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Machine-comprehensive study of comparability and reproducibility for laser powder bed fusion of corrosion resistant steel 316L/1.4404

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Abstract

Additive Manufacturing of metallic components by means of laser-based powder bed techniques earns increasing importance for industrial applications due to the increased sustainability resulting from the high resource efficiency and an effective value chain. However, for further industrial penetration different challenges have to be overcome. The most urging challenge is the warranty and control of a constant high quality of the components. This includes the requirement of a reliable good machine-comprehensive comparability of components goodness. Important factors are the respective machine concept, which differs remarkably in inert gas conduction or powder supply, the quality of the powder with its morphological properties, age and storage conditions, as well as the respective system parameters. The results of a standard VDI 3405-2 based round robin test for the steel 316L (1.4404) are discussed, at which five partners with different machines participated. The implementation is not based on ideal conditions, but addresses the respective best practice of the participants, which covers industrial reality at a high degree. Thereby, the differences between included machine concepts and scattering within a manufacturing order is discussed. With this, the existing gap of standardization of properties for laser powder bed fusion of the well-established material 316L/1.4404 shall be closed analogue to a series of other materials within the VDI-standard family 3405. Based on the results obtained, manufacturing processes can be

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designed to be more resource-efficient and thus contribute to the sustainability of the used additive manufacturing processes

Keywords: laser powder bed fusion; steel; reproducibility, round robin test

1. Introduction

The machine concepts currently available on the market for L-PBF processes differ in some design-related aspects. Smurov et al. [1] have analyzed the most common plant concepts with regard to their characteristics.

The developments of the now more than 20 manufacturers of systems for additive manufacturing of metals in powder beds show an increasing diversification in terms of system configuration. Depending on the manufacturing task, there are highly adapted machine types, whereby both the number of laser or optical systems and the build volume vary. Particularly with regard to the size of the build chambers, there is currently a trend towards larger installation space volumes. Currently, systems with a build chamber volume of 250 to 280 mm account for the largest proportion of systems sold [2]. The diversity of system technology described above is accompanied by a wide range of achievable and resulting properties. By Ahuja et al [3] a significantly large variation of the technological properties of six different partners could be explained. Here, both property differences between the components of the different partners and a strong variance within the construction jobs of individual partners were detected. The reasons for the described variance were discussed as the choice of parameters, the orientation or positioning in the build space, the used components of the optical bench and the "aging" of the system over the build job duration. In further experiments conducted by the National Institute of Standards and Technology [4]–[6], a uniform approach was used to specifically exclude influencing variables. Only new powder from one batch was used and the generation of the samples was carried out on identical equipment from one manufacturer with defined process parameters. Nevertheless, significant deviations in the mechanical properties were found. The variance between the different plants was three times that of individual plants. In the recommendations for implementation resulting from the trials [7], the plant characteristics are not taken into account and an experimental procedure for the transferability of process parameters is also not defined.

In this contribution, the results of a round-robin study by means of L-PBF-Processing using the widespread material 316L / 1.4404 are discussed.

2. Methods

2.1. Used machines

The later described build jobs were performed on three different machines:

- TRUMPF TruPrint 3000
- CONCEPT LASER M2 Cusing
- SLM Solutions SLM 250HL

2.2. Platform Design and experimental procedure

To carry out the planned round-robin test, it was necessary to take into account the specimen types, orientations and states required in VDI Guideline 3405 Sheet 2. This resulted in the following specimens for each used L-PBF-machine, each in the as-built condition and in the stress-relieved condition:

- 15 tensile specimens each, machined on all sides (DIN 50125 Form B 5 x 25) in upright, horizontal and 45° orientation
- 4 cubes for hardness measurement and chemical analysis with an edge length of 15 mm
- 4 cubes for metallographic and examinations with an edge length of 10 mm and
- 2 cuboids (10 mm x 10 mm x 50 mm) for surface examinations

For a uniform performance of the round-robin test, it was necessary to develop a platform design that fitted to all used machine setups. For this purpose, the following criteria were considered in order to draw global conclusions on the machine comparability and parameter transferability. The following criteria were taken into account:

- build volume / platform size
- Barrier areas (e.g. screws etc.)
- Coating direction
- Gas flow direction

Furthermore, five platform areas were defined in order to detect local deviations of the resulting property profiles. The described criteria resulted in the platform design shown in Fig. 1.

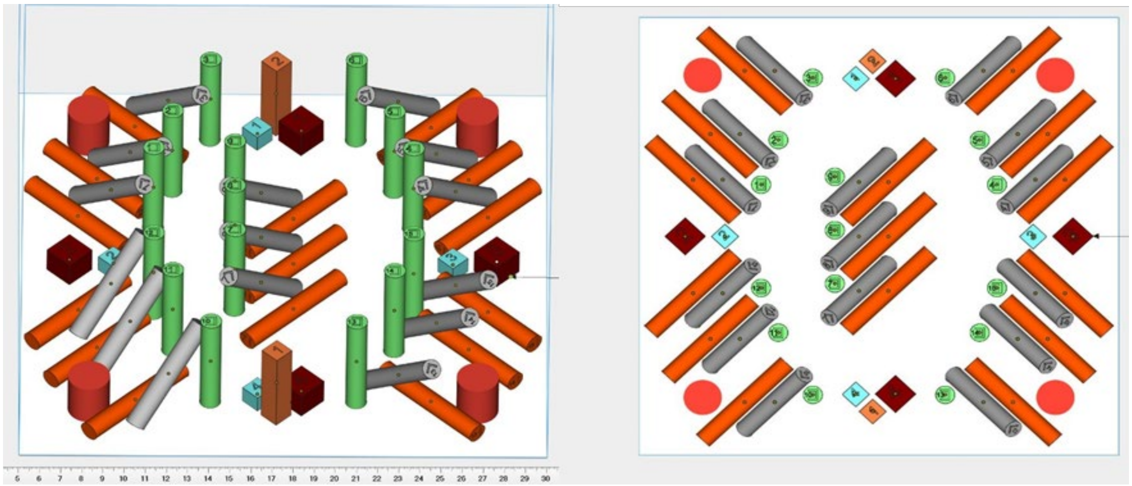

Fig. 1. Platform design for round-robin test (left: ISO view, right: top view)

For the conduction of the build jobs a “best practice” routine was agreed. A separate parameter set with optimized settings concerning laser power, scanning speed, etc. was chosen for each machine. Furthermore the “best running” powder was used for each machine, whether it was virgin powder, used powder or mixture of both.

The heat treatment was a stress relieving heat treatment at 650°C for 30 minutes for each machine specific build job.

2.3. Characterization methods

The powder particle size distribution for the used powder of every participant of the round-robin test was analyzed by laser diffraction particle size analyzer LA 950 by Horiba according to DIN ISO 13320. The apparent densities, ρ_{app}, of the powders were measured by the funnel method according to DIN EN ISO 3923.

The chemical composition of the generated cubes was analyzed by optical emission spectroscopy. The used device was a wavelength-dispersive spectroscope *SPECTROMAXx.* The analysis areas were freshly ground directly before the measurement, 5 individual analyses were prepared in each case and the mean, minimum and maximum values were determined.

Density of cuboid test samples was evaluated by Archimedean principle using a balance and by metallographic method using a light microscope. For metallographic density determination the samples were metallographically prepared by a standard routine. Afterwards, 12 images from different positons of the samples cross section were recorded by 10x-objective and the porosity (density) of the individual images was determined by grey level analysis. The given values of density represent the respective mean value of every sample and their standard deviation.

After machining the raw samples to samples according to DIN 505125 B 5x25, tensile tests were carried out in order to determine the mechanical properties according to DIN EN ISO 6892-1 using a Zwick Z1476 testing machine.

3. Results

3.1. Powder characteristics

The results of the powder characterization are shown in Table 1. All powders fulfill the requirements of laser powder bed fusion, although they differ in their characteristics: the finest powder with the narrowest distribution – the range between d_{10} and d_{90} value – was used on the M2 Cusing machine. This powder shows also the lowest apparent density. The coarsest powder was used on the TruPrint 3000. A medium coarse powder with a broad distribution was used for manufacturing on the SLM 250^{HL}. The powders on the TruPrint 3000 and SLM 250^{HL} show only weak differences in apparent density.

Table 1. Properties of the powder, which was used from by the participants of the round robin test

Used machine	d_{10} / µm	d_{50} / µm	d_{90} / µm	ρ_{app} / g/cm^3
TruPrint 3000	28,7	41,3	53,8	4,46
M2 Cusing	20,1	28	39,6	4,02
SLM 250^{HL}	21,2	31,7	50,6	4,33

3.2. Chemical Analysis

The results of the chemical analysis for the as-built samples and heat-treated samples are summarized and compared to standard values for the material 316 / 1.4404 in Table 2 and 3.

For all tested samples, there was good agreement with the standard. Only slight deviations in the molybdenum content were found for one machine type, which can be a result of the used powder.

Table 2. Chemical composition in as-built state

wt%	**C**	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Cu**	**N**	**Fe**
MAX	0,028	0,74	1,25	0,020	0,0106	17,42	2,58	12,89	0,0502	0,0409	67,1
MEAN	0,020	0,68	0,93	0,017	0,0086	16,98	2,48	12,33	0,0374	0,0357	66,3
MIN	0,016	0,60	0,68	0,014	0,0063	16,62	2,39	11,60	0,0263	0,0284	65,6
STANDARD	0,030	1,00	2,00	0,045	0,0150	16,5-18,5	2,00-2,50	10,0-13,0	-	0,1000	Balance

Table 3. Chemical composition in heat-treated state

	C	**Si**	**Mn**	**P**	**S**	**Cr**	**Mo**	**Ni**	**Cu**	**N**	**Fe**
MAX	0,021	0,74	1,30	0,022	0,0131	17,33	2,58	12,73	0,0770	0,0404	67,1
MEAN	0,018	0,66	1,00	0,018	0,0093	16,94	2,44	12,18	0,0478	0,0357	66,5
MIN	0,016	0,58	0,80	0,014	0,0071	16,55	2,35	11,52	0,0264	0,0284	66,1
STANDARD	0,030	1,00	2,00	0,045	0,0150	16,5-18,5	2,00-2,50	10,0-13,0	-	0,1000	Balance

3.2. Density

The results of the density measurements on cuboid test samples are summarized in Table 4. Samples, which were manufactured by “best practice parameter” at the M2 cusing machine, show a smaller density than the samples from the two other machines. Furthermore, Archimedean and metallographic densities differ remarkably, i.e. the metallographic density is more than 1% higher for all machines than the Archimedean density. It is believed, that metallographic density gives more reliable results, although it covers only a 2-dimensional section of the sample. The reason is, that small disturbances in the Archimedean density measurements, e.g. presence of small air bubbles at the rough sample surface, might cause a reduced density and this error is more serious for samples with a density close to the theoretical value, which is the case here. In conclusion, all studied machine set-ups are suitable to achieve densities close to the theoretical value.

Table 4. Results of Archimedean and metallographic density measurements for the 3 LPBF machines

Maschine type	Archimedean density / gcm^{-3} (%)	Metallographic density / %
TRUMPF TruPrint 3000	7,89-7,9 (98,7-98,8)	99,98 ± 0,03
M2 Cusing	7,87-7,89 (98,4-98,7)	99,84 ± 0,13
SLM Solutions SLM 250^{HL}	7,88-7,9 (98,5-98,8)	99,96 ± 0,06

3.3. Mechanical properties

The mechanical properties of tensile test coupons, which were manufactured on the different machines, are summarized in Tables 5-7. Furthermore, the respective standard deviations are added for comparison. All investigated beam melting machines fulfill the requirements of mechanical properties, i.e. reach or even exceed the properties for conventionally manufactured 316L/1.4404 material.

Table 5. Mechanical properties and their standard deviations for 316L/1.4404 test samples manufactured using a TruPrint 3000 machine

	As-built			Heat-treated			Conventionally manufactured [8]
	0°	45°	90°	0°	45°	90°	
Young's Modulus in GPa	154 ± 18	199 ± 32	155 ± 16	171 ± 22	209 ± 46	154 ± 10	
Yield strength $R_{p0,2}$ in MPa	456 ± 8	531 ± 16	505 ± 4	424 ± 6	482 ± 12	466 ± 4	400
Tensile strength R_m in MPa	574 ± 8	649 ± 20	636 ± 4	583 ± 6	653 ± 18	642 ± 6	600 to 930
Elongation at break A_t in %	41,0 ± 5	42,0 ± 5	31,0 ± 1	40,0 ± 3	39,5 ± 3	32,5 ± 1	25

The chosen build job layout was developed to identify possible positions in the building space of the respective machines for whom the mechanical properties show a systematic deviation. For the present case no such positions could be identified for the used machine set-ups and it is concluded, that high performance parts can be manufactured independently from their position at the built platform within the specifications.

Although no position-specific variation of mechanical properties was observed for the studied machines, we noticed some differences between the respective machines.

The mechanical properties show a distinct anisotropy in dependence from the sample orientation. This process-inherent phenomenon is caused by directional heat removal against the building orientation, which causes a directional solidification. Typically, samples in 0° orientation (standing) show the highest ductility and lowest strength, while samples in 90° orientation (lying) behave vice versa and 45° oriented samples lie between both. This is the case for samples, which were manufactured using a M2 Cusing or SLM 250^{HL} machine (Tables 6 and 7) but not observed for the manufacturing at a TruPrint 3000 machine (Table 5), where the 45° oriented samples combine the highest strength and good ductility. Stress relieving heat treatment leads to an increase of tensile strength and a reduction of yield strength and ductility in all cases.

In addition, samples, which were manufactured on the M2 Cusing machine, show the highest tensile strength, approximately 50 to 100 MPa more than for samples from TruPrint 3000, although the achieved density was slightly lower. The scattering of mechanical properties within one build job for manufacturing on M2 Cusing and SLM 250^{HL} is comparably low, which is visible in the low standard deviation for yield strength, tensile strength and elongation at break (Table 6 and 7). The TruPrint 3000 machine shows a moderate increase scattering for elongation at break and yield strength and tensile strength in 0° and 90° orientation. However, for samples, which were manufactured in 45° orientation on TruPrint 3000, a significantly increased standard deviation is observed for yield strength and tensile strength.

Table 6. Mechanical properties and their standard deviations for 316L/1.4404 test samples manufactured using a M2 Cusing machine

	As built			Heat treated			Conventional manufactured [8]
	0°	45°	90°	0°	45°	90°	
Young's Modulus in GPa	160 ± 10	191 ± 20	197 ± 22	192 ± 20	201 ± 16	216 ± 16	
Yield strength $R_{p0,2}$ in MPa	520 ± 2	594 ± 2	610 ± 4	492 ± 10	552 ± 20	572 ± 4	400
Tensile strength R_m in MPa	624 ± 4	689 ± 6	718 ± 6	636 ± 6	702 ± 12	733 ± 4	600-930
Elongation at break A_t in %	40,5 ± 2	37,0 ± 3	35,0 ± 1	34,5 ± 3	33,5 ± 2	32,5 ± 1	25

Table 7. Mechanical properties and their standard deviations for 316L/1.4404 test samples manufactured using a SLM Solutions SLM 250^{HL} machine

	As built			Heat treated			Conventional manufactured [8]
	0°	45°	90°	0°	45°	90°	
Young's Modulus in GPa	180 ± 20	187 ± 26	184 ± 14	189 ± 14	194 ± 18	191 ± 16	
Yield strength $R_{p0,2}$ in MPa	509 ± 8	549 ± 6	541 ± 10	461 ± 4	488 ± 4	493 ± 6	400
Tensile strength R_m in MPa	602 ± 8	646 ± 8	650 ± 8	607 ± 6	647 ± 8	661 ± 6	600-930
Elongation at break A_t in %	47,0 ± 3	40,0 ± 2	36,0 ± 3	46,0 ± 2	39,0 ± 2	36,0 ± 2	25

4. Conclusion

The preliminary results of a round-robin test for the 316L/1.4404 stainless steel are presented at which three partners with different machine set-ups participated. The involved machines are a TruPrint 3000 by Trumpf, a M2 Cusing by Concept Laser and a SLM 250^{HL} by SLM Solutions. The implementation of the round-robin test is based on the standard VDI 3405-2, but the arrangement of the test samples was modified to allow the identification of positions with potential deviating properties. The implementation of the round-robin test by every partner is based on the individual "best practice", which includes a free choice of used manufacturing parameters and powder (fresh powder, used powder, mixture of both). Differences in chemical compositions of the final parts were observed, which could be attributed to variable compositions of the used powder batches. Comparable density values were obtained by the 3 studied machines, but the resulting mechanical properties differ remarkable in the as built condition and after additional stress relieve heat treatment.

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