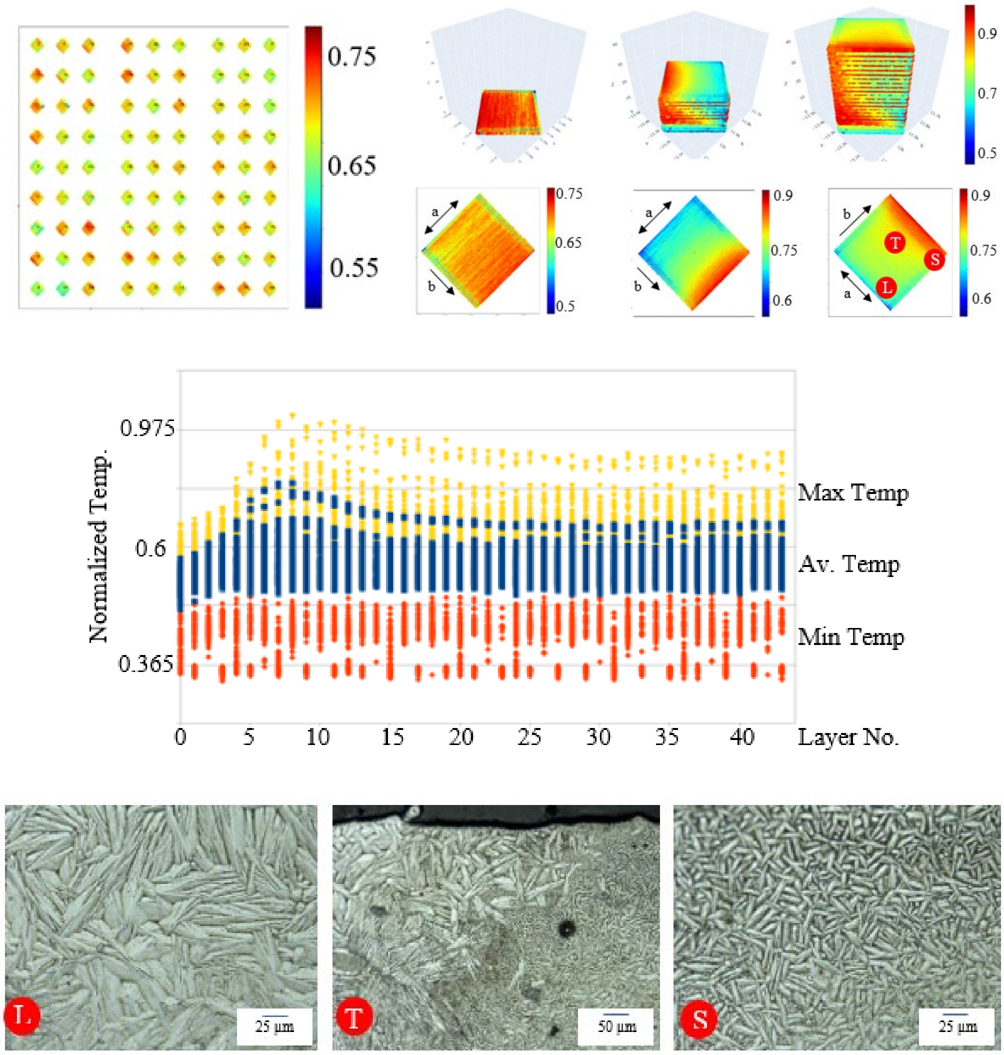


Figure 1 (a) The normalised temperature history in: a random build layer (left) and bottom, middle, and top layers (right), (b) temperature values during the entire build layers, and (c) the resulting granular microstructure [7].

The Effect of the Layer Number on the Melt-Pool Temperature

Figure 1 (a) shows the normalised temperature within the build layers. The normalised temperature scale in which the first layer (left) reached 75% while the upper layers (right) reached more than 90% of the maximum recorded temperature value. The reason behind the lower temperature levels occurring at the lowest layer is that the build plate was at room temperature and that heat can be dissipated to the cold surrounding. As the build process progresses, more thermal energy is added to the build part hence the layer temperature also increases for higher layers relative to the lowest layers, see Figure 1 (b).

The Effect on the Grain Size

It was noted that a consistent temperature level was obtained in the lower layers over the entire AM part as an indication of the high cooling rate which is caused by the temperature difference and the cold build plate. In contrast, the upper layers and because of the lower cooling rate, low temperature levels were recorded at the laser scan starting side (pointer a) and increasing in the beam scanning propagation direction (pointer b). This temperature variation and the different cooling rates resulted in three clear zones of grain sizes, large (L), transition (T), and small (S) related to the low, mid, and high cooling rates respectively.

The Effect of the Powder Layer Thickness on the Melt-Pool Temperature

The applied layer thickness of the metal powder has a significant effect on the achieved melt-pool temperature. The following Figure 2 shows that the increase in the layer thickness increases the melt-pool temperature when the same processing parameters were applied. The three parts in this figure were built in one process and in three different layer thickness of 30, 60, and 90 microns from left to right respectively. The part with the 90 microns layer thickness showed the highest temperature achieved during the entire build process. This can be explained by the increase in the amount of the gaps between the powder particles with the increase in the layer thickness. These gaps represent inert gas pockets and act as heat insulators and impede the thermal conductivity with the previous layers hence the increase in the melt-pool temperature.

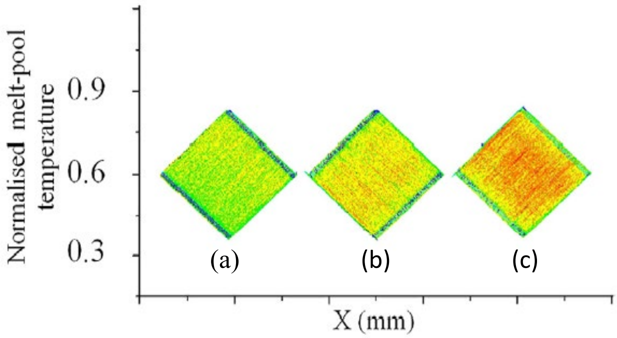


Figure 2 Graph of the increase in the melt-pool temperature with the increase in the build layer thickness from (a) 30 to (b) 60 to (c) 90 microns [5].

The Effect of the Laser Scanning Strategy

The laser scanning strategy is represented by several terms and can be designed in many ways. The following Figure 3 is an example for the effect of the hatch scanning direction. In this figure, the scanning direction was oriented in an angle with reference to the AM part sides. The short alteration of the laser tracks at the corners generates over-heated zones and result in a clear increase in the melt-pool temperature. This phenomenon can be a major problem creating thermal residual stresses and a variation in the granular microstructure and other mechanical properties between the bulk material and any thin sections in the produced part.

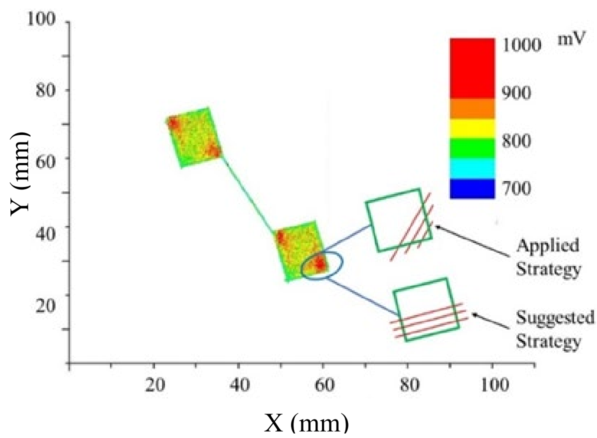
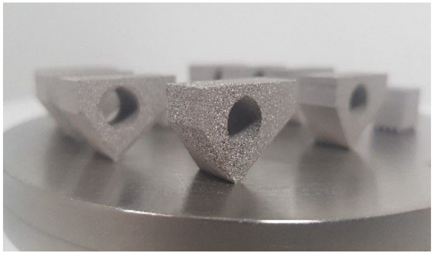


Figure 3 Graph of the applied and suggested scanning strategies to reach consistent temperature levels in L-PBF process.

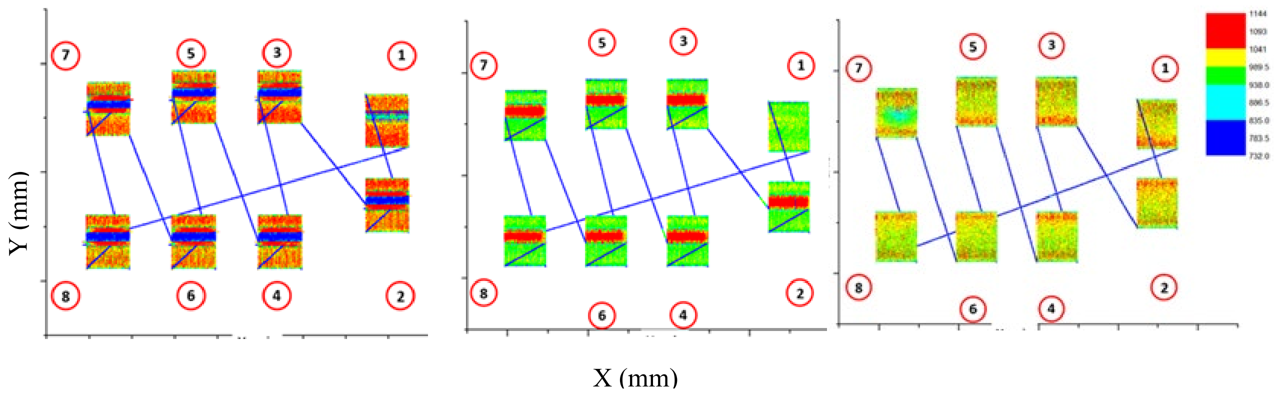
In order to avoid or eliminate this effect, it is recommended to (a) re-design the scanning strategy and hatching orientation in the proper direction alongside the part's body in order to give the time for the resolidified material to cool down, (b) in the case of the complex geometry where it is impossible to apply one singular scanning direction, it is suggested to re-design the main body into several sub-parts and carry out the scanning orientation accordingly, and (c) post processing by heat treatment and annealing is the optimum solution for the thermal stresses release and microstructure enhancement.

The Effect of the Parts Geometry

The internal features and part's design also have a significant effect on the melt-pool temperature levels during the build process. For example, building a part with internal cavity, horizontal channel or hole means the un-fuse of metal powder particles (at low temperatures) inside fully fused and solidified build layer (at high temperature) which will result in an ultra-high cooling rates in specific regions, thermal stresses anisotropic mechanical properties and microstructure. Moreover, during the closing of these features, i.e. the melting of the first build layer over the channel-top, extremely high temperatures can be reached at these regions caused by the reduced heat conductivity of the un-melted powder particles and the gas pockets underneath, see Figure 4. The latter result agrees well with that reported by Obeidi et al. [5].



(a)



(b) (c) (d)

Figure 4 (a) Picture of stainless steel part printed through hole and of thermal layer profiles build layer (b) through the hole, (c) in the first layer above the hole after channel closure, and (d) several layers after the closure.

The main body showed noticeable elevated temperatures as the build process progresses and because the built mass of the body is still small to absorb the applied thermal energy. This also agrees well with the (temperature-layer) plot in Figure 1 (b). In Figure 4 (c), the maximum temperature level was reached at the channel region when the first layer after the channel closure was reached. The main body exhibited a decreased temperature since there is sufficient amount of solid material to absorb the thermal energy and dissipate it which also agrees well with the discussion of plot (b) in Figure 1.

Conclusion and Outlook

From the above discussion and results, it is clear that the melt-pool temperature can be widely varied within the AM produced part and also across each build layer. This temperature variation can negatively affect the produced part properties and imposes the need for post processing. Such processes include heat treatment for the thermal residual stresses release and achieving a homogenous microstructure. The most effective technique used to eliminate this problem is preheating the powder and the build plate. This procedure produces a better control over the global temperature in addition to the significant control on the cooling rate and then the residual stresses, the grain size and phase formation. A real time measurement of the temperature with a closed loop control system could provide an optimised solution in this regard. This requires the development of an ultra-fast data analysis model capable of processing the IR data and generates correction feedback in a time shorter than laser beam transition between two consecutive points in order to re-adjust the laser beam power and avoid the temperature raise. This is feasible but difficult to be achieved at the current time. Another drawback in using the pyrometers is represented by the requirement for the correct translation of the measured data from mV to temperature measured in degree Celsius. Usually, AM printers' manufacturers do not offer this kind of conversions because it depends on the processing conditions as well as the alloy and powder morphology properties that is being used. In this regard, a calibration process is necessary to be performed on the different types of metal powders. The exact temperature values, rather than the (mV) values, however give a better process understanding of how the temperature field relates to the resulting microstructure and ultimate the AM part properties.

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