Binder Jetting of 316L process simulation tools evaluation

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ABSTRACT

Binder Jetting has become one of the most popular Additive Manufacturing technologies over the years due to its low cost and fast production times, nevertheless this technology has a steep learning curve due to the shrinkage induced to parts during sintering. Since shrinkage is not uniform along the part, it's hard to efficiently determine what areas will be distorted hence this needs to be taken into consideration when designing a new part and many iterations need to be printed until dimensional accuracy is achieved, as a result production time and cost significantly increase. New Binder Jetting simulation tools are being developed and tested; this software will help the technology be more robust and user-friendly for the industry. The software computes a sintering simulation and can provide displacement results making support positioning more efficient, in addition, newer versions of the software can export a compensated model which will be able to be sintered without supports. To evaluate the simulation software, a dimensional test artifact model was designed and printed, then compared with the software predicted model simulation results. The simulation software was used in an initial evaluation of the test artifact geometry to identify areas of concern in the model and document them so efficiency when predicting material behavior during the sintering process can be evaluated. In addition, an evaluation of the effects of different sintering process parameters on the physical and mechanical properties of the material will be analyzed considering the inert sintering atmosphere of the process. Finally, printing parameters of the machine such as layer thickness, binder saturation, and recoat speed among others will also be evaluated.

INTRODUCTION

Metal Additive Manufacturing is an important technology that enables the production of complex-shaped components and structures with high mechanical properties and a minimal material loss, which is a gradually improving the manufacturing sector [1]. Binder Jetting is an additive manufacturing technology that became popular in the early 1990s, it receives interest from the industrial communities because it allows the manufacturing of complex shaped components without involving the melting of the material and rapid solidification that can induce defects producing unwanted results [2].

The Binder Jetting process consists of binder droplets being selectively deposited onto the powder bed, the powder with binder mix is then quickly cured and then another layer of metal powder is deposited on top of the previous layer, this process is repeated until the pre-liminary part called green part is completed. The green part then proceeds to be cured for 4 hours and then is carefully depowdered since it can easily break because the particles are not properly joined together yet. To join the particles together, the green part will be subjected to a sintering process under an inert atmosphere to avoid oxidation, this process will properly bind together the metal particles.

SIMULATIONS

Simufact Additive is a powerful simulation software of metal additive manufacturing, recently, its manufacturer Hexagon added a new function to simulate the sintering process in Binder Jetting parts; distortion, shrinkage, residual stress, and temperature results can be provided by the software. The software can also predict and compute a compensated model to counter the distortion on the printed part, producing a final product without the need of many iterations [4].

Sintering Profile

Predefined time and temperature values were used, nevertheless material and green density of the printed part had to be manually inputed. Once the software has all the required information, the simulation will provide a result similar to the one that can be provided by an actual sintering process.

Meshing

The mesh of the analyzed geometry is shown on the Figure 1, the overall dimensions of the artifact are 50 x 17 x 12 mm, the average element size is about 3 mm. This element size is based on the previous knowledge learned with simulations on the same software.

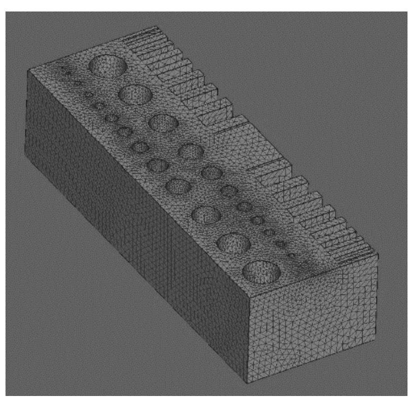


Figure 1. Finite element mesh of the artifact design

MATERIALS AND METHODS

Powder

The powder feedstock used in this printing work was gas-atomized 316L stainless steel supplied by Sandvik Osprey Powders with a spherical shape and a size range of 38 ± 5 microns, chemical composition is reported in Table 1.

	Fe	C	Si	Mn	P	S	Cr	Ni	Mo
316L	Balance	≤ 0.030	≤ 1	≤ 2	≤ 0.045	≤ 0.03	16-18	10-14	2-3

Table 1. Chemical composition (wt%) of the used Stainless steel 316L powder

The powder goes through a process of optical characterization using a CAMSIZER X2 Microtac Retsch that provides precise particle size and shape information of powders in a measuring range from 0.8 µm to 8 mm, Figure 2 shows that Xc min displays the particle width, which is determined from the narrowest of all measured chords Xc, this characteristic is comparable with a sieve analysis [5].

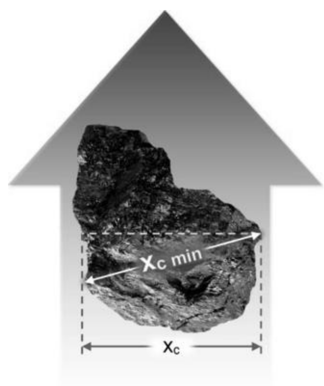


Fig 2. Size definition of a particle

To define the shape of the particle the compactness must be calculated, this is determined by the particle length Xfe max and the particle area A. Generally, perfect circles or spheres have a compactness equal to 1, for all other shapes the compactness is < 1. The shape definition equation is calculated using Equation 1.

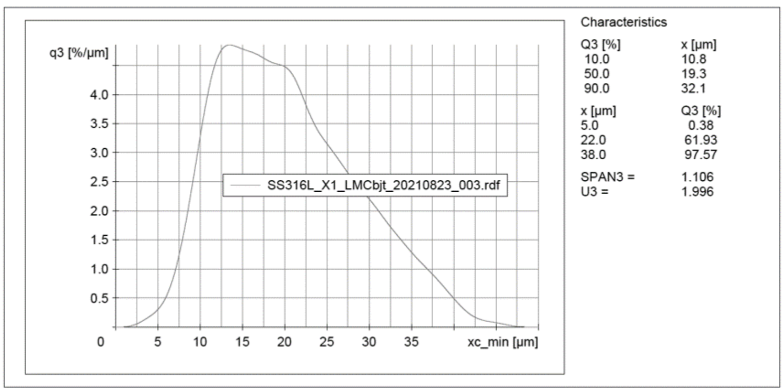
$$Compct = \frac{\sqrt{\frac{4A}{\pi}}}{x_{Fe\ max}}$$

Eq 1. Calculation of the Compactness

The results of the size analysis are shown in Table 2 and Graph 1, the stock powder had a particle size distribution of D10: 10.8 µm, D50: 19.3 µm, and D90: 32.1 µm.

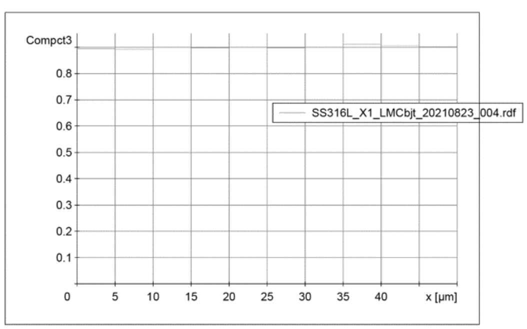
Size class	[µm]	p3 [%]	Q3 [%]	1-Q3 [%]	q3 [%/µm]	xc_min3	Compct3
0.0	5.0	0.38	0.38	99.62	0.076	4.2	0.895
5.0	10.0	6.74	7.12	92.88	1.348	8.5	0.892
10.0	15.0	22.89	30.01	69.99	4.578	12.6	0.900
15.0	20.0	23.14	53.15	46.85	4.628	17.5	0.897
20.0	25.0	19.26	72.41	27.59	3.852	22.3	0.896
25.0	30.0	13.29	85.70	14.30	2.658	27.4	0.894
30.0	35.0	8.70	94.40	5.60	1.740	32.3	0.899
35.0	40.0	4.50	98.90	1.10	0.900	37.1	0.899
40.0	45.0	0.99	99.89	0.11	0.198	41.6	0.904
45.0	50.0	0.10	99.99	0.01	0.020	45.6	0.855
> 50.0		0.01	100.00	0.00	0.000	76.7	0.911

Table 2. Size definition of the powder



Graph 1. Size distribution of the powder

The results of the shape characterization are shown in the Graph 2.



Q3 (b/l=0.9) = 68.76 %

Graph 2. Shape characterization of the powder

Finally, the powder was analyzed with a JSM-IT500 Scanning Electron Microscope [6] to observe particle shape under a microscope with a magnification of 50 μm, 20 μm and 5 μm in the Figures 3, 4 and 5, respectively.

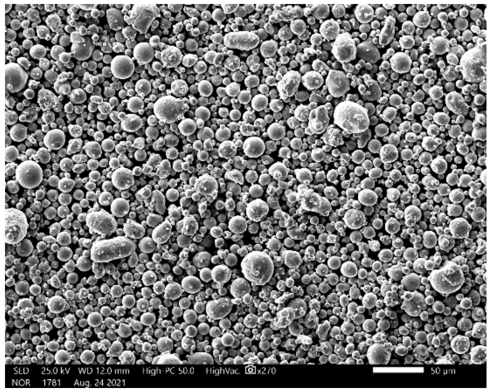


Figure 3. Microscope picture of 316L powder taken SEM Machine with a magnification of 50 μm

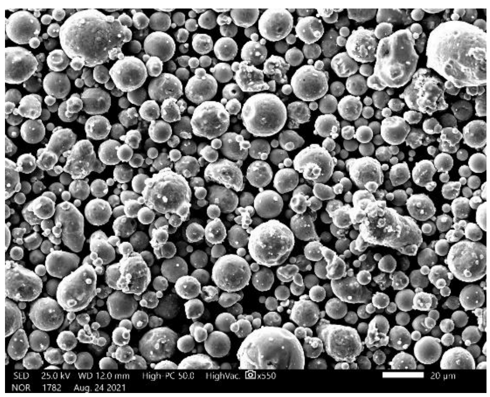


Figure 4. Microscope picture of 316L powder taken SEM Machine with a magnification of 20 μm

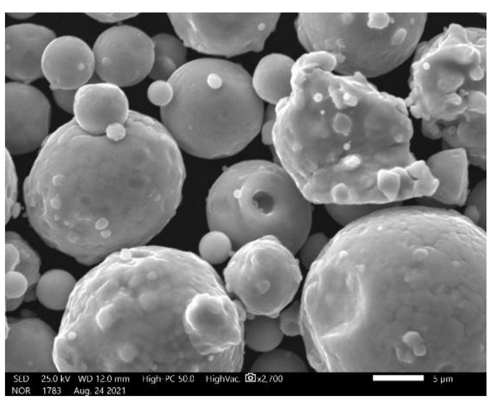


Figure 5. Microscope picture of 316L powder taken SEM Machine with a magnification of 5 μm

Printing Process

The samples were printed using an Innovent+ metal 3D printing system manufactured by ExOne in 2018 as an upgrade version of the Innovent released in 2016, with a build volume of 160 x 65 x 65 mm [7]. The binder used was an aqueous-based solution provided by ExOne containing monobutylether, isopropanol and ethylene glycol. The first two evaporate during the curing while the ethylene glycol cross-links producing PEG [8].

The printing parameters used for this build are reported in Table 3. These parameters have been selected based on previous printing experience.

Drying Time (s)	Bed Temperature (°C)	Recoat Speed (mm/s)	Roller Rotation Speed (rpm)	Roughing Roller Rotation Speed (rpm)	Roller Traverse Speed (mm/s)
10	40	35	600	300	10

Table 3. Printing Process Parameters

After the model is fully printed, a curing process was carried out at 200 °C for 4 hours in air using a Yamato DX402C furnace.

Post Process Sintering

Sintering bonds metal particles via mass transport mechanism and bring them to a denser state [9]. The loss of free surface energy during the sintering process can be explained by surface and bulk transport mechanisms. Surface transport methods do not cause densification, bulk transport processes, on the other hand, cause neck expansion as well as shrinkage [10].

For the sintering process we used a Carbolite Gero Model CTF12/TZF12 tube furnace in Argon atmosphere at 4 different temperatures, first, the temperature was raised at a rate of 5 °C per minute until 600 °C was reached, then it stays at that temperature for 30 minutes, the temperature is then increased at the same rate until it reaches 1000 °C and stays at that temperature for 2 hours, after this, temperature was increased to the final temperature of 1410 °C with a rate of 5 °C, and stays at that temperature for another 2 hours, finally, we decreased the temperature at a controlled rate, this slow decrement in temperature avoids drastic deformations on the part.

Figure 6 shows the graph of the sintering profile, with a graphic demonstration of temperature against time.

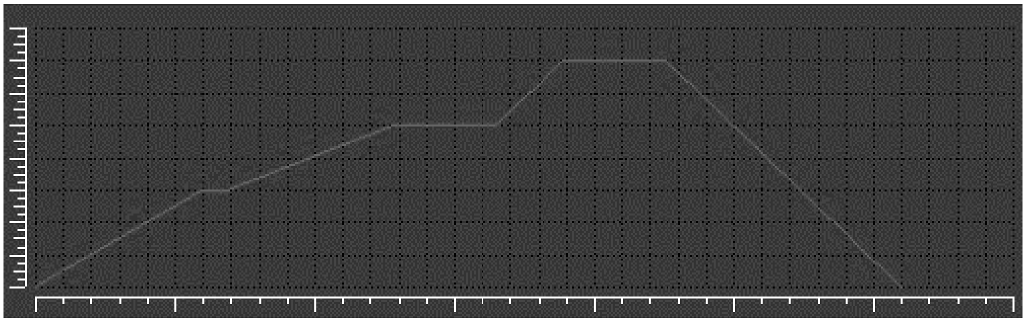


Figure 6. Graph of the Sintering Process of Time against Temperature. Same one used for the Simufact simulation

RESULTS AND DISCUSSION

Simulation Results

Simulation results predicting shrinkage and deformation of the part are shown in Figure 7, and the real sintered part is shown in Figure 8, comparing these two figures, is clear that the simulated part has more deformation in the front face of the design, the hole and fin features also have greater deformation compared to the sintered part, the features got reduced by 12% of the initial dimension on the x direction. In addition, the part has a significant distortion in the thin walls, and some eventually broke due to this distortion. The difference in our results can be due to several factors, such as the shape of the ceramic crucible on which the part was sitting during the sintering, this affects how the gas flow hits the green part and sintering orientation which varies the distribution of heat on the surface of the place with the surface of the green part.

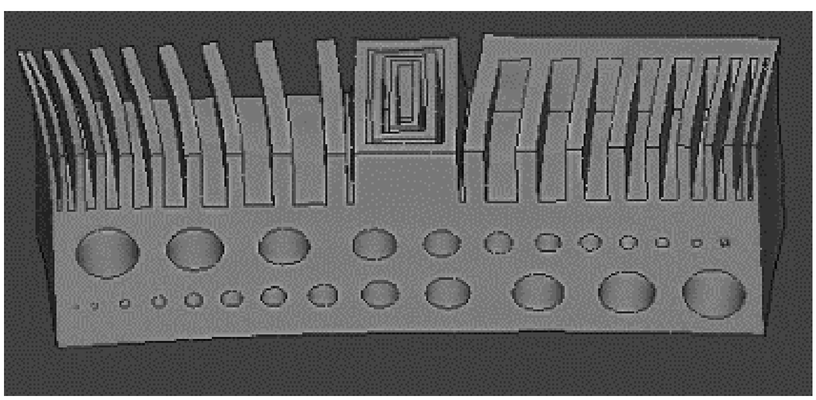


Figure 7. Simulation of the original part on the Simufact Software

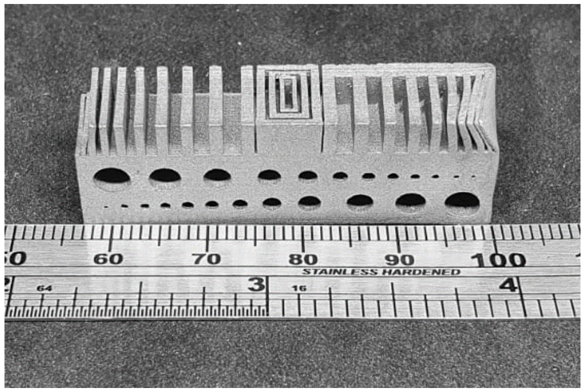


Figure 8. Sintered part before the compensation

The compensated part showed dimensional changes, shown in Figure 9. A dimensional change of 50 mm to 59 mm along the x direction was done to counter shrinkage and deformation of the part. Figure 10 shows the dimensional change and the quality in the fin features once the part has been subjected to the sintering process.

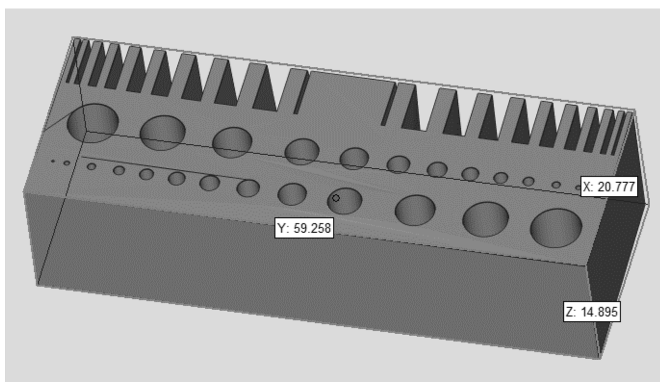


Figure 9. Compensated part with the new dimensions

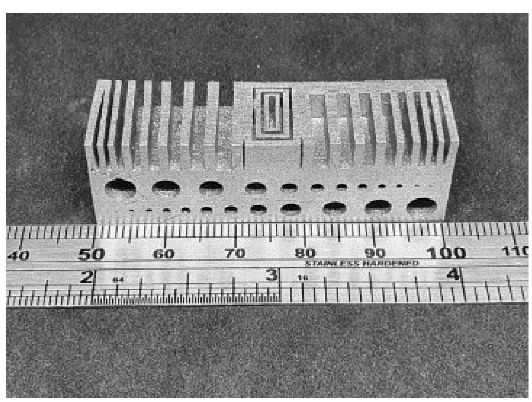


Figure 10. Sintered part with the compensated dimensions

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