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Analysis and recycling of bronze grinding waste to produce maritime components using directed energy deposition

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Abstract

Additive manufacturing promises a high potential for the maritime sector. Directed Energy Deposition (DED) in particular offers the opportunity to produce large-volume maritime components like propeller hubs or blades without the need of a costly casting process. The post processing of such components usually generates a large amount of aluminum bronze grinding waste. The aim of the presented project is to develop a sustainable circular AM process chain for maritime components by recycling aluminum bronze grinding waste to be used as raw material to manufacture ship propellers with a laser-powder DED process. In the present paper, grinding waste is investigated using a dynamic image analysis system and compared to commercial DED powder. To be able to compare the material quality and to verify DED process parameters, semi-academic sample geometries are manufactured.

Keywords: Additive Manufacturing; Directed Energy Deposition; Recycling; Powder Analysis; Maritime Components

1. Introduction

Metal additive manufacturing is widely used in the industry to manufacture near-net-shape, complex components. The most important metal AM technologies such as Laser Powder-bed Fusion (L-PBF) or Laser-Powder Directed Energy Deposition (DED) mostly use gas-atomized metal powders (Gibson et al. 2021). While AM technologies in general offers possibilities for sustainability, the production of the feedstock powders is

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linked to a high energy consumption which not only has a negative impact on the sustainability but also increases material costs (Kellens et al. 2017).

This study will investigate, whether it is possible to use grinding waste (GW) for the DED process. The GW investigated for this purpose comes from the production of aluminum bronze ship propellers at Mecklenburger Metallguss GmbH, Germany. The post processing of such parts includes several grinding steps to finish the propeller surfaces and achieve the final blade shape. During grinding, large amounts of aluminum bronze GW are generated. While a small fraction of this waste can be recirculated to the casting process by re-melting, the largest part is usually scrapped and discarded.

In the literature, several studies are dealing with reusing materials for various powder-based AM processes. For example, reuse of powder and the effect of powder degradation in L-PBF was assessed by Gruber et al. for IN718 (Gruber et al. 2021) or by Gorji et al. for 316L stainless steel powder (Gorji et al. 2019). Powell et al. summarized various aspects of the degradation of reused AM powders. Particle size distribution (PSD), particle morphology and chemical composition were named as the most critical powder properties. (Powell et al. 2020)

Other authors investigated to use chips from grinding and milling processes for AM. Fullenwider et al. recycled machining chips from 304L stainless steel and used the resulting material to successfully produce single weld tracks via DED. They utilized a dual-stage ball milling process to refine the metal chips and enhance the particle morphology. The authors state that they achieved a near-spherical morphology with particle sizes from 38 µm to 150 µm (Fullenwider et al. 2019). In addition to PSD and morphology, material and composition specific challenges include contamination of the particles with cooling lubricate or foreign particles like fibers or ceramic particles from grinding processes (Powell et al. 2020). While conventional DED powder is spherical with a usual size of 40 µm to 150 µm, particles from machining processes are elongated and sharp-edged. This reduces flowability and can impair the conveyance of such material in the powder carrier system of DED machines.

Based on the high cost for virgin AM powders and the large amount of GW produced in propeller manufacturing, the present paper investigates whether it is feasible to manufacture end-use components from recycled GW with DED. Specimens from commercial powder (CP) for DED are manufactured for reference.

2. Experimental setup and procedure

The DED experiments were performed on a Trumpf TruLaser Cell 7020 and a 2kW Trumpf TruDisk Nd:YAG laser with a wave length of 1030 nm. The powder carriage system from GTV, Germany, used a grooved feeding disk and Helium as carrier gas with a flow rate of 4 l/min. From the feeding disk, the DED feedstock material was transported through hoses to the three-jet powder nozzle. Argon with a flow rate of 10 l/min was used as shielding gas.

The GW processed for this study was from aluminum bronze (CuAl10Fe5Ni5). The composition is listed in Tab. 1. This alloy is common for producing ship propellers due to its high strength and corrosion resistance in sea water. The material was collected directly after the grinding process. As a benchmark and reference material, commercial DED aluminum bronze powder (Oerlikon Metco 51NS, CuAl9.5Fe) was used. The composition is listed in Table 2.

Table 1: Chemical composition of the grinding waste CuAl10Fe5Ni5

Cu	Al	Fe	Mn	Ni
Bal.	8.5 – 10.5 %	4.0 – 5.5 %	<3.0 %	4.0 – 6.0 %

Table 2: Chemical composition of the commercial DED powder Oerlikon Metco 51NS CuAl9.5Fe

Cu	Al	Fe
Bal.	8.5 – 10.75 %	0.5 – 2.0 %

To evaluate the GW and the CP before welding, the materials were analyzed using light optical microscopy (LOM) with a Zeiss Axio Imager. Furthermore, the materials were examined with a Microtrac CamSizer X2. This system performs dynamic image analysis (DIA) by taking pictures of a particle stream using high-resolution cameras. Based on the high-contrast pictures of the particles, a software analyzes a large quantity of particles. The results allow a direct comparison to sieving analyses and give detailed information on various characteristics regarding the particle morphology and size, such as sphericity or width-to-length-ratio.

Sieving was performed on a Haver & Boecker EML 200 digital plus N sieving machine using a sieve with a nominal mesh width of 125 µm.

3. Results and Discussion

3.1. Grinding waste and powder analysis, Sieving

Initially, the GW as well as the CP were analyzed via LOM. Fig. 1 shows LOM images of CP and the GW. The material included different types of particles in terms of morphology and material. Both fine, small grains and long chips with serrations and rough edges were visible. Furthermore, ceramic particles (diameter >300 µm) as well as fibers from the grinding belts could be observed.

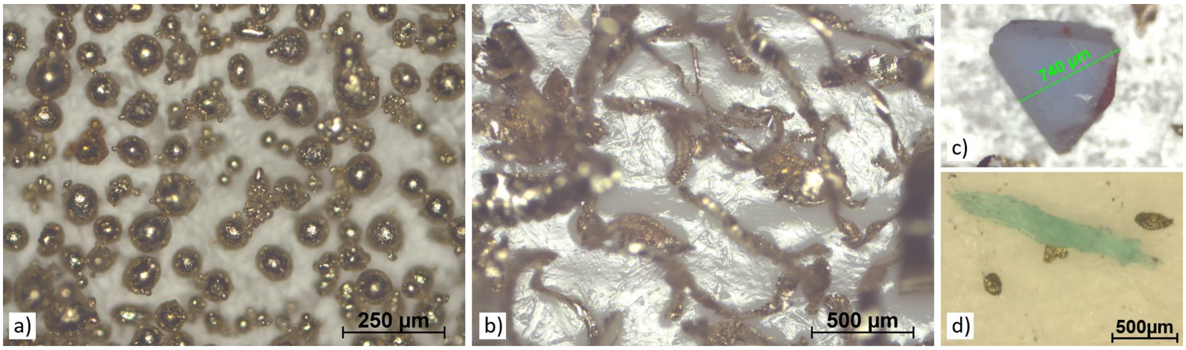

Fig. 1: LOM images: a) commercial DED powder, b) as-collected grinding waste with long and serrated chips, c) ceramic particle from grinding, d) textile fiber from a grinding belt.

It can be stated that the as-collected GW, without any separation or preparation, was not suited for the DED process. The morphology and size of the chips and ceramic particles would have impaired the material conveyance to the nozzle, so that clogging was likely. The as-collected material was therefore not used for welding experiments.

As a first step in recycling the GW, sieving was performed to improve the PSD for the DED process. A 125 µm mesh sized sieve was used to remove coarser particles. Sieving with a smaller grid sieve to remove small particles was not performed. Approx. 80 % of the original material remained unsieved and was not used for further experiments. Fig. 2 shows a SEM images of the resulting material. While elongated chips were still present, remaining ceramic particles were not visible under the LOM. While this indicates that the majority of the foreign ceramic particles may have been filtered out, very fine particles may have still been present in the material. Also, fibers could not be observed via LOM or in the SEM images.

To analyze large quantities of chips and determine, whether usable particles in terms of size and shape were in the GW, DIA was performed. DIA is capable of analyzing large quantities of particles, generating statistical data on particle-specific characteristics for size and shape. Fig. 3 shows actual gray-scale images taken via DIA, the derived particle contours and calculated data on sample particles from CP and two particles from the sieved GW. A common value in AM to determine powder size distribution is the minimal width of a particle $x_{c,min}$. The shown sample particles had $x_{c,min}$ values of approx. 100 µm. For spherical AM powders, $x_{c,min}$ is a suitable basis for comparison. However, when it comes to particles like chips from milling or grinding, $x_{c,min}$ does not allow a sufficient statement about the nature of the material. This is, because only the smallest width of a particle, but not the length or the curvature are represented in $x_{c,min}$. Another parameter that measures the longest straight chord ("feret") in a particle is $x_{Fe,max}$. For elongated particles this value gives a better picture of the examined material. To measure the sphericity of the material, a width-to-length-ratio b/l and the value for sphericity $SPHT$ can be used as additional characteristics.

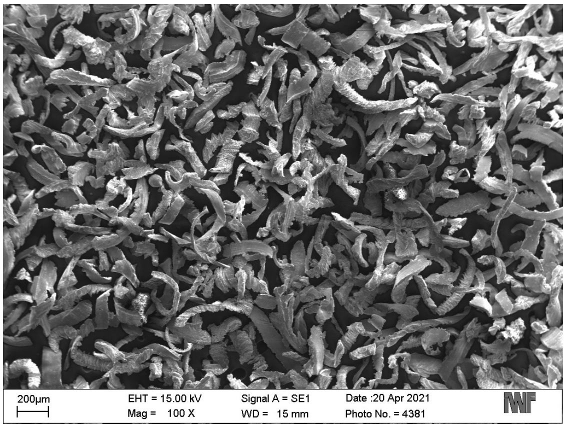

Fig. 2: SEM image of sieved grinding waste.

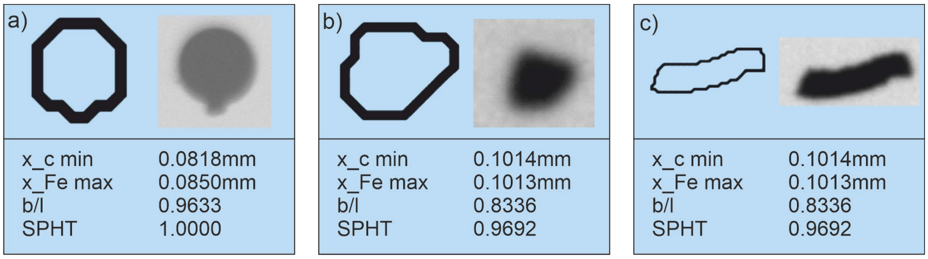

Fig. 3: Particles recorded and evaluated via DIA: a) Commercial powder particle with satellite, b) relatively spherical particle from the grinding waste, c) elongated chip from the grinding waste.

Fig. 4 a) and b) show the DIA particle distribution results for $x_{c,min}$ and $x_{Fe,max}$. The graphs show the results for the CP as well as both stages of the GW (unsieved and sieved). The sieved material shows a good overlap with the CP for the $x_{\mathrm{c,min}}$ parameter. 90 % of both materials are smaller than 123 µm and 130 µm, respectively

($D_{90,51NS} = 123\ \mu m$, $D_{90,Sieved} = 130\ \mu m$). When analyzing $x_{Fe,max}$, more than 50 % of the sieved material have a higher max. feret diameter than 90 % of the CP ($D_{50,Sieved} = 166\ \mu m$, $D_{90,51NS} = 150\ \mu m$).

The DIA results quantitively show that the overall particle size could be reduced significantly, and it can be stated that sieving improved the PSD. However, the results also highlight the limitations of sieving: The relevant factor for particles to find their way through the sieve is not their length or volume, but their continuous minimum diameter ($x_{c,min}$). To recycle the material properly, other enhancement and preparation steps will be necessary. To improve particle morphology, ball milling as used by Fullenwider et al. (Fullenwider et al. 2019) or plasma spherioidation as dicussed by Powell et al. (Powell et al. 2020) are promising approaches.

As stated above, this study aimed to check feasibility of the approach. Since sieving improved flowability and PSD significantly, the sieved GW was used to conduct experiments and manufacture DED sample specimens.

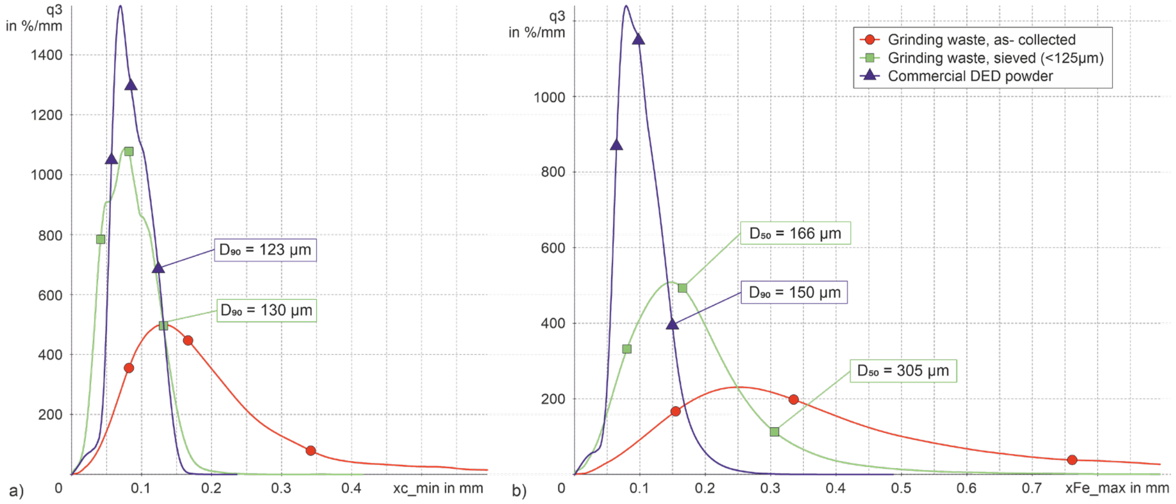

Fig. 4: DIA results comparing commercial DED powder with grinding waste before and after sieving: a) $x_{c,min}$, and b) $x_{Fe,max}$.

3.2. Conveyance testing

Before using the sieved GW to manufacture specimens, it was tested whether and up to which mass flow the material could be transported with the powder carrier system to the DED nozzle. As stated above, a powder carrier system with a grooved feeding disk and carrier gas Helium were used. Initial tests with a 5 mm groove in the disc were not successful. The holes in the groove blocks, through which the material is sucked from the groove and transported through hoses towards the process head, were too small and clogged immediately. By using a larger groove (11 mm) and respective groove blocks, the sieved material could be successfully delivered to the nozzle.

Mass flow tests were performed and revealed that clogging mainly occurred at the nozzle holes which had the smallest diameter in the powder carrier system. In addition, small hose diameters and small bending radii of the powder hoses in the machine increased the risk of clogging. The tests showed that a max. mass flow of approx. 7 g/min were possible before the system clogged. To reduce the risk of clogging during welding and to increase overall process stability, the DED experiments were conducted with a mass flow of $\dot{m}_{Sieved} = 6\ g/min$. The risk of clogging was furthermore mitigated by a reduction of the hose length from the powder hopper to the nozzle from approx. 8 m down to 2.5 m.

3.3. DED experiments

For this study, cubes where manufactured both from the CP and the sieved GW from the ship propeller grinding process. As for the powder analysis, the CP served mainly as a reference and benchmark for the manufacturing of DED cubes. The specimens where manufactured from 10 layers, each with a layer height of 1mm. A meandric tool path strategy with an overlap factor of 50 % was used for each layer. The substrate was 316L with a thickness of 6mm. The DED parameters to build up the cube from CP are listed in Tab. 3.

Table 3: DED parameters for commercial powder Oerlikon Metco 51NS, CuAl9.5Fe

Laser power $P_{L,51NS}$	Feedrate f_{51NS}	Mass flow $\dot{m}_{51NS}$	Laser spot d_{Laser}
$1300\,W$	$800\,\frac{mm}{min}$	$13\,\frac{g}{min}$	$1.5\,mm$

Based on the mass flow of $\dot{m}_{Sieved} = 6\,g/min$ for the sieved GW, the DED parameters for the CP were adapted following an approach that was, for example, used by Petrat et al. (Petrat et al. 2019). The mass energy E_M and the line energy E are used to calculate laser power P_L, mass flow $\dot{m}$ and feedrate f for different parameter sets, based on one initial parameter set. The line energy E is the quotient of laser power P_L and the federate f (equation 1). The mass energy E_M is the quotient of the laser power P_L and the mass flow $\dot{m}$ (equation 2).

In the present study, both mass energy and line energy from the CP parameter set were kept constant to calculate the laser power and federate for the recycling material. Petrat et al. applied this approach to manufacture specimens only from a single alloy, Inconel 718. In this study, the alloy composition of the GW (CuAl9.5Fe) was different to the CP (CuAl10Fe5Ni5). Although the main element of both elements was copper, this means that this approach cannot be used without limitations. However, since the tests of this study were mainly feasibility studies and, additionally, only a limited amount of sieved GW was available which prevented extensive studies, this approach was followed.

$$E = \frac{P_L}{f} \tag{1}$$

$$E_M = \frac{P_L}{\dot{m}} \tag{2}$$

Table 4: Calculated DED parameters for recycled grinding waste CuAl10Fe5Ni5

Laser power $P_{L,51NS}$	Feedrate f_{51NS}	Mass flow $\dot{m}_{51NS}$	Laser spot d_{Laser}
$600\,W$	$370\,\frac{mm}{min}$	$6\,\frac{g}{min}$	$1.5\,mm$

3.4. Manufactured DED specimens

Specimens were manufactured with a Trumpf TruLaser Cell 7020. To detect possible clogging of the powder system, it was checked whether material was blown through all three nozzle holes of the processing head before and after every weld. A single weld track, a surface clad of 20 mm x 20 mm and a cube of the same size consisting of 10 layers were manufactured from sieved GW using the adapted parameters discussed above (see Tab. 4). The specimens are depicted in Fig. 5 a) and b). Reference geometries shown in Fig. 5 c) and d) were manufactured from CP using the parameters listed in Tab. 3.

During the welding process with the GW, there was increased smoke development whose intensity and appearance differed greatly from normal welding fumes. The smoke settled on the substrate and created a black coating. Most of the debris could be removed with alcoholic cleaner. However, at the sides of the cube, dark areas were still present. The welded material composition might explain the smoke formation: On the one hand, it is likely that oxides were a cause for the smoke. During the grinding process, such oxides form as frictional heat is generated between the grinding belt and the part. In addition to oxides, remaining organic fibers from the grinding belt and a certain level of moisture may also have caused the smoke. In any case, this smoke indicates a strong contamination of the GW that must be significantly reduced to manufacture functional parts.

The single weld track exhibited an irregular height profile in addition to uneven edges at the transition to the substrate. This indicates uneven material feed, which probably resulted from the inhomogeneous GW. The manufactured specimens have significant inclusions on their surfaces. Especially on the cube, these defects caused the surface to be wavy and uneven.

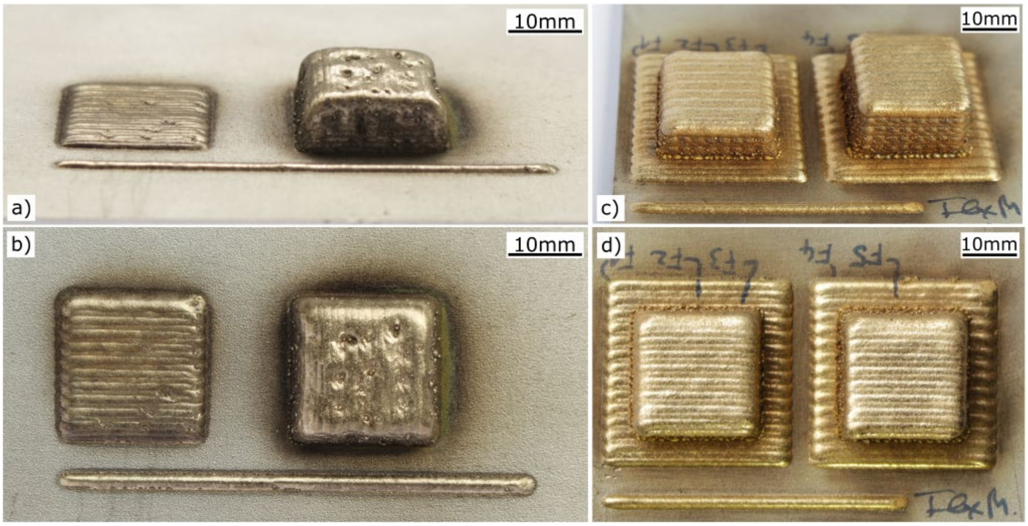

Fig. 5: Manufactured specimens from sieved grinding material (a and b); Specimens from commercial DED powder: single weld track, cube with 10 layers, cube with 20 layers (c and d).

Metallographic cuts were made from both 10-layer cubes from recycled and commercial powder. The polished sections are depicted in Fig. 6 and Fig. 7.

The irregular surface of the GW cube, which was already visible before the cut, becomes particularly apparent in the cross-section. Compared to the cube made from CP, the cube made of GW showed a significantly higher porosity. Furthermore, large defects were present, which can be classified as lack of fusion defects. It is noticeable that the shape of the voids resembles the shape of chips. It can therefore be assumed that these are defects caused by the insufficient melting of larger chips. At least in one void, unmolten particles were visible. Furthermore, the metallographic sections reveal inclusions which may be ceramic particles from the grinding process. Assuming that large chips were causing the lack of fusion defects, the ball-milling approach applied by (Fullenwider et al. 2019) is a promising method to increase the material quality. To reduce the amount of foreign particles, a magnetic separation can be used.

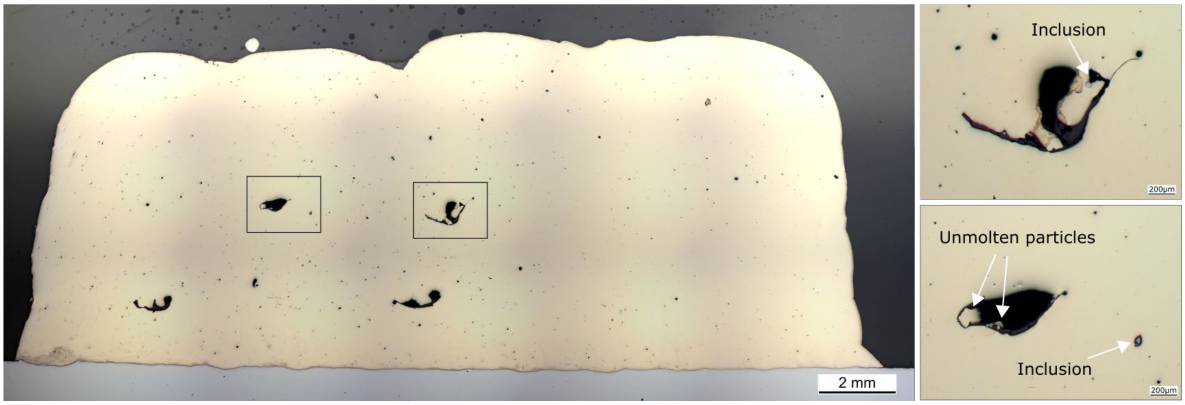

Fig. 6: Polished sections of 10-layer cube from sieved grinding material.

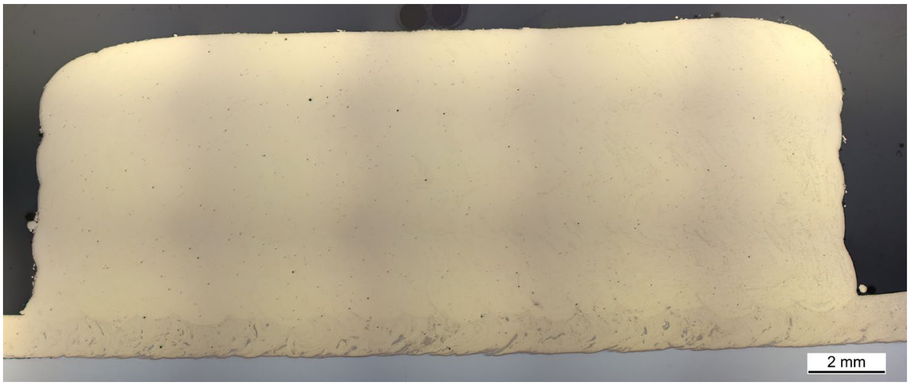

Fig. 7: Polished section of the manufactured cube from commercial powder.

4. Conclusion

In this study, sieved grinding waste from the production of aluminum bronze chip propellers was analyzed, sieved and used as feedstock material to manufacture specimens via DED. The following statements can be summarized:

- Sieving improved the particle size distribution and morphology. The majority of large particles can be separated out. However, the sieved material still shows unfavorable morphology in comparison to gas atomized commercial DED powder.The flowability of the grinding material was increased by sieving, which gave the possibility to use the material with DED.
- DED specimens could be manufactured with the sieved grinding material using adapted parameters from a commercial aluminum bronze DED powder. The produced specimens showed significant surface defects. Metallographic cuts revealed lack of fusion defects, ceramic inclusions and increased porosity compared to a reference specimen from standard DED powder.
- The feasibility to use aluminum bronze grinding waste – with minimal effort in recycling and preparation – as feedstock material for DED could be shown. The results indicate that the approach is promising.

- In order to increase feedstock quality, process stability and material properties, further processing of the material (ball milling, magnetic separation, plasma spheroidisation, etc.) will be necessary.

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