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Effect of recycling powder on the fatigue properties of AM Ti6Al4V

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Abstract

Additive manufacturing (AM) techniques offer significant advantages with respect to conventional manufacturing (CM) ones such as the realization of highly customized components both dealing with their geometry and their mechanical properties. An important advantage of AM is the significant reduction of wasted material with respect to CM. However, AM techniques, such as the powder bed fusion, involve during the production an amount of powder higher than that needed to realize the final component even if the excess of powder in not interested by the melting process and can be recovered and used again. However, it is obvious to expect that the new powder feedstock that include this reused powder has different morphology characteristics since it has been subjected to a thermal history in the building chamber. These changes in the material feedstock can results in a different morphology of defects and consequently in different fatigue properties even for AM components realized with the same design geometry and same process parameters. In the present study, the effect of the use of recycled powders on the fatigue properties of AM Ti6Al4V has been investigated by considering specimens realized from virgin powder and recycled powder. The specimens fracture surfaces are investigated to correlate the effect of the powder on fatigue properties with the effect on the defects' morphology.

Keywords: Fatigue properties; Additive Manufacturing; Recycling powder

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1. Introduction

Several industrial sectors, such as automotive (Schimek, Springer, Kaierle, Kracht, & Wesling, 2012; Schmitt, Mehta, & Kim, 2020), aerospace (Bici et al., 2018; Dey, Liou, & Nedic, 2013; Gasser, Backes, Kelbassa, Weisheit, & Wissenbach, 2010; Kellner, 2014), biomedical (Chen et al., 2020; Wang, Arabnejad, Tanzer, & Pasini, 2018; Zadpoor, 2019; Zadpoor & Malda, 2017) and nuclear (Stucker, Obielodan, Ceylan, & Murr, 2010), have shown a growing interest in additive manufacturing (AM) techniques. This is mainly due to the significant advantages that AM offers with respect to conventional manufacturing (CM) techniques; it can create highly customized components in which the mechanical properties can be varied by manipulating the geometry, such as with architectural materials (Benedetti et al., 2021) or varying the material feedstock throughout the component (Bandyopadhyay, Zhang, & Bose, 2020; Rafiee, Farahani, & Therriault, 2020; Reichardt et al., 2021); it allows for the fabrication of replacement parts (Fatemi et al., 2019). Another important advantage of AM is the significant reduction of wasted material with respect to CM. However, some AM techniques, such as the powder bed fusion ones, involve during the process an amount of powder higher than the one needed to realize the final component; this exceeding powder, not melted during the component production, can be collected and used again. On the other hand, the powder feedstock obtained using this reused powder alone or mixed with other virgin powder is expected that to have different morphology characteristics due to the thermal history of the recycled powder in the building chamber during their previous use. Starting from powder presenting satellites, i.e., tiny particles attached to the surface of the powder particles, it can be seen that, with increasing the number of reuses, the satellites are melted (Popov, Katz-Demyanetz, Garkun, & Bamberger, 2018) and, as a consequence, decreased (Bellini et al., 2022; Carrion, Soltani-Tehrani, Phan, & Shamsaei, 2019) or completely removed (Emminghaus, Hoff, Hermsdorf, & Kaierle, 2021) while the particle size distributions narrow (Carrion et al., 2019; Emminghaus et al., 2021; Strondl, Lyckfeldt, Brodin, & Ackelid, 2015) probably due to the raising of the smaller particles in the building chamber or due to the adhesions of the smaller particles to larger ones (Sutton et al., 2020). The flowability of the powder have been also reported to be affected by the recycling number, showing different behaviors with changing the material (Emminghaus et al., 2021; Strondl et al., 2015; Sutton et al., 2020). Besides, the reused powders show an increment of defects due to the sieving procedures, responsible for deformation and broken particles, and due to the thermal history in the building chamber that causes bonded satellites metallization, elongated particles, etc (Ahmed et al., 2020; Popov et al., 2018). An increment in the oxygen content, even above the limit of 0.2% defined by ASTM, can be observed due to the exposure of the powder to the ambient atmosphere during the sieving or during the removal of the printed component from the building chamber (Bellini et al., 2022; Ghods et al., 2020; Petrovic & Niñerola, 2015; Yusuf, Choo, & Gao, 2020).

Even if the quality of the final component depends on various factor such as the process parameters (Gong, Rafi, Gu, Starr, & Stucker, 2014; Kasperovich, Haubrich, Gussone, & Requena, 2016) and post-processing heat treatments (Kimura, Ogawa, & Itoh, 2021; Shao, Mahtabi, Shamsaei, & Thompson, 2017; Zhang, Ham, Shao, Shamsaei, & Thompson, 2020) but also geometry, orientation and so on, the different morphologic characteristics of the material feedstock, that depends also on the atomization process used (Iebba et al., 2017; Ng, Jarfors, Bi, & Zheng, 2009), can results in a different morphology of defects and consequently in different fatigue properties even for AM components realized with the same design geometry and same process parameters.

The present study investigates the effect of the use of recycled powders on the fatigue properties of AM Ti6Al4V, realized through electron beam melting (EBM), by considering specimens realized from three different powder feedstocks: virgin powder; powder recycled up to five times; powder recycled more than a hundred times. The specimens fracture surfaces have been investigated to correlate the effect of the powder on fatigue properties with the effect on the defects' morphology.

Nomenclature

AM	additive manufacturing
CM	conventional manufacturing
EBM	election beam melting
f	frequency
Y	geometry factor
LOF	lack of fusion
R	nominal load ratio
SEM	scanning electron microscope
SIF	stress intensity factor
ΔK_I	mode I stress intensity factor range
$\Delta\sigma$	nominal stress range
$\sqrt{area}$	square root of the defect effective area

2. Materials and Methods

In the present study three different batches of Ti6Al4V (grade 5) powder feedstocks have been considered to investigate if recycled powders can affect the fatigue properties of AM components. Two different recycling strategies have been considered: the first recycling strategy, named strategy A, considers a powder feedstock obtained from powders recycled more than 100 times while the second recycling strategy, named strategy B, considers powders recycled up to 5 times. Finally, a virgin powder feedstock has been considered for comparison.

Fatigue tests have been carried out on specimens machined from bars built with the three different powder feedstocks through the EBM technique. The geometry of the tested specimens is reported in Figure 1.

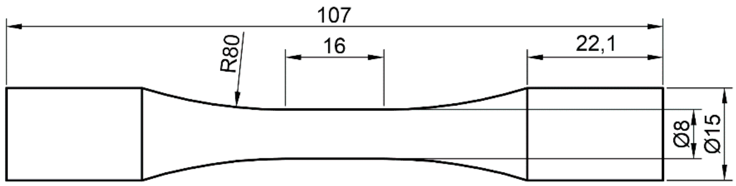

Figure 1: Tested specimen geometry (measures in mm)

All the tests were performed with a servo-hydraulic axial-torsional machine INSTRON with maximum load capacity of 250 kN. Ten fatigue tests have been performed for each different set under load control at a frequency $f = 10Hz$ and with a nominal load ratio $R = 0.01$.

The fracture surfaces of all the specimens have been analyzed through SEM investigation in order to identify the critical defect leading to the fatigue failure and apply a fracture mechanics method in order to explicitly consider the effect of the defect on the fatigue behavior.

Various defect morphologies can appear in AM components; Murakami (Murakami, 2019) proposed a method to account for the size of the initial defect considering the square root of the defect effective area ($\sqrt{area}$) defined as a smooth contour projected perpendicular to the loading direction that circumscribes the irregularly shaped defect, as shown in Figure 2. The main characteristics of a defect are its size, shape and position. In particular, the most detrimental defects in AM components are usually at or near the component surface, especially when the component is left in the as-built condition (Molaei et al., 2020). According to Murakami (Murakami, 2019) method, the SIF can be evaluated as:

$$\Delta K_I = Y \cdot \Delta\sigma\sqrt{\pi\left(\sqrt{area}\right)} \quad (1)$$

where the SIF geometry factor, Y, is 0.65 for surface defects and 0.5 for internal defects (Solberg et al., 2019).

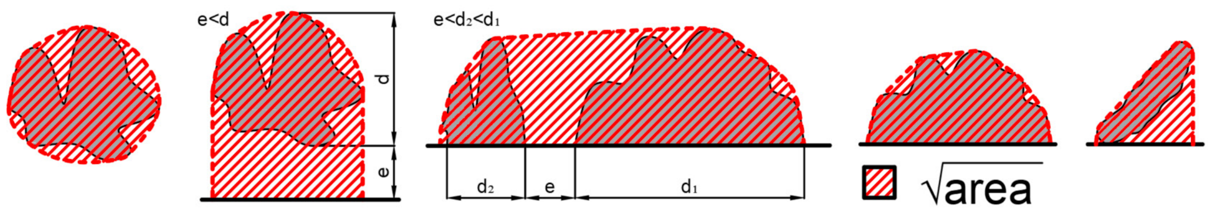

Figure 2: Effective area of irregularly shaped defects according to the Murakami $\sqrt{area}$ method

3. Results and Discussions

The fatigue tests results for all the three different sets of specimens are reported in Fig. 3a as nominal stress range on the net section, $\Delta\sigma$, vs the cycles to failure. As it is possible to observe the data seem to agree well between them if summarized in terms of nominal stress on the net section. However, the scatter between the data is quite high as it is possible to appreciate through the scatter index $T_{\Delta\sigma}$ reported in Fig. 3a. Such a scatter should be addressed to the significant amount of lack of fusion (LOF) defects found on the fracture surface of the tested specimens that lead to failure (see Fig. 4a). Figure 4b shows the mean value of $\sqrt{area}$ for the critical defects of each set together with their standard deviation as error bars in the diagram; the mean value of the defects $\sqrt{area}$ increases with the number of recycling while showing a lower degree of randomness by looking at the standard deviation of the defects size.

Finally for each specimen the critical defect $\sqrt{area}$ have been used to evaluate the ΔK_I and plot the fatigue results as ΔK_I vs cycles to failure. From Fig. 4b, it is possible to say that if the effect of the defects found inside the specimens is explicitly taken into account through, for example, Murakami's method, no substantial difference can be noticed between the different recycling strategies; besides, the data agree well also with the fatigue results of the specimens built from virgin powder suggesting a similar fatigue behavior for the specimens from recycled and virgin powder, even if it must pointed out that the last ones show a slightly lower fatigue strength in the LCF regime. The agreement between all the fatigue tests results from the three sets of specimens is also obvious by looking at the low scatter index that can be obtained considering all the data in the present study.

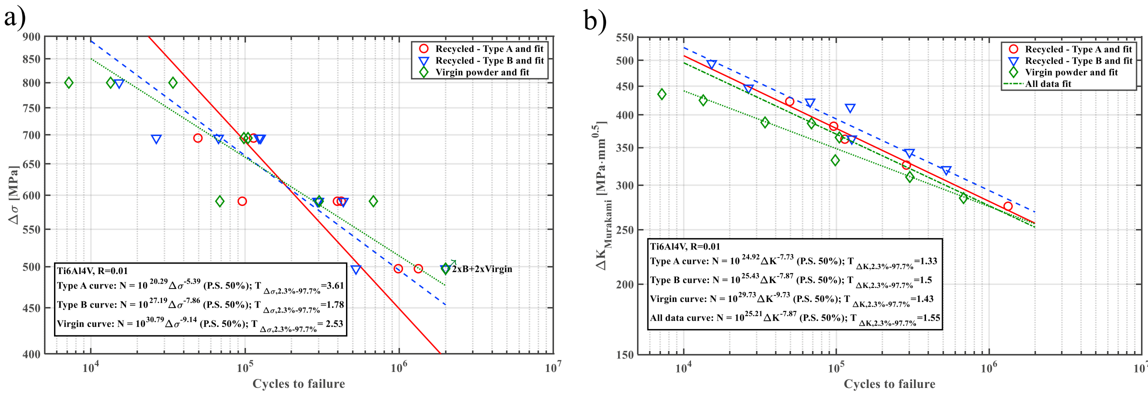

Figure 3: Summary of the fatigue tests results through: a) nominal stress range Δσ vs cycle to failure diagram; b) ΔK vs cycles to failure diagram.

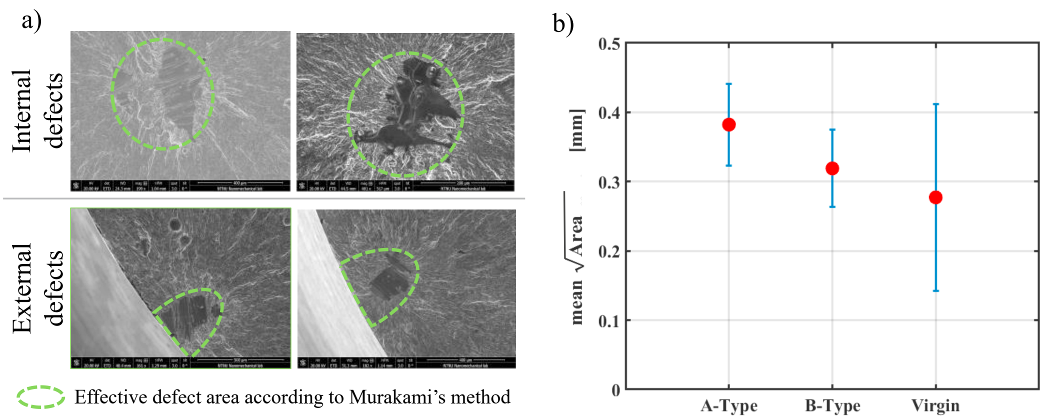

Figure 4: a) Examples of the effective area according to Murakami's method for both internal and external defects; b) mean value of the critical defects to failure √area for the three different sets of specimens considered with the error bars indicating the standard deviation.

4. Conclusions

In this work the use of recycling powder on the fatigue behavior of AM components have been investigated by considering specimens built with virgin powder and with powder recycled according to two different strategies. The specimens fracture surfaces have been analyzed through SEM investigation in order to identify the critical defect leading each specimen to failure. The effective critical defect $\sqrt{area}$ have been evaluated according to Murakami's method and the ΔK have been exploited to explicitly consider the effect of the LOF defects on the fatigue behavior of the specimens.

The results of the study show that:

- The average size of the critical defects inside the specimens considered increased with increasing the number of recycling for the powder feedstock while showing a lower degree of randomness by looking at the standard deviation of the defects size.
- If the effect of defects is properly accounted for, such as through the Murakami's Method, no significant difference can be appreciated in the fatigue behavior of the specimens considered in the present study
- Specimens built with virgin powder illustrated a slight deviation from the other sets at higher load levels

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