

Reuse of 316L stainless steel towards zero-waste laser powder bed fusion

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Abstract. Aiming to enhance the adoption of sustainable practices in the Italian manufacturing sector, this study investigated the application of powder reuse in laser powder bed fusion (L-PBF) processes. Within the “Made in Italy-Circular and Sustainable” (MICS) Extended Partnership, backed by the European Union Next-GenerationEU, an alternative reuse strategy was studied through 316L stainless steel specimens fabricated from powder subjected to five and ten reuse cycles. Compared with virgin powder data, the characterization performed through particle size analysis, hardness, and tensile testing shows that ten reuse cycles do not affect part or powder quality significantly. The results support extended powder reuse potential, highlighting how L-PBF can facilitate zero-waste production and foster Italy’s transition toward greener and circular practices, improving the competitiveness of made-in-Italy products while minimizing both resource consumption and material waste.

Introduction

The Italian manufacturing industry and made-in-Italy products stand out in global markets as design and technical quality hallmarks. In particular, the mechanical and machinery production industries achieve excellence through high production quality standards and innovation [1]. Nevertheless, the manufacturing sector in Italy faces the challenge of maintaining competitiveness as the new Industry 5.0 paradigm urges the adoption of sustainable practices [2]. While already an implicit objective of Industry 4.0, environmental impact reduction has now become one of the core guiding principles of the new industrial revolution. In this context, the MICS (Made in Italy - Circular and Sustainable) Extended Partnership, funded by the European Union Next-GenerationEU, identifies Additive Manufacturing (AM) techniques as the solution Italian manufacturing companies should adopt to optimize resource consumption and minimize waste [3].

Among metal AM technologies, Laser Powder Bed Fusion (L-PBF) is the most popular, with a 54% market share as of 2020 [4]. Despite being most appropriate for low-to-medium production volumes [5], L-PBF enables reproducing complex and lightweight components, redesigned through topology optimization techniques or lattice structures, which would otherwise be unfeasible using traditional manufacturing processes. Furthermore, L-PBF allows processing a wide variety of materials, including steel alloys, titanium alloys, aluminum alloys, and nickel-based superalloys [6]. On the other hand, just a small fraction of the powder loaded in any L-PBF machine is melted during part manufacturing. The remaining portion is left on the building plate or collected into an overflow tank. Since feedstock can account for up to 30% of the build cost [7], reusing the non-consumed material is necessary to maximize powder usage efficiency and reduce the costs associated with the process [8]. However, unmelted powders collected at the end of the process are contaminated by spatters [9], an inevitable by-product of laser-powder interaction that differs from virgin powder in morphology, porosity, and surface oxidation [10]. Powder

degradation can thus be exacerbated following multiple reuse cycles, triggering the formation of defects and oxygen inclusions that might negatively impact the quality and performance of printed parts [11]. For this reason, different reuse strategies have been implemented in recent years to investigate how feedstocks and parts are affected by powder reuse [12]. Single-batch reuse represents the most used approach as reusing the same batch of powder in successive builds until it becomes insufficient allows to directly assess degradation. Despite offering high traceability, this method leads to accelerated powder degradation as fresh material replenishment is avoided [13]. For this reason, other studies focused their attention on refreshing strategies, mixing reused and virgin powder after a variable number of builds. Such blending results in a homogeneous feedstock that offsets degradation, ensuring powder and part quality remain consistent across multiple reuse cycles [14]. However, the recurrent addition of virgin powder only partially reduces the economic and environmental impact of L-PBF, emphasizing the need for closed-loop techniques where recycles replace virgin materials [15]. Top-up strategies can then represent a viable solution, as reused powder is loaded back into the dispenser tank after each build. Despite offering simpler powder handling than other strategies, such approaches may result in layered powder beds and virgin powder contamination since blending is not typically performed when powders are reintroduced into the system [12].

The previous considerations underscore the necessity for reuse strategies to minimize powder degradation while also ensuring resource and cost efficiency. In this context, the present article proposes an alternative approach to establish closed-loop powder reuse within a zero-waste perspective. Since manufacturing companies often delay the adoption of sustainable practices due to financial, logistical, and informational barriers [16,17], a scenario in which all the virgin powder was first consumed is considered. The strategy was thus devised to perform the first reuse cycle according to the single batch approach while successive cycles were carried out in a top-up fashion to maximize resource efficiency and minimize waste. However, blending was also performed to homogenize the feedstock before each new print. The devised reuse method thus proposes slow down degradation and reduce costs associated with powder waste through the progressive dilution of reused powders. A preliminary assessment was conducted to evaluate the effectiveness of the proposed strategy through the reuse of 316L stainless steel powder. Specifically, the particle size distribution, hardness, and tensile strength after five and ten reuse cycles were investigated and compared with benchmarking values provided by the supplier for virgin powder.

Materials and methods

Metallic powder and reuse strategy

In this study, gas-atomized 316L stainless steel powder supplied by Carpenter Additive Ltd, USA, was used. The virgin-state feedstock was characterized by a particle size distribution of $D_{10} = 19.8 \mu\text{m}$, $D_{50} = 31.2 \mu\text{m}$, and $D_{90} = 49.1 \mu\text{m}$, and chemical composition as shown in Table 1.

Table 1. Chemical composition of the supplied virgin SS316L powder in (wt.%).

Fe	Cr	Ni	Mo	Mn	Si	C
Bal.	16.0 - 18.0	11.0 - 14.0	2.0 - 3.0	< 2.0	< 1.0	< 0.03

A systematic strategy was devised to start with single-batch reuse at the first iteration and then dilute the progressively reused powder by blending it manually with the remainder in the dispenser tank. At each reuse step, the excess powder collected after printing was sieved in a Retsch AS300 control vibratory sieve shaker with a 63- μm mesh size and then dried in a Nabertherm LH 60/12 furnace for 4 hours at a holding temperature of 70 °C. A schematization of the strategy and experimental activities is provided in Fig. 1, where R_i and B_i indicate the i -th reused powder and build job, respectively. The starting batch used in this work consisted of excess powder collected from previous builds manufactured with only virgin powder. Such residue was sieved to remove

larger spatters and agglomerations and dried to remove moisture. The batch was labelled R_1 to underline that it underwent a first reuse cycle. Since no significant degradation is typically observed in the powder after just one reuse cycle [12], R_1 powder was assumed to be equivalent to virgin powder. Following a first build job produced using exclusively R_1 , the unmelted powder in the build volume and overflow tank was collected, sieved, and dried. This residue was labelled R_2 to underline that a second reuse cycle was performed and then loaded back into the dispenser tank, where it was mixed with the remaining R_1 powder. A second build job was thus produced using the resulting blend of R_1 and R_2 . Consequently, the powder reclaimed after the second build and labelled R_3 after sieving and drying was blended with the powder in the dispenser to form the feedstock used in the third build. The devised strategy was iterated over 10 reuse cycles, so each successive build was manufactured using blends of powders with progressively longer reuse histories. By the 10th build job, the feedstock thus consisted of a blend spanning all reuse cycles from R_1 through R_{10} . The 5th and 10th reuse cycles were chosen for powder and part characterization to provide a preliminary assessment of the proposed reuse strategy, since they represent the intermediate and final points of the reuse path.

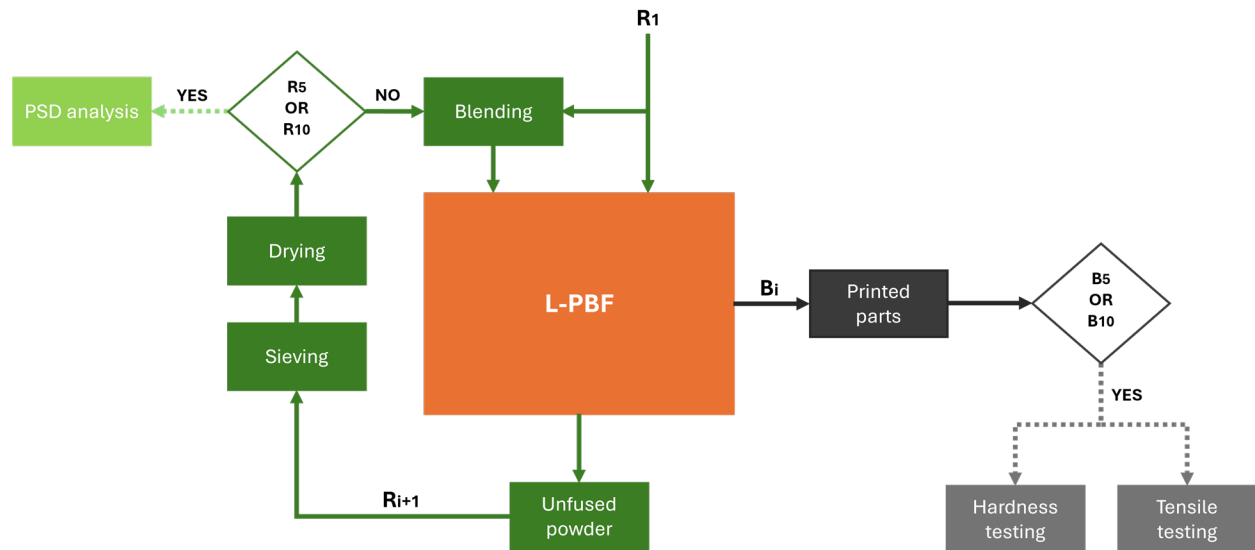


Figure 1. Schematization of the reuse strategy proposed in this article.

Each build was fabricated with a Print Genius 150 L-PBF machine (Prima Additive srl, Italy), mounting a 300W continuous Yb-fiber laser operating at a 1070 nm wavelength. The process was conducted in an inert argon atmosphere, keeping the oxygen level below 0.1%, as the shielding gas was constantly blown in the build chamber to remove spatter and laser plume. The following process parameters were used: 130 W laser power, 100 μm laser spot diameter, 900 mm/s scanning speed, 50 μm hatch distance, and 30 μm layer thickness. Layers were processed against gas flow using a stripe scanning strategy with 67° inter-layer rotation. The build platform was preheated and kept at 80 °C during each build. In the builds labeled B_5 and B_{10} , a 30×30×5 mm³ prism and three horizontally built cylinders (10 mm diameter, 115 mm length) were fabricated to characterize hardness and tensile strength, respectively. The volume of these builds (27096 mm³) occupied ~17% of the deposited powder bed. To avoid altering spatter formation and maintain powder reuse consistency, the same powder volume was consumed in the other builds to fabricate cubic and cylindrical samples destined for laboratory activities.

Powder and part characterization

The 5th and 10th reuse cycles were chosen for powder and part characterization to provide a preliminary assessment of the proposed reuse strategy, since they represent the intermediate and final points of the reuse path.

After sieving and drying, R₅ and R₁₀ powder samples were collected for the particle size distribution (PSD) analysis performed with a Malvern 3000E laser diffraction analyzer, according to the ASTM B822-17 standard [18].

Data provided by the supplier [19] were used as benchmarks for comparison with properties achieved using only virgin powder. All specimens were removed from the build plate via Wire Electrical Discharge Machining (WEDM). After polishing, the top surface of each prism was subjected to nine Rockwell-B hardness tests according to ISO 6508-1 [20] using an Officine Galileo hardness tester. The tensile specimens (Fig. 2) machined from the printed geometry were designed and tested according to ISO 6892-1 guidelines [21]. The uniaxial tensile tests were conducted at room temperature using a Galdabini Sun 5 testing machine with a cross-head displacement rate of 0.0085 mm/s.

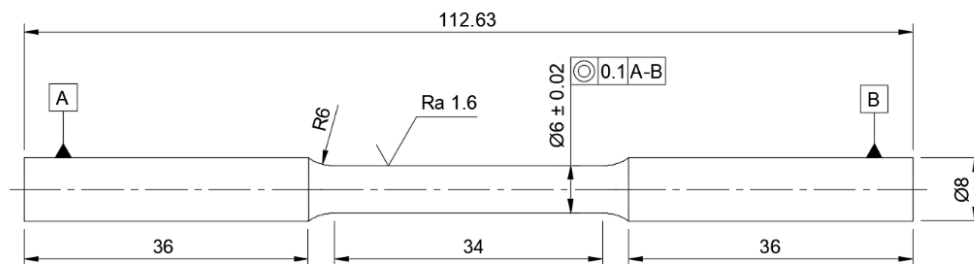


Figure 2. Tensile specimen after machining (dimensions in mm).

Results and discussion

The PSD analysis reported in Fig. 3 revealed a progressive coarsening of the powder over the ten reuse cycles. However, this result directly stems from the implementation of powder reuse since particles larger than layer thickness are spread past the build area in the L-PBF process, and more are collected for reuse. While D₁₀ and D₅₀ values remained relatively stable, the more pronounced increase exhibited by D₉₀ (14 %) can be mainly attributed to increased spatter formation and agglomeration mechanisms leading to the accumulation of larger particles that survived sieving. The stable values of D₁₀, particularly between the 5th and 10th reuse cycles, suggest that the proposed dilution-based reuse strategy helps mitigate the preferential loss of fine particles typically observed in single-batch reuse [13]. By systematically mixing powders with different reuse histories, the method implemented in this study appears to be compatible with refreshing strategies, which generally have a minimal effect on PSD over ten reuse cycles [12].

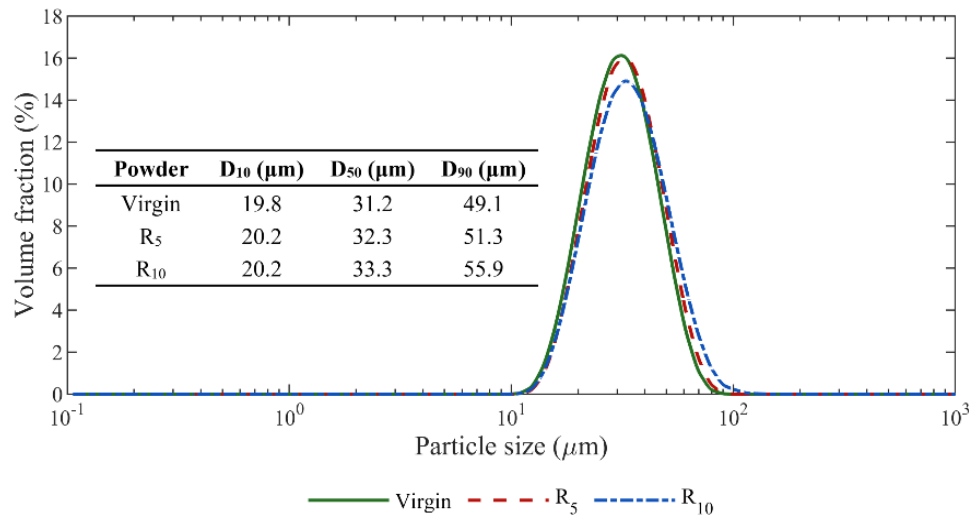


Figure 3. Particle size distribution of 316L powder at virgin state, 5th reuse, and 10th reuse.

The tensile properties and hardness results in Fig. 4 and Table 2, respectively, further reinforce the stability achieved by the proposed approach. Indeed, the increase in larger particles helps retain mechanical properties by improving flowability and packing density [22].

Fig. 4a shows that the engineering tensile stress-strain responses after five and ten reuse cycles remain consistent and comparable despite performing powder reuse multiple times in between. Furthermore, Fig. 4b demonstrates that the yield strength (YS) and ultimate tensile strength (UTS) achieved do not exhibit significant deviations from the virgin powder baselines of 552 MPa and 703 MPa, respectively. However, it is important to note that a significant reduction was instead observed in ductility compared to virgin powder. Indeed, Fig. 4b depicts a decrease in the elongation at break (A) from 57 % to 43 % and 41 % at the 5th and 10th reuse cycles. However, considering that the results achieved by both builds B₅ and B₁₀ compare well with each other and reflect the same trend of stress values, the difference with the benchmark was attributed to the supplier testing the tensile properties of virgin powder builds with shorter specimen gauge length according to a different standard [19]. Overall, these findings clearly show that a reuse strategy based on reused powder dilution allows tensile performances to remain within acceptable ranges. Most importantly, the results compare favourably with findings from commonly performed reuse strategies. Indeed, in their review study, Werner et al. [12] observed that most results in the literature indicate minor or no changes in the tensile properties and ductility of stainless steels subjected to either single-batch or top-up powder reuse. Insignificant changes in YS, UTS, and A were also observed when refreshing strategies were adopted to reuse different alloys. However, further comparison with the present study cannot be drawn at the moment, as the effects of refreshing on stainless steel parts have never been investigated.

The Rockwell B hardness measurements further validate the robustness of the proposed methodology. As shown in Table 2, the measured values of 94.3 ± 1.0 HRB and 93.4 ± 1.1 HRB at the 5th and 10th reuse cycles show no significant deviation from the baseline value associated with builds fabricated using only virgin powder, again drawing a parallel with results achieved using single-batch reused 316L stainless steel powder [13].

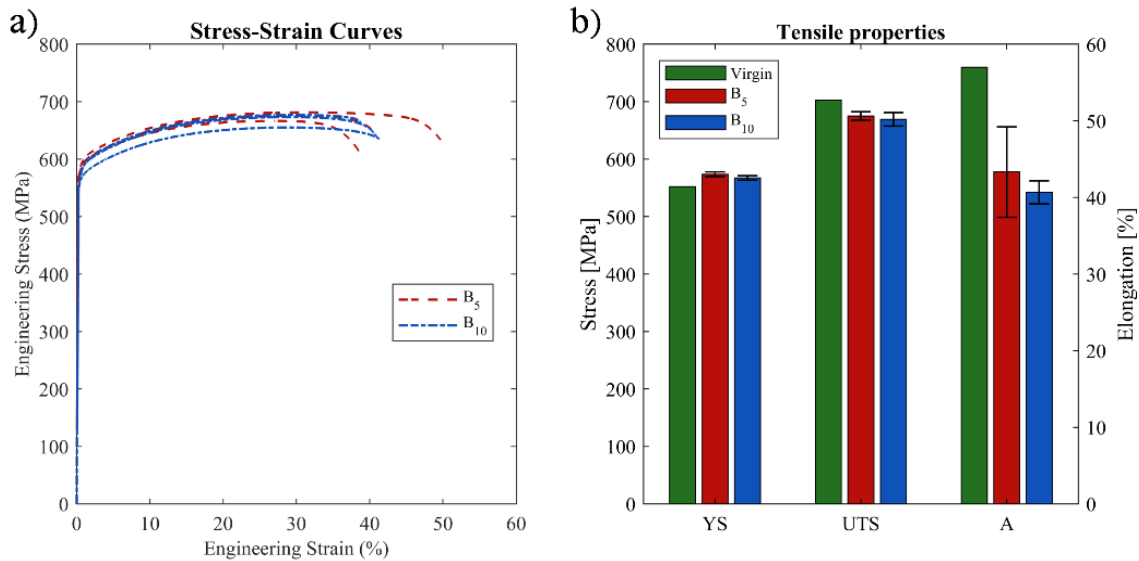


Figure 4. Results of uniaxial tensile testing on prints B₅ and B₁₀: (a) engineering stress-strain curves (b) tensile properties comparison with powder supplier benchmark data for virgin powder.

Table 2. Results of Rockwell B hardness testing.

Build	Rockwell B hardness [HRB]	
	Average	Standard deviation
Virgin	93.0	-
B ₅	94.3	1.0
B ₁₀	93.4	1.1

Even though limited to the 5th and 10th reuse cycles, this study shows that systematically diluting 316L stainless steel powders with different reuse histories has limited effects on particle size distribution and part properties. Comparing the devised method to commonly performed reuse strategies, where minor variations among different studies are largely attributed to differences in sieving practices and testing methodologies, it is possible to conclude that reuse does not compromise the mechanical properties of parts if powders are sieved to limit particle size below 63 μm throughout consecutive reuse cycles. Although further studies are needed to fully evaluate the influence of the proposed strategy on both powder and part properties, the preliminary results presented in this study show potential for extended powder reuse. Through careful optimization of blended proportions, dilution-based strategies may thus represent a competitive alternative to conventional reuse approaches for L-PBF powders. Even though blending powders adds to powder handling procedures and therefore represents a drawback to this technique, ensuring consistent part performance while extending the feedstock’s life cycle without relying on powder rejuvenation represents a desirable advantage from environmental, economic, and quality perspectives. Dilution-based reuse would hence provide a valuable asset from an industrial perspective, as it could help manufacturers retain competitiveness on the market with reduced environmental footprints.

Conclusions

This study proposed a novel powder reuse strategy to improve the environmental and economic impact of the L-PBF technology through closed-loop reuse within a zero-waste perspective. By blending 316L stainless steel powders subjected to progressive reuse cycles, the following results were observed after five and ten iterations:

- Despite the typical coarsening of larger particles, the powder size distribution shows no significant variation, and the preferential loss of fines is halted;
- Yield strength, ultimate tensile strength, ductility, and hardness remain consistent and within a comparable range to parts manufactured using only virgin powder.

This dilution-based strategy aligns with results achieved by conventional powder reuse approaches but ensures consistent feedstock and part performance while avoiding the production of waste and the addition of fresh powder. Despite providing preliminary results for 316L stainless steel, this study poses a promising foundation for the proposed strategy to offer a valid solution to balance cost-efficiency, environmental sustainability, and part quality. Future works should thus investigate the effects of extended reuse on additional part and powder properties, as well as other L-PBF alloys, to further validate the robustness of the proposed method and foster its adoption in industrial additive manufacturing workflows. Future studies should also investigate how powder microstructure, composition, morphology, and oxygen content evolve with reuse. Such analysis would provide further insight into powder stability, thus reinforcing the findings and enhancing the completeness of the present study.

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