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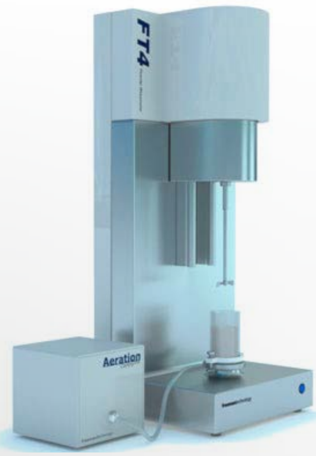
DEVELOPING AN ADDITIVE MANUFACTURING SUITABILITY (AMS) FACTOR: EFFORTS TOWARDS A GENERIC APPROACH TO DETERMINING PRINTABILITY

POWDER FLOW

Those working with powders in AM processes routinely need to answer the question "Can I print with this?" Researchers developing new materials, manufacturers assessing alternative supplies, and engineers optimising a powder production process or recycling strategy all benefit from being able determine processability without running a print trial. A powder that processes well won't necessarily result in high quality finished components but it's an important first step towards success.



FT4 Powder Rheometer

There are signs of emerging consensus with respect to key elements of a specification that can answer this question, notably the need for multiple bulk powder properties including parameters that can adequate describe flowability and spreadability. Here, we discuss work by researchers at the Ecole de Technologie Superieure (Montreal, Canada) to define an AM Suitability (AMS) factor and the subsequent use of this concept by researchers from Oerlikon AM (Feldkirchen, Germany). This work provides evidence of the potential to use dynamic, shear and bulk properties, all measured with the FT4 Powder Rheometer® (Freeman Technology, Tewkesbury), to confirm printability.

Establishing an AMS

Researchers at the Ecole de Technologie Superieure[1] studied the performance of three commercial supplies of Ti-6Al-4V in a laser powder bed fusion (LPBF) printer (M280, 400 W, EOS GmbH, Munich, Germany). Powder lots produced by gas atomization (Powder 1) and by plasma atomization (Powders 2 and 3) were carefully chosen to enable independent investigation of the impact of particle size and shape. **Table 1** shows particle size and sphericity for each of the powders as determined by computer tomography (CT - XT H225 X-ray µ-CT, Nikon, MI, USA). Powder 1 and 2 are similar with respect to particle size and distribution while Powder 3 is finer, with a broader span. The greater sphericity of Powder 2 and 3, relative to Powder 1, is directly attributable to production route.

Powder Characteristics		Powder 1	Powder 2	Powder 3
Particle size distribution	D_{10}	25.3	25.9	20.3
	D_{50}	35.8	36.7	32.7
	D_{90}	46.4	50.3	43.9
	Span [6]	0.59	0.66	0.72
Sphericity	D_{10}	0.46	0.64	0.55
	D_{50}	0.79	0.93	0.84
	D_{90}	0.91	0.97	0.93
	Mean	0.73	0.88	0.79
	Std Deviation	0.18	0.15	0.16
	Span [6]	0.57	0.35	0.45

Table 1: Powder lots were chosen to enable the independent investigation of particle size and sphericity - Powder 3 has a broader particle size distribution centred on a finer size; Powder 1 is manufactured by gas atomization which produces less spherical particles than plasma processing (Powders 2 and 3).

Bulk powder properties were measured to determine how differences in particle size and shape might impact print performance. In LPBF processes, printing high quality parts with minimal porosity relies on the rapid formation of thin, dense, uniform powder layers during recoating, with minimal disturbance to emerging parts and surrounding loose powder. From the parameters measurable with the FT4 Powder Rheometer the researchers identified seven properties of relevance (see **Table 2**): the dynamic properties of Basic Flowability Energy (BFE), Specific Energy (SE) and Aerated Energy (AE); the bulk properties of compressibility (Compressibility Index – CI), permeability, and Bulk Density (ρ_c), and the shear property, Cohesion coefficient (c).

	Criterion	FT4 Indices
Powder Bed Density	Good Packing Ability	↑ Conditioned Bulk Density (ρ_c)
		↓ Compressibility (CI)
	Low Entrapped Air	↑ Conditioned Bulk Density (ρ_c)
		↓ Compressibility (CI)
	Good Ability to Release Entrapped Air	↑ Permeability (↓PD)
Powder Bed Uniformity	Low Tendency to Agglomerate	↓ Aeration Energy (AE)
	Low Mechanical Interlocking	↓ Specific Energy (SE)
		↓ Cohesion Coefficient (c)
	Low Resistance to Flow	↓ Specific Energy (SE)
Minimal Disturbances		↓Basic Flowability Energy (BFE)

Table 2: Multiple properties measurable with the FT4 Powder Rheometer can be directly related to characteristics of relevance to LPBF processability.

Figure 1 shows values of these properties for each of the three powders in the form of a radar plot. Data are normalised to the maximum value measured across all three lots, permeability is expressed in the form of Pressure Drop (PD) and Bulk Density as specific volume. In this form lower values of all the properties are advantageous and minimising enclosed area identifies powders with the best properties. Powders 2 and 3 are clearly identified as superior to Powder 1.

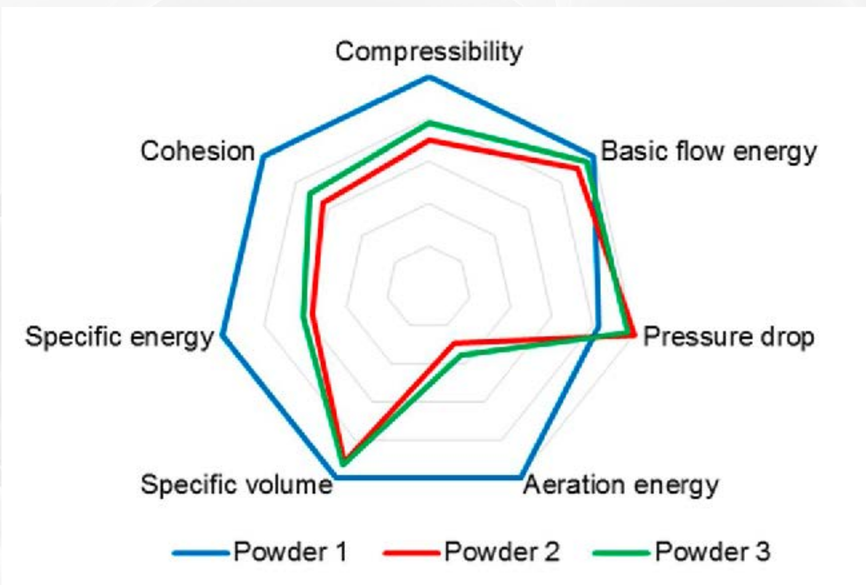


Figure 1: A radar plot of relevant properties for each of the three powder lots illustrates the similarity of Powders 2 and 3; Powder 1 which is significantly different.

An AMS factor was defined to mathematically express the same approach and calculated for each powder (see **Table 3**).

	Powder 1	**Powder 2**	**Powder 3**
AMS	0.975 ± 0.09	0.717 ± 0.01	0.759 ± 0.04

Where:

$$AMS = \left(\frac{1}{\rho_c} + CI + PD + SE + AE + BFE + c\right)/7$$

Table 3: AMS factor values summarise and quantify difference between the powders making them a valuable tool for supply comparison.

These values identify Powder 2 as the best powder (lowest AMS value) and suggest that for this set of powders, shape has a more dominant impact than size. Powders 2 and 3 exhibit closely similar properties, despite their differences in particle size, and the substantially worse score of Powder 1 is directly attributable to its irregular shape.

The printing performance of the three powders was assessed in trials at two powder layer thicknesses (30 and 60µm) by measuring powder bed density measurement, part density, surface finish, minimum printable design features, and tensile strength. A full discussion of these data is beyond the scope of this note but, in summary, the results show that Powder 2 produces denser powder beds and printed parts with superior properties, relative to the other two lots. An important finding is that although differences in the quality of finished components showed less variability than rheological properties, parts printed with Powders 2 and 3 using a layer thickness of 60µm showed comparable properties to those printed with Powder 1 using a layer thickness of just 30µm. This illustrates the potential to increases processing rate through the selection of Powder 2 and 3 and suggests that AMS rankings have real value for supply comparison.

In this study powder flowability was also assessed via traditional techniques, by both Hall and Gustavsson flow meter and by tapped density methods, Hausner Ratio and Carr's Index. All these methods ranked the powders identically with respect to flowability. However, tapped density methods provided minimal differentiation, classifying all three powders as 'excellent'. Furthermore, while Hall flowmeter testing suggested minimal difference between Powder 2 and Powder 3, Gustavsson flowmeter data suggests close similarity between Powder 3 and 1. None of these methods provide insight into how changes in particle size and shape influence specific powder properties such as packing behaviour to elucidate the recoating process.

In contrast, the AMS factor approach:

- provides a sensitive and relevant differentiator of the value of different supplies
- supports the development of a more fundamental understanding of how particle size and shape impact a range of properties that define performance
- can be measured for all powders
- offers opportunity for further refinement for example by tailoring weightings for more sensitive performance differentiation.

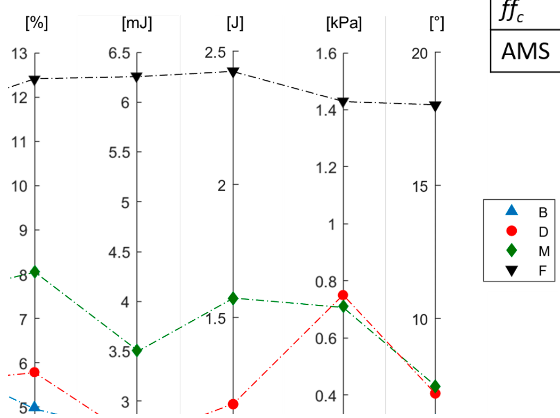
Using the AMS Factor

A team led by researchers from Oerlikon referenced and adopted this same AMS factor approach to assess the processability of blends for in situ alloying in an LPBF process[2]. There is exciting scope to use LBPF to create new materials by alloying metals as printing proceeds. The chemistry is complex but the need to identify powder blends that will process well is strictly analogous to standard LBPF processes and a vital aspect of blend optimisation. A modified AMS factor, AMS' was used to rank four different blends: Blend B is a baseline blend of two commercial alloys, Inconel 718 and CoCr75, while D, M and F contain elemental fines including Co and Cr of different size and morphology.

The AMS' factor defined by this team uses six parameters, omitting permeability and AE measurements, replacing BFE with Consolidated Flow Energy (CFE), a related dynamic property, and using Unconfined Yield Strength (UYS) values previously measured with a Schulze shear cell in place of c. Wall Friction Angle (WFA), an additional shear property, is also included see below:

$$AMS' = (1 / CBD + CI + SE + CFE + UYS + WFA).1 / 6$$

Figure 2/Table 5 shows the recorded measurements along with calculated values of AMS' and flow function coefficient (ff_c), a parameter derived exclusively from shear cell data that classifies flowability. On the basis of ff_c values, Blend B is classified as free-flowing (ff_c>10), Blend M and D as easy flowing (ff_c of between 4 and 10) and blend F as cohesive (ff_c of between 2 and 4). AMS' ranks the suitability of the blends in the order B > D > M > F.



Values in [a.u.]	Blend B	Blend D	Blend M	Blend F
ff_c	12.86 ± 0.33	4.91 ± 0.30	4.91 ± 0.10	2.84 ± 0.02
AMS	0.41 ± 0.02	0.49 ± 0.03	0.55 ± 0.01	0.96 ± 0.02

Figure 2/Table 4: Measuring multiple properties and determining an AMS' factor enables a robust assessment of processability; dynamic and bulk properties differentiated blends (D and M) that were indistinguishable by shear cell analysis alone.

These researchers directly highlight the limitations of simple techniques such as Hall Flow Index for assessing the suitability of complex, heterogeneous, elemental blends, and, conversely, the value of shear, dynamic and bulk testing for the more detailed elucidation of behaviour. It is noted that while shear data fail to differentiate blend D and M, bulk and dynamic properties are particularly distinct for these two samples, illustrating the benefits of a multi-technique approach. The AMS' figure usefully summarises all relevant properties and is confirmed as a 'reliable indicator for processability'. The trend in AMS' was found to correlate with increasing levels of fines in the blends but morphology also influences the results. While Blend F has the highest level of fines it also consists predominantly of irregularly shaped particles, exhibiting far lower sphericity than the other lots, helping to explain its outlying behaviour.

As in the previous study there is discussion of the opportunity to refine AMS', weighting the terms differently on the basis of their relevance, where established. However, in this application, chemistry is a substantially complicating factor in the development of robust links between powder rheology and the properties of printed components.

Conclusion

These studies illustrate the potential to combine multiple powder properties, as measured with the FT4 Powder Rheometer, to determine a single figure of merit quantifying suitability for AM. Dynamic, shear and bulk properties all have relevance when it comes to quantifying behaviours that impact printability such as flowability, packing efficiency, ability to release air and compressibility. By taking account of multiple relevant properties the AMS factor provides a robust assessment of processability that can be used to assess the likely impact of changes in particle size and morphology, successfully differentiate supplies and identify materials with superior performance.

References

[1] S.E. Brika et al 'Influence of particle morphology and size distribution on the powder flowability and laser powder bed fusion manufacturability of Ti-6Al-4V alloy. Additive Manufacturing 31 (2020) 100929

[2] M.S. Knieps et al 'In situ alloying in powder bed fusion: The role of powder morphology' Mat Sci and Eng A, 807 (2021) 140849

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