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Investigation Towards AlSi10Mg Powder Recycling Behavior in the LPBF Process and Its Influences on Mechanical Properties

C. Weiss*, J. Munk*, C.L. Haefner†

*Fraunhofer-Institute for Laser Technology ILT, Germany, 52074 Aachen
†RWTH Aachen University, Chair for Laser Technology, Germany, 52074 Aachen

Abstract

Parts fabricated by Laser Powder Bed Fusion (LPBF) technique allow for a high material utilization of a single powder batch, since unfused powder material can be reconditioned and reused in subsequent manufacturing jobs. Due to process induced spatters however, the quality of the powder may change during recycling, which in turn can affect the mechanical properties of built parts. Therefore, a better understanding on the recyclability of the powder material is needed. Within this work, the powder ageing behavior of the lightweight aluminum alloy AlSi10Mg in the LPBF process is investigated. A standard build job is developed and built with ageing powder in 10 consecutive jobs with no refreshing between the cycles. The powder properties as well as the mechanical properties at static load for two different build orientations are investigated. The comprehensive analyses suggest that the powder coarsening may lead to improved mechanical properties during recycling for AlSi10Mg.

A substantially improved version of this paper appears in a special issue of the TMS publication *JOM*, March 2022.

Introduction

Additive manufacturing (AM) techniques like the Laser Powder Bed Fusion (LPBF) process allow for manufacturing of highly complex, three-dimensional and near net shape parts without cost intensive tools. In LPBF, powder material is exposed layer by layer until the final part is built. One advantage of this process is that powder material is only melted where the part is to be built. Unfused powder material after processing can be collected and reconditioned for further build processes. This fact plays an essential role when it comes to economic and ecologic assessment of LPBF. The production and atomization of the powder material are cost-drivers as well as energy intensive processes. Identification of potentials to save and recondition powder material allows for higher sustainability of AM since the amount of new powder manufacturing can be avoided. [1]

Especially when it comes to series application of LPBF, the specifications of the powder material as well as of the final parts have always to be met and are monitored closely. By reusing powder material, however, diverse influencing factors like disposal of spatters in the powder bed might lead to changes in powder properties. Since the changes in powder properties affect the material properties directly, possible recycling influences have to be known beforehand or at least have to be dealt with accordingly [2]. Especially light-weight alloys like AlSi10Mg are of high interest in the industrial applications thanks to their high strength-to-weight ratio. Nevertheless, due to the reactive nature of this alloy, changes in powder properties are a serious challenge.

Several authors already investigated the influence of powder recycling in the LPBF process for AlSi10Mg, a short literature overview and state of the art is presented in the following. An overview of the literature and the essential data gathered is given in Table 1.

Reference	LPBF system	Virgin powder	Recycled powder	Sieve-Ø	Reuse cycles
Asgari et al. [3]	EOS M290	$x_{50} = 8.8 \pm 7$ µm	$x_{50} = 9.9 \pm 8$ µm	60 µm	1
Del Re et al. [4]	EOS M280	$x_{10} = 12.8$ µm $x_{50} = 27.7$ µm $x_{90} = 51.3$ µm	$x_{10} = 11.7$ µm $x_{50} = 24.9$ µm $x_{90} = 45.6$ µm	60 µm	8
Maamoun et al. [5]	EOS M290	$x_{10} = 11.77$ µm $x_{50} = 28.04$ µm $x_{90} = 54.09$ µm	$x_{10} = 10.6$ µm $x_{50} = 27.1$ µm $x_{90} = 52.6$ µm	70 µm	18
Rafieazad et al. [6]	EOS M290	$x_{50} = 8.8 \pm 7$ µm	$x_{50} = 13.7 \pm 7$ µm	-	5
Cordova et al. [7]	SLM 280	$x_{50} = 38.5$ µm	$x_{50} \sim 43$ µm	100 µm	6

Table 1. Short literature overview on powder recycling investigations of AlSi10Mg in Laser Powder Bed Fusion processing

Asgari et al. [3] investigated the effect of reusing AlSi10Mg powder material once. After the build job, they reconditioned the powder material by sieving with a 60 µm mesh. No information on the build job layout is given in the source. The authors conclude that no influence of one powder reuse is detectable on powder properties as well as mechanical properties. Nevertheless, the used powder material is well below typical ranges of particle size distribution for the LPBF process (typ. 10-60 µm according to *Vock et al*. [2]) and therefore not representative for state of the art applications.

In *Del Re et al.* [4], the authors built a defined build job consisting of cylindrical bars and fatigue samples for eight reuse cycles of the powder material. In between the cycles, the unused powder in the powder hopper and the sieved powder from the overflow and build plate are homogenized and used for the subsequent built job. The authors observe a reduction of lager particles during recycling which is attributed to the sieving mesh of 60 µm. The mechanical properties show a low reduction during recycling. Due to the chosen methodology, however, no clear trend of the powder recycling state on the mechanical performance can be identified due to the fact that used powder is refreshed with virgin-like powder material from the hopper.

Maamoun et al. [5] used a fresh and 18 times recycled powder in order to investigate the effect of thermal post-processing on LPBF parts. The authors showed in their analyses that the reused powder was slightly finer. EDS comparisons of the powders revealed no significant differences in chemical composition. Microstructural analysis of manufactured samples showed no influence of the powder recycling state. However, no further explanation on the 18 times recycled powder and no build job information is given in this literature. Therefore, the exact interaction of the recycling state cannot be interpreted.

In *Rafieazad et al*. [6] the influence of 4 and 5 times recycled powder is investigated and compared to virgin powder on the obtainable relative density and microstructure. Higher usage of the powder material resulted in an increase in particle size distribution. Furthermore, analysis showed that using recycled powder leads to higher density of internal defects attributed to larger particle size of reused powder and irregular shape of the particles. The used powder, nevertheless, is not typical for LPBF processes as stated above. The fact that no more general information on recycling procedure is given, an interpretation of the results once again is difficult for general statements on powder recycling.

The influence of recycling Ti6Al4, IN718, Scalmalloy and AlSi10Mg on changes in powder properties was studied in *Cordova et al.* [7]. The six times recycled AlSi10Mg powder material showed a higher particles size distribution compared to the virgin powder. Towards morphology, larger deformations towards a teardrop shape and an increase of satellites could be observed in the recycled state. With EDX measurements, an increase of almost double in oxygen content for recycled AlSi10Mg powder was found due to oxide formation. Flowability was measured with the Hall flowmeter. Better flowability of recycled powder was attributed to loss of fine particles during recycling. One of the final statements of the paper is that lightweight alloys like Ti6Al4V and AlSi10Mg are most influenced by recycling, provoked by changes in particle size distribution and thus affecting the powder flowability.

In summary, the literature overview has shown that, until now, no clear investigation of powder recycling for AlSi10Mg on the changes of powder properties in combination with mechanical performance of built samples is present. Therefore, within the next chapters, a powder recycling methodology as well as a defined build job layout is presented and is experimentally built on a commercially available LPBF system. The powder properties (chemical composition, particle size distribution, flowability and morphology) as well as the static mechanical performance of tensile samples are investigated. Calculation of correlation factors help to understand the influences of powder reusage in LPBF.

Methodology and Analysis Methods

In order to evaluate the discrete correlation between the powder recycling state and the resulting properties of the powder material as well as the influence on the mechanical performance, a systematic approach for the recycling study has been defined. The developed procedure is illustrated in Figure 1.

The analysis of the fresh/virgin powder material serves as the reference for the recycling study. For the first build job, the whole amount of available virgin powder is filled into the LPBF system. A predefined build-job, which will be explained further below, is built with the fresh powder material until the machine runs out of powder. After processing, the remaining unused powder material in the overflow as well as unfused powder in the process chamber is collected, sieved in order to remove the process induced by-products like spatters and consecutively homogenized. The sieved powder material is then again filled into the LPBF system and the next identical build job is run. No refreshing or blending is done between the cycles, thus the applied methodology represents a worst-case scenario for industrial applications. The maximum achievable built height is reduced for every consecutive use cycle of the powder material. Samples of the sieved powder and the sieve residue are analyzed for each powder use cycle for an identification of powder recycling influences onto the powder material itself. The samples of each of the total 11 build jobs (#1 reference with fresh powder, #2 … #11 recycling study) are afterwards cut from the build plate and prepared for mechanical characterization.

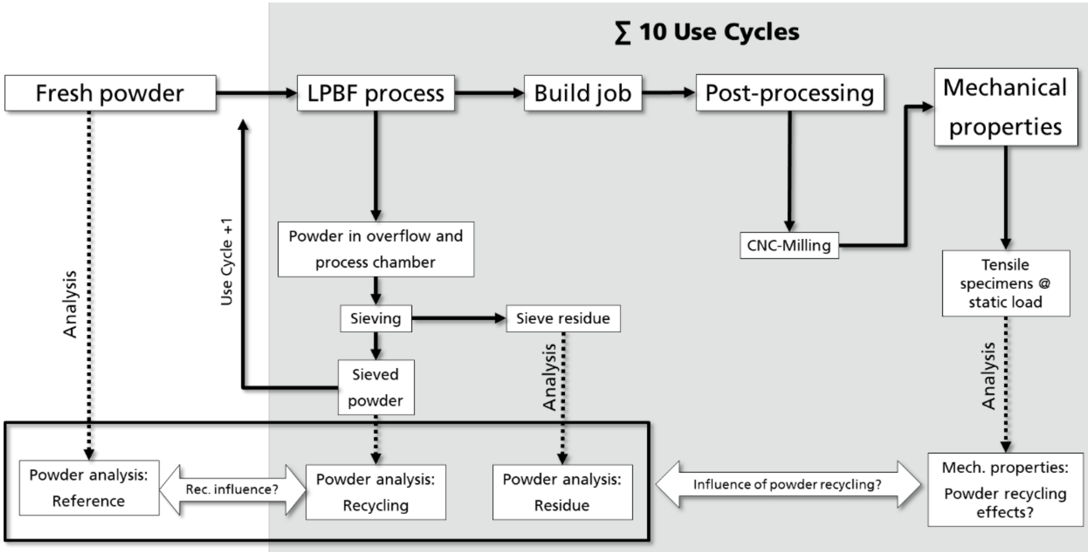
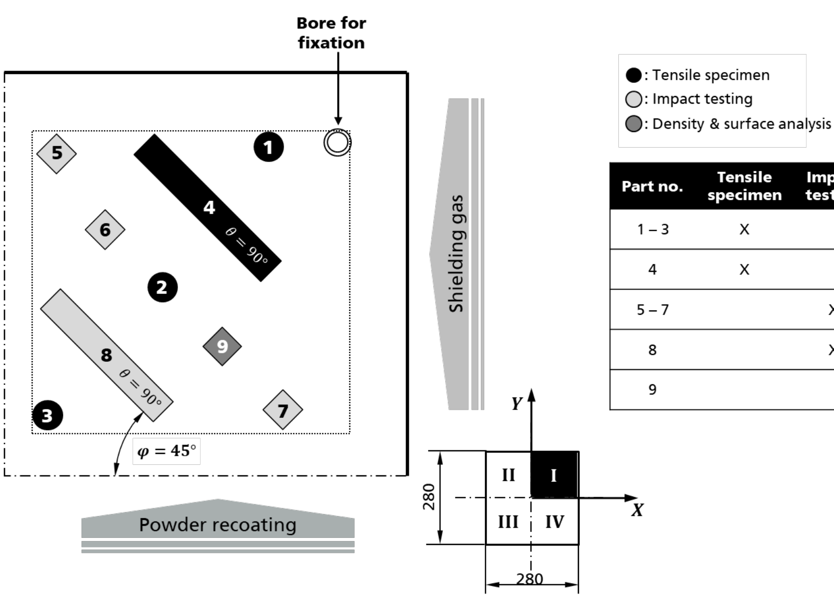


Figure 1. Schematic of metal powder recycling study and analysis steps

The build job design with the sample geometries is schematically shown in Figure 2 for one quarter of the build plate. Overall 4*9 = 36 samples are manufactured per build job. The samples 1-3 are described as standing cylinders with a diameter d of 10 mm and serve as blanks for tensile investigations. Part number 4 represents a lying tensile specimen of the same dimension and is manufactured as a wall-like geometry. Part geometries number 5-8 are built for other analyses that are not part of this paper. Sample number 9 is a standing block with 10x10 mm² cross-section in x-y-plane for analysis of the relative density and vertical surface roughness. Since all parts are built until the machine runs out of powder in each cycle, a constant ratio of exposed surface / available substrate surface of 9,33 % can be calculated for each layer.



Part no.	Tensile specimen	Impact testing	Density & surface	Polar angle θ
1 – 3	X			0°
4	X			90°
5 – 7		X		0°
8		X		90°
9			X	0°

Figure 2. Schematic of the build job design for one quarter of the built plate (left) and identification of build samples as well as their respective investigative goals (right)

The minimum build height for tensile specimens defined in VDI 3402 Part 2 [8] is least 60 for standing cylinder blanks that act as tensile specimens. Therefore, the necessary build height in the last use cycle of the powder material must be at least 60 mm. Based on pre-calculations, 70 kg of virgin powder are needed. AlSi10Mg powder material is used for recycling investigations. For the LPBF processing, a commercially available SLM280HL, SLM Solution Group AG, with twin laser configuration and a maximum available laser power of $P_{L,max}$=400 W is used. The powder is stored in a hopper above the build plate and transported into the recoater by a spinning axle. Industrial established process parameters from the machine manufacturer with a layer thickness of D_S=60 µm are applied for all parts, the build plate is preheated to $T_{Preheat}$ = 200 °C. Argon acts as the processing gas. Reconditioning of the powder between use cycles is carried out with a 90 µm mesh width of the sieve.

The powder property "particle size distribution" is quantified with a Camsizer X2, Retsch Technology. The dynamic imaging of powder particles is determined according to standard ISO 13322-2. The flowability of the powder material is characterized with a Revolution Powder Analyzer (RPA), PS Prozesstechnik GmbH. Therefore, a powder filled cylinder is rotated and pictures of flowing avalanches are recorded. A deeper explanation of the measuring device can be found in [9]. Changes in chemical composition of the powder material are determined by an external provider via inductively coupled plasma – atomic emission spectrometry (ICP-AES) method.

Analysis of vertical surface roughness of the #9 parts is done by the optical metrology system Alicona InfiniteFocus, Alicona Imaging GmbH. A 10x5 mm² large measuring area is defined for the build samples and a mean value for surface roughness is generated subsequently. The relative density of the samples is determined by means of light optical microscopy (LOM). Therefore, segments of the specimens are cut perpendicular to the build direction from the part and consecutively grinded as well as polished. A Keyence VHX-6000, Keyence Germany GmbH, is used for image generation of the cross-sections. The analysis of the relative density is performed with the open source software ImageJ. The cross-sections are furthermore analyzed regarding the hardness. Therefore, a hardness tester HP-Qness is used. Testing of the hardness is carried out according to Vickers HV5. A rectangular pattern with 5x10 indentations is used.

Evaluation of the mechanical properties of the built samples are tested with tensile samples of the form DIN-50125 B5x25. The blanks #2 and #4 of the build jobs (Figure 2) are used for cutting and machining operations to generate the tensile standing and lying specimens, respectively. Since Figure 2 only represents one 4th of the build layout, overall n=4 samples for standing and lying tensile samples can be generated per use cycle and are tested accordingly. Since changes in mechanical properties are not expected before the 4th use cycle and in order to keep the mechanical testing in reasonable range, every 2nd use cycle of samples beginning at the 4th reuse are analyzed.

Influence of Powder Recycling on Powder Properties

Within this chapter, the characterization of the virgin powder material is given as well as the influences of powder recycling on the powder properties itself is shown. Ongoing, in Figure 3 the measured particle size distribution of the virgin powder as well as a SEM picture is given. The particle size distribution shows a monomodal distribution with peak particle size in the range of about 30 µm. The characteristic values for d_{10}, d_{50} an d_{90} are 27.3 µm, 39.7 µm and 59.2 µm respectively. Overall, the analysis confirms the nominal particle size distribution of 20-63 µm. In the SEM picture it can be observed that the powder shape is slightly deformed, derived from the many elongated particles shown. Also, quite a few agglomerations and satellite formations in the powder material can be seen. Both these factors are probably associated with the powder atomization method.

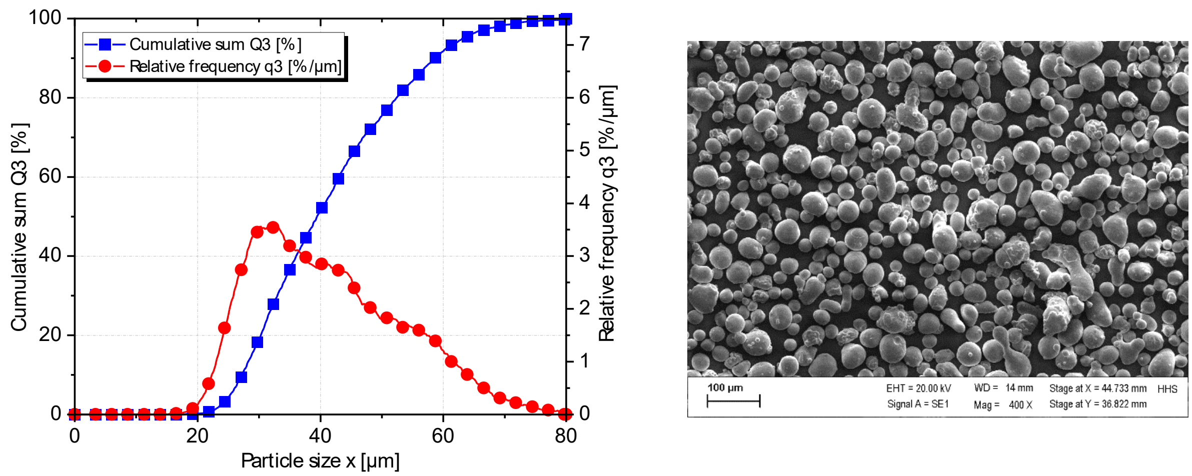


Figure 3. Measured particle distribution of virgin AlSi10Mg powder (left) and SEM picture of virgin powder (right)

The chemical analysis of the virgin powder material (Table 3) shows no hints of impurities or large deviations in the powder material compared to VDI-3405 2.1 standard [10]. Therefore, the powder material can be used for the recycling study.

Chemical element [wt.-%]	**Al**	**Fe**	**Cu**	**Mg**	**Mn**	**Si**
VDI-3405 2.1	Balance	0.55	0.05	0.20…0.45	0.45	9.0 … 11.0
Measured	89	0.122	0.0021	0.34	0.0030	10.2

Table 2. Chemical composition of virgin powder compared to VDI-3405 standard

General information on the run recycling study build jobs is given in Figure 4. Logically due to the setup of the build program, the build height and build time decline in an almost linear manner with higher use cycles. Overall, 1475 mm height and more than 286 hours of build time are accumulated throughout the 11 build jobs. Build job pictures in Figure 4 show the differences in reached build height in cycle 0 and cycle 11. While a build height of 200 mm with virgin powder in cycle 0 is realized, ~82 mm can be manufactured in the 10th reuse cycle of the powder material. Hence, the minimum height of 60 mm in the last cycle is reached.

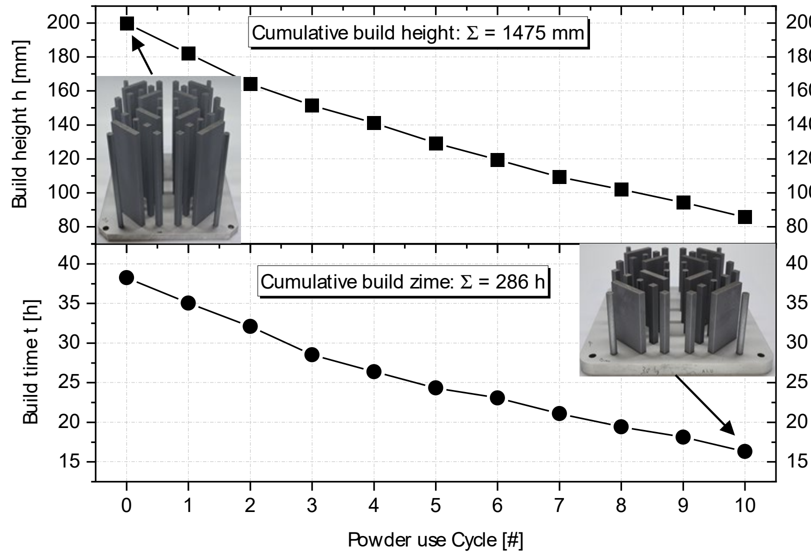


Figure 4. Reached build height (above) and needed build time (below) for the powder recycling study

In Figure 5 (left), the summary of particle size distribution measurements according to DIN 13322-2 over the use cycles of the powder material is shown. As it can be observed, the powder becomes coarser with increasing number of reuse cycles. While the d_{10} value only marginally increases from 27.3 µm in virgin state to 28.3 µm at the end of the build jobs, the d_{90} value shows an increase of 4 µm to about 62.4 µm. Throughout the build jobs and recycling of the powder, a steady increase in powder particle size can be seen. The coefficient of determination R^2 ranges from 0.33 for d_{10}-values to 0.49 for d_{90}-values. These observations are conform with the results in *Seyda* [11], where a constant recycling of Ti6Al4V powder material is associated with increasing formation of spatters (coarsening of powder material) and abrasion of fine particles due to the shielding gas flow over the build plate (loss of fine powder).

The characterization of the change of powder flowability is also shown in Figure 5 (right). The surface fractal, a descriptor for the fractal dimension of a surface after the avalanche, shows no influence on the recycling of the powder material, the observed values vary between 1.71 and 1.94. The same can be seen for the rest angle, which describes the angle of the powder material after an avalanche. The avalanche angle however shows a very strong dependency on the recycling state of the powder material. While high values for the avalanche angle can be seen for the fresh powder, with increasing use cycles the avalanche angle becomes smaller. A high correlation factor $R^2=0.87$ between the values can be seen. The change in avalanche angle is closely connected to the change in particle size distribution of the powder. Powders with higher degree of fine particles typically show bad flowability behavior due to interlocking and agglomeration of particles [12]. Since the particle sizes in the recycling study become larger and fine particles get lost due to handling operations i.e., therefore better flowability on the avalanche angle can be explained. The raw data for particle size analysis and flowability investigations can be found on the bottom of Table 4.

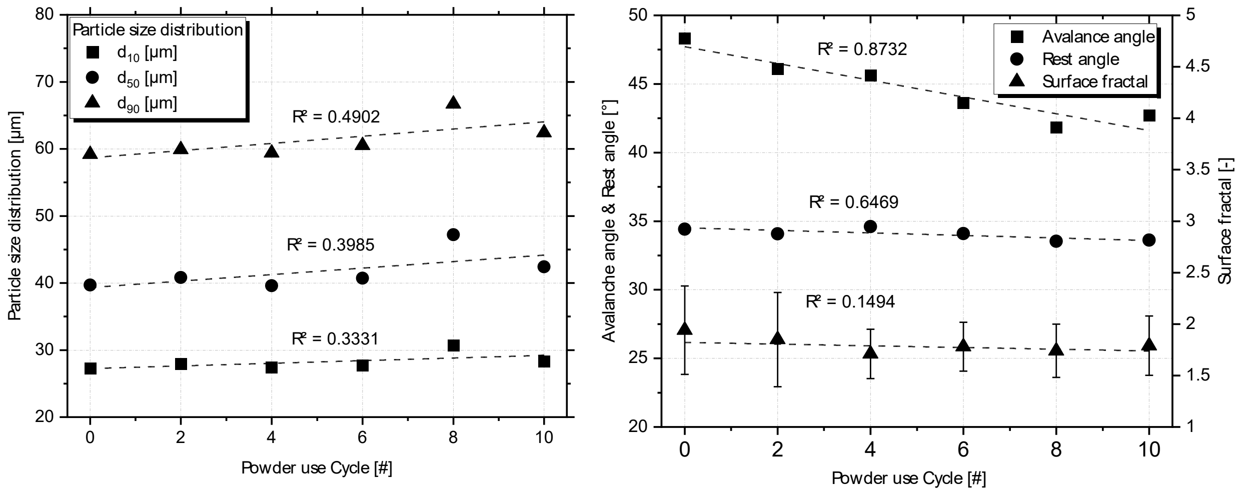


Figure 5: Analysis of the particle size distribution (left) and flowability (right)

		Powder use cycle [#]					
		0	2	4	6	8	10
Particle size distribution	d_{10} [µm]	27.3	27.9	27.4	27.7	30.7	28.3
	d_{50} [µm]	39.7	40.8	39.6	40.7	47.2	42.4
	d_{90} [µm]	58.2	59.9	59.4	60.5	66.7	62.4
Flowability	AA [°]	48.34	46.10	45.62	43.63	41.84	42.70
	RA [°]	34.42	34.08	34.60	34.10	33.54	33.62
	SF [-]	1.94	1.85	1.71	1.78	1.76	1.79

Table 3. Raw data for powder recycling

The trend of larger particles during recycling can also be seen in Figure 6, where SEM pictures of the material are shown in virgin condition (above) and after 10 recycles (below) for pre-process, post-process and sieve residue state. Example particles for elongated shape and agglomerate state are marked. After the first use and sieve process (upper middle), larger amounts of agglomerations can be detected. The powder in sieve residue is characterized by mostly very large sintered particles with diameter d_{Res} ~ 200µm. The SEM pictures confirm the observation of powder coarsening and fine particle loss as shown in Figure 5.

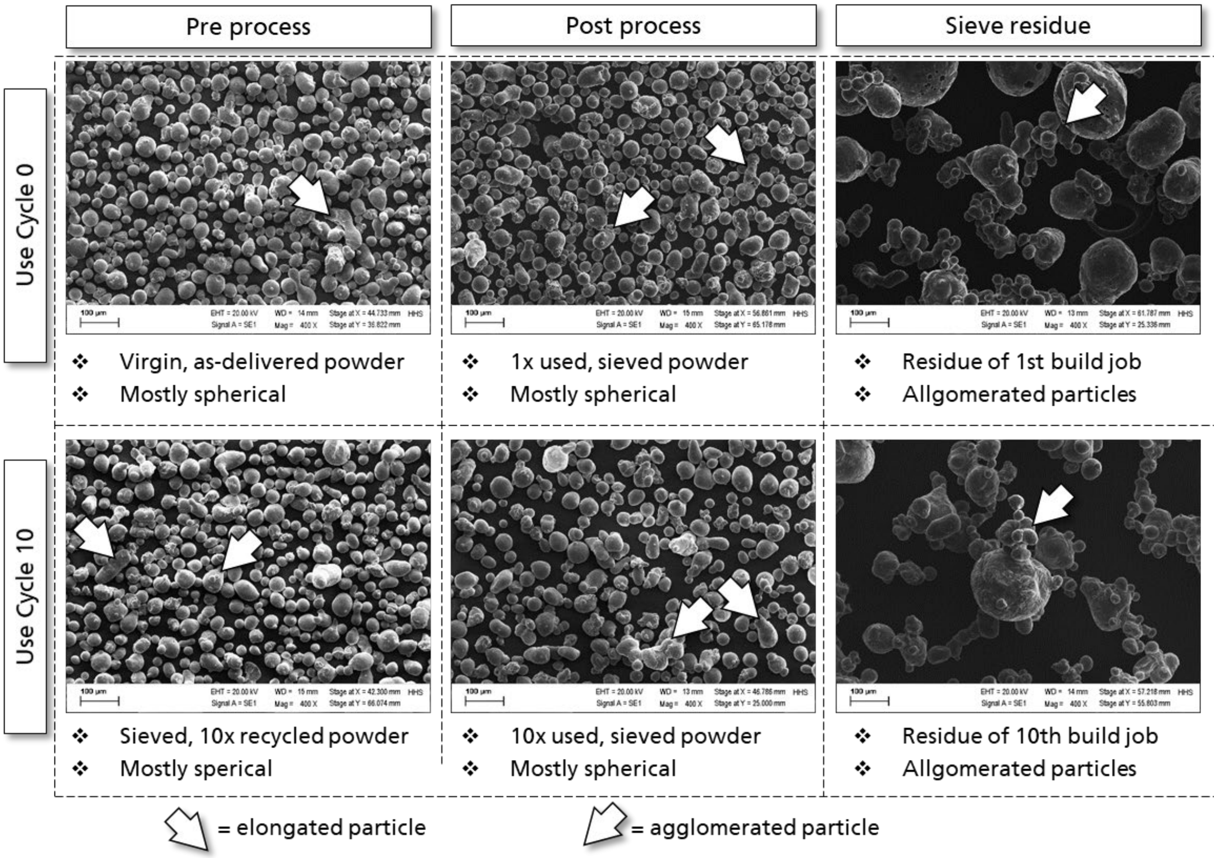


Figure 6. SEM pictures of powder material pre-process (left), post-process and sieved (middle) and sieve residue (right) for the fresh powder material (upper) and 10th use cycle (lower)

The analysis of the chemical composition of the powder material during recycling is shown in Figure 7. The main alloying elements Aluminum, Silicon and Magnesium as well as the trace elements oxygen and hydrogen were analyzed as indicators. For the main constituents of the powder, no change can be observed during recycling. Therefore, the powder composition does not significantly age and the powder may be reused in practical trials. Nevertheless, especially for the hydrogen content of the powder material a slight drift towards higher values with increasing ageing can be shown. While fresh powder has a high hydrogen content of ~ 850 ppm, a saturation at ~ 900 ppm hydrogen content can be found. The increase in hydrogen content may be attributed to longer powder handling operations with increasing use cycles. Hydrogen content in aluminum may lead to increased porosity of LPBF manufactured samples and therefore lower mechanical performance since hydrogen solubility in the phase change liquid ⇨ solid drops by a factor of ~ 10 [13]. This influence of powder handling and ageing should be kept into mind as powder is continuously recycled in LPBF processing. Drying operations for the reduction of hydrogen content in metal powder may advance the build quality of parts. Within this work, nevertheless, no additional drying in done between cycles.

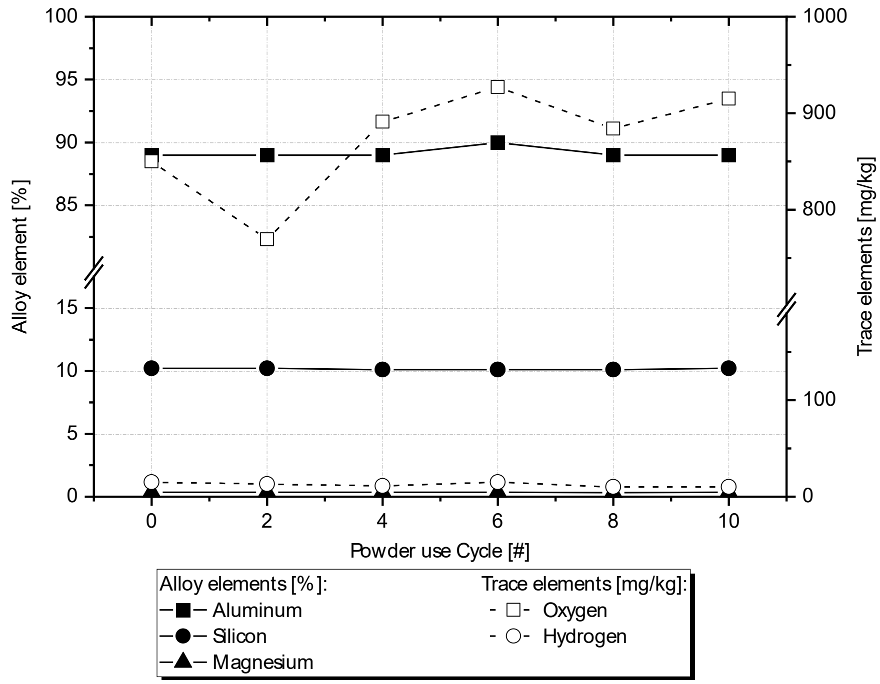


Figure 7. Chemical analysis (alloying elements and trace elements) of the powder material for the powder recycling study

Influence of Powder Recycling on Part Performance

The analysis of the relative density and hardness of specimen geometry #9 of the build layout is given in Figure 8. The relative density reached in the samples reaches the target density of ρ_{min}> 99 % meeting the industrial requirements and machine manufacturer specifications for the used material and parameter set [14]. Moreover, the standard deviation of the relative density slightly decreases with ageing powder material. Within the ageing study, a minimal trend in increasing relative density with higher use cycles can be seen. This observation might be closely connected to the better flowability of the powder material, which results in higher apparent powder layer density / packing of the powder material [2, 15]. The hardness nevertheless, shows a more distinct trend during the powder recycling study. While the lowest hardness ~100 HV5 can be detected for parts made of the virgin powder material, a steady increase towards ~115 HV5 can be seen for 10 times reused powder material. As described before, the trend of increasing relative density due to recycling might lead to higher hardness values. However, the strong fluctuations of the data shown by the standard deviation make a clear connection not possible.

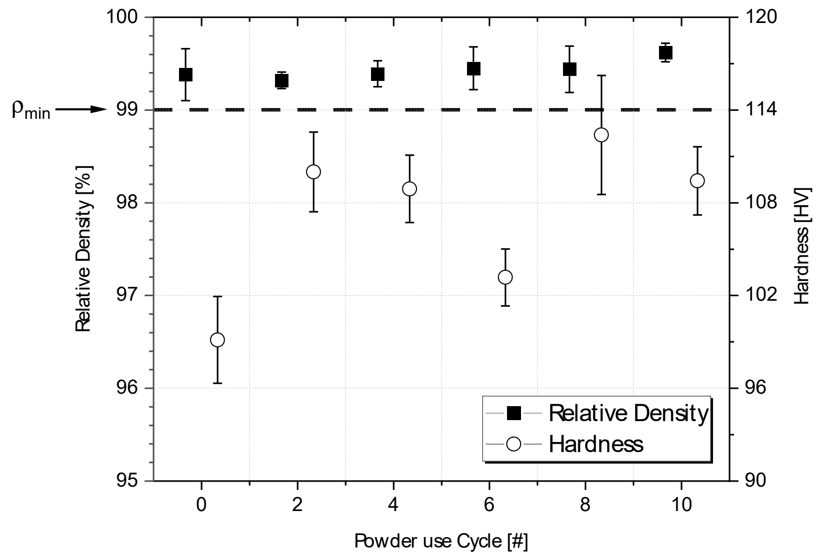


Figure 8. Analysis of the relative density and hardness of the built samples for the powder recycling study

In Figure 9 left, the measured surface roughness for vertical surfaces over the use cycles of the powder material can be seen. The arithmetic roughness R_a as well as the peak to valley roughness R_z are calculated from non-destructive optical measurements. As it can be observed in the graph, the recycling of the powder material only has a minimal influence on the resulting surface roughness with no clear observable trend. While in use cycle 0 an average value of R_a of ~12 µm and R_z of ~120 µm is measured, in use cycle 10 the result is about ~11 µm R_a and 100 µm R_z. For better illustration, two pictures of the measurements of use cycle 2 and 10 are depicted in Figure 9 right. Both pictures use the same legend given on the right side. While in the left picture three roughness tips with a height of over 60 µm can be seen, only one single roughness tip for use cycle 10 (right picture) is observed. This results in slightly higher roughness values for use cycle 2. In VDI-3405 Part 2.1, the as-manufactured mean surface roughness R_z is given in the range of 72 - 141 µm for AlSi10Mg parts [10]. Since the roughness values of all use cycles are in the defined range and no tendency in regard to use cycle influence can be seen, this leads to the conclusion that the recycling influence on roughness is negligible at least for vertical surfaces.

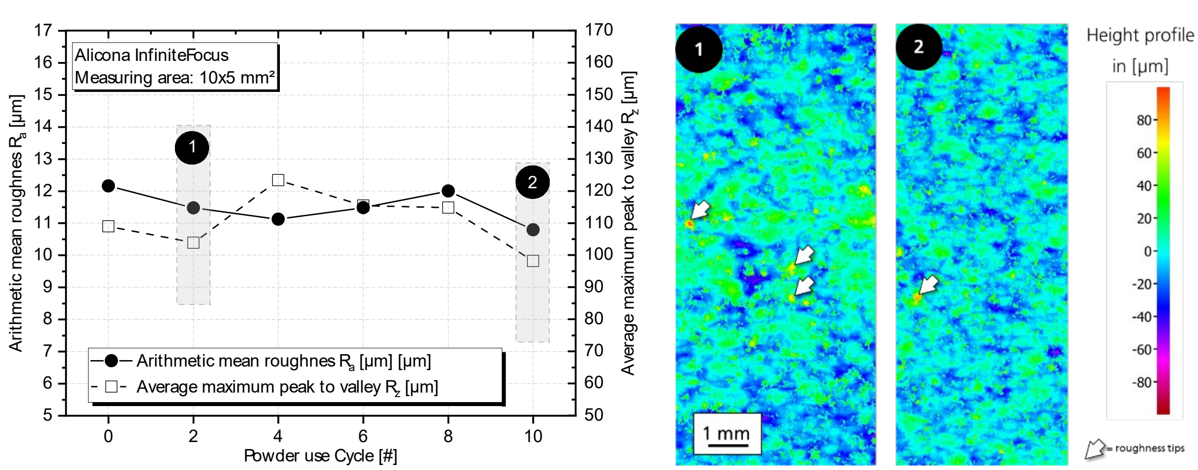


Figure 9. Analysis of the vertical surface roughness for the powder recycling study (left) and examples of surface morphologies for cycle 2 and 10 (right)

Within the next paragraphs, the analysis of the mechanical properties of built samples in the recycling study is given. Mechanical testing is done with non-heat treated, machined samples. Per built direction, a total of four samples is evaluated.

The graphical analysis of yield strength is shown in Figure 10, the data is clustered in vertically and horizontally build specimens. The first observation that can be made is that the horizontally built specimens have a higher yield strength compared to vertically built specimens. This observation is connected to the build anisotropy during manufacturing, leading to higher mechanical strength perpendicular to the build direction of the samples which has been shown in *Machonachie et al*. [16]. This correlation can be observed throughout the recycling study. Second, the data shows an increase in mechanical performance with higher usage of the powder material with peak properties in use cycle 8, where the powder was detected to be coarsest. Moreover, the correlation factor R^2 for the yield strength is given in the figure below. The data of vertical and horizontal specimens show a medium factor of correlation, meaning there is a possible connection of recycling state of the powder material on the yield strength of the build parts. The increase of mechanical properties could be associated with the coarsening of the powder material and increase of flowability within the recycling procedure. Especially for the used LPBF system, where the powder material is transported from a reservoir above the build chamber into the recoater by an spinning axle, increased flowability of the material during recycling might lead to better densification of the powder bed on the build plate and therefore might be associated with higher mechanical properties.

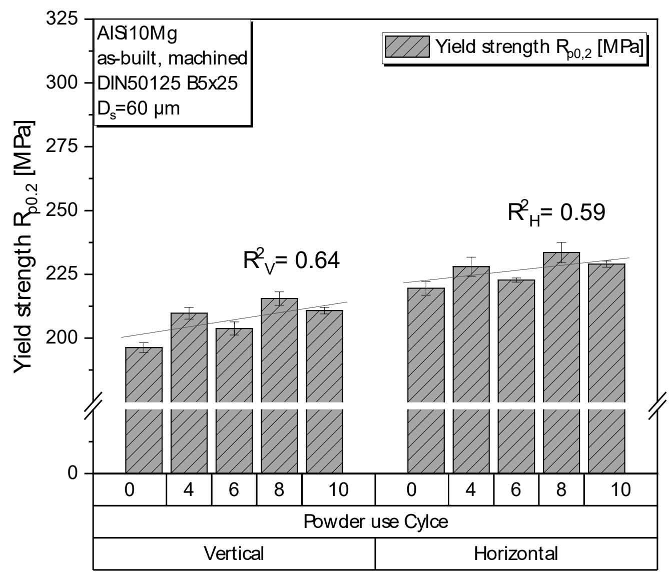


Figure 10. Comparison of yield strength for vertical and horizontal specimens of the recycling study

For further investigation on the correlation of the yield strength on the recycling state of the powder material, an ANOVA (*analysis of variances*) study is performed on the dataset. A Tukey-test with significance level $\alpha = 0.05$ ich chosen. The result of the significance of the recycling study is given in Table 6 for the yield strength. Each powder reuse cycle is compared to one another in regards to statistically significant differences. The **bold** numbers mark these datasets. Special attention should be paid to the diagonal of the ANOVA study, in which use cycle Z is compared to Z-2. For the vertically built specimens, it can be seen that in cycle 10 no significant difference to cycle 8 can be detected. Otherwise, the analysis identifies clear dependencies of the yield strength on the powder recycling state. This connection of dependencies on the other hand is not as clear for the horizontally built specimens, where the data scatters more.

ANOVA study for vertical and horizontal specimen for the recycling study – yield strength										
	Vertical specimen					Horizontal specimen				
	Z0	Z4	Z6	Z8	Z10	Z0	Z4	Z6	Z8	Z10
Z0	-	**0.00015**	**0.00599**	**0.00000**	**0.00000**	-	**0.01572**	0.62930*	**0.00174**	**0.00677**
Z4		-	**0.03027**	**0.03945**	0.97906*		-	0.20406*	0.17125*	0.99179*
Z6			-	**0.00007**	**0.01030**			-	**0.00237**	0.09816*
Z8				-	0.10939*				-	0.33198*
Z10					-					-

Table 4. Results for ANOVA-analysis of powder recycling study for yield strength; "**bold**" indicates significance, "*" indicates no significance

The analysis of the ultimate tensile strength UTS is given in the next few paragraphs. The methodology is identical as shown for the yield strength. As shown for the yield strength, an increase in mechanical performance with higher usage of the powder material can be observed for vertical and horizontal specimens (see Figure 11). Once again, this might be attributed to better flowability characteristics of the powder material due to loss of fine particles with ongoing recycling. Furthermore, the same observation of higher strength for horizontally built samples can be detected as shown before. The factor of correlation R^2 nevertheless is slightly higher compared to the yield strength, indicating a possible hint of higher sensitivity of UTS compared to YS.

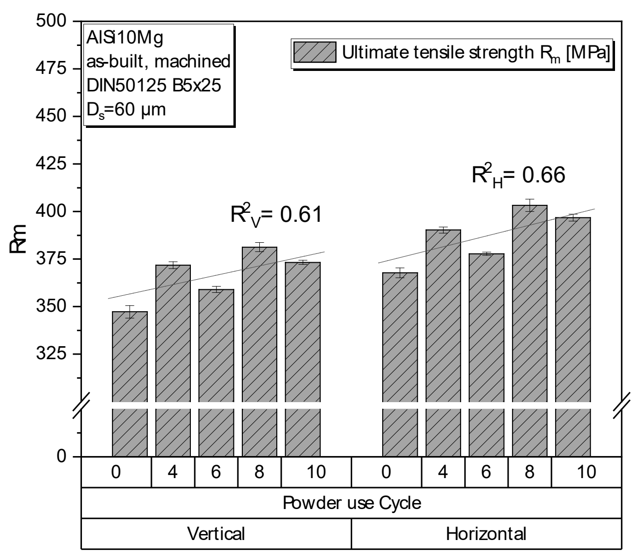


Figure 11. Comparison of ultimate tensile strength for vertical and horizontal specimens of the recycling study

The ANOVA study (shown in Table 8) identifies higher significant differences for the ultimate tensile strength compared to the yield strength. Nevertheless, the raw data however shows that strong fluctuations within the gained data sets can be seen. For example, the sixth recycling use clearly shows lower mechanical performance than cycle four and/or eight (direct neighbors in this study). Therefore, no general conclusion of the recycling influence on mechanical performance can be drawn, but a possible hint of changes in mechanical response to powder use could be identified.

ANOVA study for vertical and horizontal specimen for the recycling study – ultimate tensile strength										
	Vertical specimen					Horizontal specimen				
	Z0	Z4	Z6	Z8	Z10	Z0	Z4	Z6	Z8	Z10
Z0	-	**0.0000**	**0.00006**	**0.0000**	**0.0000**	-	**0.0000**	**0.00041**	**0.0000**	**0.0000**
Z4		-	**0.00002**	**0.0060**	0.90978*		-	**0.00003**	**0.0002**	**0.0175**
Z6			-	**0.0000**	**0.0000**			-	**0.0000**	**0.0000**
Z8				-	**0.00340**				-	**0.0175**
Z10					-					-

Table 5. Results for ANOVA-analysis of powder recycling study for ultimate tensile strength; "**bold**" indicates significance, "*" indicates no significance; V = vertical specimen, H = horizontal specimen

Conclusion and Outlook

Powder recycling/reuse in Laser Powder Bed Fusion allows for higher material usage and therefore higher ecological and economical efficiency. Nevertheless, the recycling of powder material might influence the properties of the powder material as well as the mechanical performance of the part due to changes in powder properties. Within this investigation, AlSi10Mg powder material was used for 11 consecutive cycles in LPBF. This alloy is of special interest to industry due to lightweight applications. A standard build job with defined number of specimens and exposure was developed. The powder properties and mechanical response of built specimens were tested throughout the recycling study in order to identify possible influences in changes and dependencies of powder ageing.

While no significant changes in chemical composition during recycling could be detected, the particle size distribution and flowability of the powder showed clear trends. The particle size became larger with increasing usage of the powder material due to possible loss of fine powder attributed to the shielding gas flow as well as coarsening due to increase of sintered particles in the powder bed. As a consequence, the flowability of the material increased which might be of special interest in regard to the used LPBF machine design where powder material is transported through an axle into the recoater.

When it comes to processability of the ageing powder material, little to no influences on relative density as well as surface roughness and hardness of the material could be identified. Influences of the powder recycling state on the mechanical response of horizontally and vertically built specimens, however, could be detected. An overview of the changes in 10th recycling state to virgin powder material is given in Table 9. While it could be shown that the mechanical performance of horizontally built specimens was higher than vertically specimen due to build anisotropy, the factors of correlation R^2 were lower. Furthermore, an ANOVA study on the mechanical dataset was performed. The study revealed that most of the data showed significant differences. Nevertheless, the low absolute deviations of ~10-30 MPa in mechanical response make it hard to conclude to direct connections between the powder recycling state and the mechanical properties.

	Relative improvement Δ (Z10-Z0) and correlation factor R^2 of yield strength YS and ultimate tensile strength UTS for vertical and horizontal specimen	
	Vertical specimen	Horizontal specimen
Δ Yield strength	14 MPa (+7%)	10 MPa (+4%)
R^2 Yield strength	0.64	0.55
Δ Ultimate tensile strength	26 MPa (+7%)	29 MPa (+7%)
R^2 Ultimate tensile strength	0.61	0.66

Table 6. Overview of change in tensile properties for powder recycling of AlSi10Mg

Even though a clear methodology and investigative approach for powder recycling in LPBF was used, no more than possible trends in influences of powder reuse on the mechanical properties are possible. Since only the two mostly used mechanical properties "yield strength" and "ultimate tensile strength" were used within this study, it could be of further interest in next investigations to identify connections of powder ageing on other mechanical response values like fatigue etc. Furthermore, the recycle limit in the presented study was limited to 10. More influences of powder ageing with higher use cycles might identify cleared trends especially when it comes to the mechanical performance of samples.

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