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**Abstract**

Powder reuse is an integral part of laser powder bed fusion (LPBF) additive manufacturing (AM). A mathematical series expression is proposed to quantify powder damage in powder reuse in LPBF AM considering various mixing ratios. A term called damage factor has been introduced and an example of an application of the series is demonstrated. Finally, a short experimental design has been suggested to verify the model.

**Keywords**

Laser powder bed fusion (LPBF); additive manufacturing; metal powder; powder reuse; powder recycling.

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## 1. Introduction

One objective of modeling powder reuse is to quantify powder usage to identify when the powder becomes unusable. In this concern, two facts are important. First, powder use in LPBF AM may cause a gradual decline in powder properties [1]. Second, virgin powder is often mixed with reused powders as a practical matter when replenishing machines or to improve powder properties [2]. Thus, conceptually, 'powder damage' is the desired measurand.

The complete connection between powder properties and part properties has not been fully understood as of now [1]. However, some understanding and standards are available and many are currently being developed [3]. This proposal suggests monitoring powder damage expressed as a series with a damage factor as a function of the number of builds. The model can be improved as more information on powder reuse becomes available. In particular, it is anticipated that not every build creates the same amount of damage to the powder. An example use case of the model is provided based on data from the literature. Additionally, an experimental design is outlined to test the assumptions in the model and calibrate the damage factor.

## 2. Model

### 2.1. Lemma

Let, $d$, represent a powder property such as powder morphology or chemical composition that limits its reuse. The powder property should be defined such that its increase is considered as powder damage. Let the maximum permissible value of the property be $d_f$. The powder damage factor, $D$, is the ratio of the powder property to the maximum permissible value: $D = d/d_f$. When the powder damage factor reaches a value of 1, the powder can no longer be reused in its current state. It is reasonable to assume that the damage factor and powder properties are a function of the build or run number, $n$: $D(n) = d(n)/d_f$. Thus, the virgin powder is represented by $D(0)$, the first build or run by $D(1)$, and so forth.

### 2.2. Model description

Let there be an initial quantity virgin powder, $V$, in units of grams. Parts are built using this powder, which consumes some fraction of powder. This requires replenishing or "top-up" action before beginning the next build. The mixing ratio, $m$, is the ratio between the amount of top-up fraction and the total quantity of powder including the recovered powder (e.g., collector, build platform, and dispenser). For a set of multiple runs, it's assumed that the build is topped up after each run with virgin powder with the mixing ratio, $m_n$, where the subscript $n$ corresponds to the run number. The powder condition is a fabricated term that multiplies the quantity of total powder (from previous condition + virgin top up) with the damage factor for a build. $D_{total}^{in}$ represents the damage factor of the powder batch prior to a build and $D_{total}^{out}$ represents the damage factor after a build.

At the beginning, there is only virgin powder,

$$D_{total}^{in} = D(n = 0) \quad (1)$$

Using this powder for **the first build** creates powder with a damage factor of

$$D_{total}^{out} = D(n = 1) \quad (2)$$

The **first top-up** action creates powder with a combined damage factor of

$$D_{total}^{in} = (1 - m_1)D(1) + m_1 D(0); \;\; m_1 = \frac{V_{added}}{V_{added} + V_{recovered}} \quad (3)$$

where $V_{added}$ is the top-up volume of powder, which was added to the recovered volume of powder, $V_{recovered}$, from the previous build. This ratio is the mixing ratio, $m_1$, associated with the first build and top-up process.

The **second build** creates powder with a combined damage factor of

$$D_{total}^{out} = (1 - m_1)D(2) + m_1 D(1) \quad (4)$$

The **second top-up** action creates powder with,

$$D_{total}^{in} = (1 - m_2)D_{total}^{out} + m_2 D(0) \quad (5)$$

which expands to :

$$D_{total}^{in} = (1 - m_2)\big((1 - m_1)D(2) + m_1 D(1)\big) + m_2 D(0) \quad (6)$$

Or,

$$D_{total}^{in} = (1 - m_2)(1 - m_1)D(2) + m_1(1 - m_2)D(1) + m_2 D(0) \quad (7)$$

The **third build** produces a combined damage factor of

$$D_{total}^{out} = (1 - m_2)(1 - m_1)D(3) + m_1(1 - m_2)D(2) + m_2 D(1) \quad (8)$$

and the **third top-up** creates a powder with

$$D_{total}^{in} = (1 - m_3)D_{total}^{out} + m_3 D(0) \quad (9)$$

which expands to:

$$D_{total}^{in} = (1 - m_3)\big((1 - m_2)(1 - m_1)D(3) + m_1(1 - m_2)D(2) + m_2D(1)\big) + m_3D(0) \tag{10}$$

Or,

$$D_{total}^{in} = (1 - m_3)(1 - m_2)(1 - m_1)D(3) + m_1(1 - m_2)(1 - m_3)D(2) + m_2(1 - m_3)D(1) + m_3D(0) \tag{11}$$

Thus, **the n<sup>th</sup> top-up** will create the powder with

$$D_{total}^{in} = (1 - m_n)(1 - m_{n-1})(1 - m_{n-2}) \ldots D(n) + m_{n-2}(1 - m_{n-1})(1 - m_n)D(n - 1) + m_{n-1}(1 - m_n)D(n - 2) + \cdots + m_nD(0) \tag{12}$$

which simplifies to

$$D_{total}^{in} = D(n)\prod_{i=0}^{n-1}(1 - m_{n-i}) + \sum_{j=1}^{n-1}\left(D(j)m_{n-j}\prod_{k=1}^{j}(1 - m_{j+1})\right) + m_nD(0) \tag{13}$$

Equation (13) shows that a general series has formed. Again $D_{total}^{in}$ is the damage factor after a build and top-up action. This is the condition of powder before the next build.

There are two comments on Eq. (13). First, it can be used to track both the overall damage of the mixture as well as the damage of powders that make up the mixture. The damage factor coefficients in the series correspond to powder with different usage that make up the mixture. These damage factor coefficients in the mixture could be used to make decisions with regard to the quality of the powder. For example, a high damage factor of a small volume fraction of powder in the mixture might occur even while the overall damage factor for the mixture remains acceptable. This may be the reason to stop reusing the powder; however, detailing this approach further is outside the scope of this paper. Here the focus is on the damage factor of the mixture. Second, while Eq. (13) was derived assuming top-up with virgin powder, it can be applied to top-up with any powder. In such cases, the incoming damage factor (another series) would take the place of $D(0)$. Thus, Eq. (13) enables robust tracking of powders after reuse for top-up with virgin and used powders.

In a special case, let the mixing ratio, $m$, be fixed. This is applicable in a real-world scenario where LPBF machines would be operated repeatedly to print the same or similar build. For example, industrial printers printing one product (e.g., a hip or dental implant) would continue to be run at a particular mixing ratio. The recent ASTM working guide regarding powder reuse (Designated WK67583) describes such a scenario with a fixed mixing ratio

[4]. If the mixing ratio is constant (i.e., $m = m_1 = m_2 = \cdots = m_n$), Eq. (13) can be rewritten as

$$D_{total}^{in} = (1-m)^n D(n) + m(1-m)^{n-1} D(n-1) + m(1-m)^{n-2} D(n-2) + \cdots + mD(0) \quad (14)$$

, which simplifies to

$$D_{total}^{in} = D(n)(1-m)^n + m\sum_{i=0}^{n-1} D(i)(1-m)^i \quad (15)$$

## 3. Application of the model

The model can be used to express powder damage as a series. One example of the application of the series has been demonstrated in the case of LPBF AM of Ti6Al4V powders. Ti6Al4V powder is susceptible to oxidization in LPBF AM [5,6]. Figure 1 shows the oxygen uptake in Ti6Al4V powders for 38 continual reuse cycles (with no virgin powder top-up) in a Renishaw AM250 machine [5]. In this case, the oxygen content of the powder can be regarded as the damage factor. It can be visualized that after 38 reuse cycles the oxygen concentration is reaching the Grade 23 or extra-low interstitial (ELI) limit (1300 ppm or 0.13 wt. % Oxygen content). The defined series can be used to model this trend.

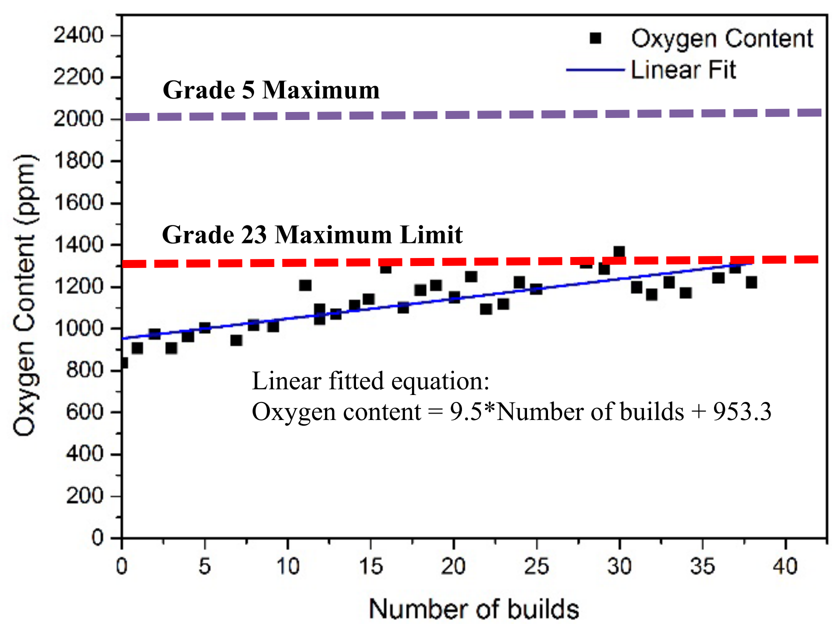


**Fig. 1.** Rise in oxygen content in LPBF additive manufacturing for Ti6Al4V powder up to thirty-eight reuse cycles (data plotted after extraction from the original source) [5]. Oxygen content is in parts per million (ppm).

The linear fit to oxygen gain versus the number of builds is

$$O(ppm) = 9.5 * (n) + 953.3 \tag{16}$$

This is the powder property relationship with the build number. Therefore the damage factor corresponding to the Grade 23 limit of 1300 ppm Oxygen, can be expressed as,

$$D(n) = (9.5 * (n) + 953.3)/1300 \tag{17}$$

Assuming a constant mixing ratio, Eq. (15) can be used to predict the damage factor when reused powder should be taken out of production based on oxygen content as shown in Eq. (18). Note, Eq. (13) could also be used in this manner.

$$\begin{aligned} D_{total}^{in}(n, m) = (0.007 * n + 0.733)(1 - m)^n \\ + m \sum_{i=0}^{n-1} (0.007 * i + 0.733)(1 - m)^i \end{aligned} \tag{18}$$

Equation (18) describes the powder condition as a series, which is a function of the number of builds. On the expansion of the series, the $i^{th}$ term refers to the fraction of powders at a specific damage level. Quite expectedly, in this case, the powder fraction dilutes with an increasing number of builds and top-ups. As it can be visualized from Eq. (18), there is a risk of having small powder fractions with high damage factors with a top-up type of reuse (i.e., continuous replenishment with virgin powder). Therefore, some strategies point towards mixing powders with similar usage history [2]. The current series approach can be applied to this situation as well by using the damage factor series for the top-up or any non-virgin powder instead of a $D(0)$ for virgin powder.

## 4. Proposed experimental design to test the model

A pre-requisite to testing the model would be to obtain the damage factor function for continual reuse. In the example from Section 3, oxygen content gain versus build number, the damage factor function was obtained from the literature. To illustrate the damage factor prediction using Eq. (18), Fig. 2 depicts the damage factors at constant mixing ratios of 0.05, 0.1, 0.3, and 0.5. The case of continual reuse without powder mixing, Eq. (17), has been denoted by the black line. It can be observed that higher mixing ratios or larger virgin powder top-up maintain a lower damage factor for more builds.

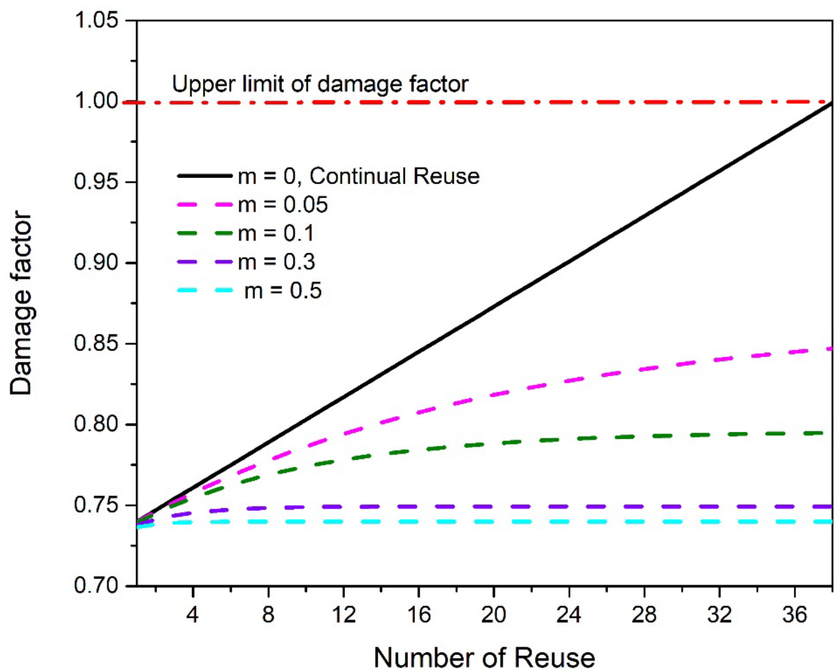


**Fig. 2.** Damage factor prediction for continual reuse ($m = 0$) and at constant mixing ratios illustrated using Eq. 18 for the example case in Section 3.

For testing the model an experimental design can be created based on the characteristics of the damage factor for different mixing ratios (i.e. Fig. 2). While the reuse strategies in the design of experiment are compliant with ASTM F3001-14 for ELI grade Ti6Al4V powder [7], they only serve to test the model. This work neither recommends nor endorses a reuse strategy. In this example, the maximum mixing ratio can be limited to 0.3 since higher mixing ratios predict little change in the damage factor. Table 1 shows an example of a proposed experimental design consisting of three mixing ratios (0.05, 0.10, and 0.30). The damage factor will be measured for each of these mixing ratios after 16 build and top-up cycles (number of reuse). Again, the data for continual reuse ($m = 0$) is already available. This experiment would test the main assumptions in the reuse model, which relies on calculating a combined damage factor using the mixing ratio and reuse cycle (build number) in a mathematical series. This strategy could be applied accordingly for testing other cases, which would vary according to the selected material and damage factor. For simplicity, the mixing ratios were chosen to be constant for every build. Practical experiments could also be designed to test the model at mixing ratios which vary with reuse.

**Table 1** Design of experiments

| Mixing ratio | Reuse cycles | Outcome |
|---|---|---|
| 0.05 | 16 | Measure the damage factor |
| 0.10 | 16 | Measure the damage factor |
| 0.30 | 16 | Measure the damage factor |

## 5. Future directions and other considerations

Many small-scale industries or research labs are not necessarily limited to similar builds. For example, a machine may build an experimental hip implant and then reuse the powder to build test cubes on the next build. In the proposed model, each build damages the powder by the same amount. Not all builds may degrade the powder by the same amount. How the damage factor might vary from one build to another according to part size/shape and changes in the printing parameters are not known. Future studies are needed to evaluate these relationships. The reuse model proposed in this work can then be extended to incorporate such dependencies. The goal is to predict the powder damage so that reuse decisions can be made without relying extensively on powder and part characterization.

## 6. Conclusion

A concept on how to predict and track powder conditions has been presented. At varying and constant mixing ratios, powder damage has been expressed as a series expression as shown in Eqs. (13) and (15). These equations can be modified to keep track of powder blends at multiple reuse cycles even accommodating top-ups of powder at different conditions. An example application has been demonstrated for the oxygen uptake in Ti6Al4V powders, Eq. (18). In this case, the oxygen uptake was considered as the damage factor. There may be more than one important damage factor (e.g., for a powder which has additional issues such as changes in flowability from reuse, moisture-induced reactions, etc.). In addition, a small design of experiments has been provided to test the model for one damage factor. The design of experiments aims solely to test the model. No particular reuse strategy has been recommended. The model intends users to improve reuse decisions and strategies.

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