Joint Special Interest Group meeting between euspen and ASPE
Advancing Precision in Additive Manufacturing
Ecole Centrale de Nantes, France, September 2019
www.euspen.eu

Challenges of combining direct metal deposition with milling for the fabrication of a rocket nozzle

Daniel Eisenbarth[1], Marvin Breuch[2], Fabian Soffel[1], Konrad Wegener[2]

[1] *inspire AG, Technoparkstrasse 1, 8005 Zürich, Switzerland*
[2] *Institute of Machine Tools and Manufacturing, ETH Zürich, Leonhardstrasse 21, 8092 Zürich, Switzerland*

eisenbarth@inspire.ethz.ch

Abstract
Direct metal deposition (DMD) is a promising additive manufacturing technology for the fabrication and repair of large components. In theory, near-net shape buildup with intermediate milling steps combines the advantages of additive and subtractive processing, as it enables both high buildup rates and an accurate surface finish. However, various challenges arise in reality during the development of a combined manufacturing process. This publication points out such hurdles, proposes new methods and shows their application for the use case of a rocket nozzle. Combining DMD and milling in one machine platform with interchangeable tools requires an accurate alignment of the additively built part with a subsequent milling step. A method is proposed that measures the offset between laser, powder stream, and tool centre point, and compensates it with the tool path. Thermal distortion has a detrimental effect on the part accuracy and is critical for combined processing. In order to achieve a seamless transition between the individual manufacturing steps, provisional protrusions are created, protecting finished surfaces from a subsequent DMD process and minimizing local distortion. Cavities and pockets limit the accessibility for milling and increase the cutting time and the number of required manufacturing steps. Interdependencies between part design, accuracy of the DMD process, milling strategy, and total production time are finally outlined.

Direct metal deposition, milling, combined processing, near-net shape fabrication

1. Introduction

The technology of direct metal deposition (DMD) gains recently high interest in the additive manufacturing (AM) community. It uses a laser beam to create a melt pool on a workpiece and blows metallic powder into it. Overlapping tracks form a layer, and multiple layers create a volumetric structure. The processing head is mainly attached to a robot or CNC machine, providing a large design space and five-axis movements. DMD is nowadays used for coatings and repair of simple geometries as shown by Kaierle *et al.* [1].

Most recently, various milling machine manufacturers integrate DMD systems for combined processing in one clamping setup, using the same motion system for additive and subtractive processes. According to Sealy *et al.* [2], a combined process is fully coupled and synergistically affects the part quality, functionality, and/or process performance. This approach breaks the dependency between buildup rate and accuracy: The larger the melt pool, the higher the achievable deposition rate with DMD. However, also the surface roughness, thermal distortion, and staircase effects increase with a larger melt pool.

By adding intermediate milling steps, a high dimensional accuracy and surface quality can be achieved while optimizing the DMD process for high buildup rates. On the opposite, a precise DMD process that generates a minimum part oversize reduces the cutting volume, processing time and tool wear of the milling process. Especially parts made from tough and high-strength materials, for instance nickel- and titanium-based alloys, benefit as further shown by Sartori *et al.* [3]. Therefore, a precise alignment of the DMD processing head with the tool centre point as presented hereafter is crucial in order that the actual position and size of the part coincide with the nominal values.

With milling, overhanging and internal features are limited, since the tool requires a line of sight as mentioned by Flynn *et al.* [4]. With a combined process of DMD and milling, areas can be finished that are no longer accessible in a later stage of production. However, the welding process with high thermal gradients leading to residual stress and distortion counteracts the high accuracy that is achieved by milling. Thus, strategies are required to minimize the effect of a subsequent additive step on already finished surfaces of the part. A suitable approach is proposed for the use case of a rocket nozzle with a 3D shape and internal, overhanging surfaces.

2. Materials and methods

2.1. Alignment of melt pool and tool centre point

Most DMD systems enable an adjustment of the laser beam and powder stream relative to the tool centre point (TCP). Bad alignment of laser and powder leads to a direction dependent process as further discussed by Eisenbarth *et al.* [5], since a varying fraction of powder reaches the melt pool in different scanning directions. This varying powder catchment efficiency influences the track height and therefore the dimensional accuracy of the part. With three-axis processing, an offset between the melt pool and the actual tool path shifts the entire part as illustrated in Figure 1.

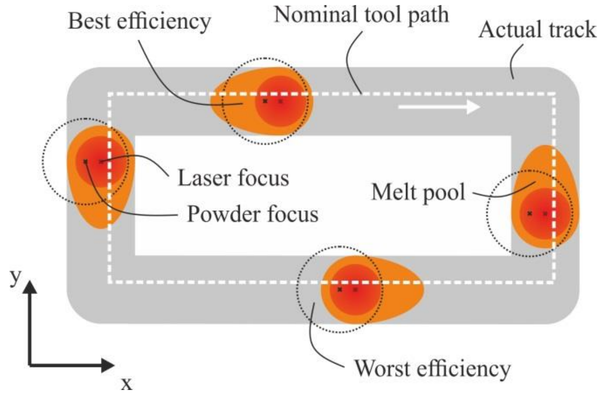

Figure 1. Misaligned laser, powder, and TCP in three-axis buildup of a hollow rectangle, shown from top [5]

Especially for five-axis and combined processing, a misalignment of the melt pool and the TCP deteriorates the part quality. A combined process should not rely on intermediate probing steps to check and realign the geometry before milling, but rather assure an inherently precise DMD process with known deviations.

The 3D powder stream and its focus can be measured by different methods as proposed by Eisenbarth *et al.* [5] or Brown *et al.* [6]. The laser can be aligned by a coaxial camera or by depositing single dots. By using a turn head or table and an adapted calibration method from Ibaraki *et al.* [7], the offset between the laser and powder focus and the TCP can be calculated. Figure 2 shows the principle: Measuring the laser or powder focus in different rotation angles α and β with activated kinematic compensation leads to two different focus points a and b. Then, the actual offset (u, v) to the TCP in the reference coordinate system can be calculated as

$$\begin{bmatrix} u \\ v \end{bmatrix} = \frac{-1}{2\sin\left(\frac{\beta-\alpha}{2}\right)} \begin{bmatrix} \sin\left(\frac{\beta+\alpha}{2}\right) & -\cos\left(\frac{\beta+\alpha}{2}\right) \\ \cos\left(\frac{\beta+\alpha}{2}\right) & \sin\left(\frac{\beta+\alpha}{2}\right) \end{bmatrix} \begin{bmatrix} p_1 \\ p_2 \end{bmatrix} \qquad (1)$$

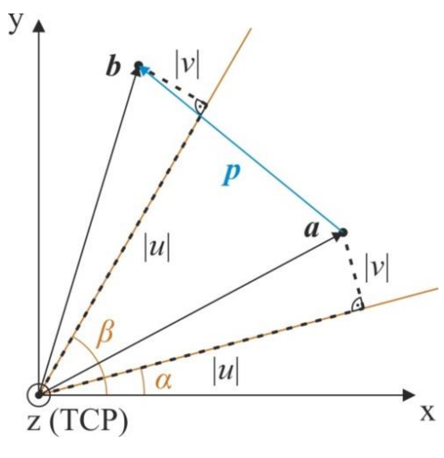

Figure 2. Offset (u, v) of the laser or powder focus relative to the TCP in the reference coordinate system [5]

Ideally, the processing head allows an adjustment of both laser and powder to reduce the offset to a minimum. Alternatively, the tool path can be adapted by five-axis kinematics equations in order to compensate existing hardware deficiencies by software measures.

2.2. Concept of provisional protrusions

Eisenbarth *et al.* [8] analyse the effects of DMD combined with intermediate and final milling on thermal distortion. For a specific use case, they show that a subsequent DMD process leads to local shrinkage by up to factor 10 of the accuracy that was reached with the previous milling step. Therefore, the alternation of DMD and milling requires strategies to ensure dimensional accuracy in the transition zone. One approach is to leave a protrusion at the top of each section. Without any measures, the process of milling and subsequent DMD leads to undersize and to a scrapped part. A provisional protrusion made by milling as shown in Figure 3 provides an extended area for the near-net shape DMD process, relocates the heat-affected zone and local distortion, and protects the finished surfaces from the laser beam and powder spatters. Subsequently, the protrusion is milled away together with the next section in order to achieve the nominal geometry. As a drawback, 5-axis milling or specific cutters are required to generate the undercut, and the global distortion behaviour needs to be taken into account.

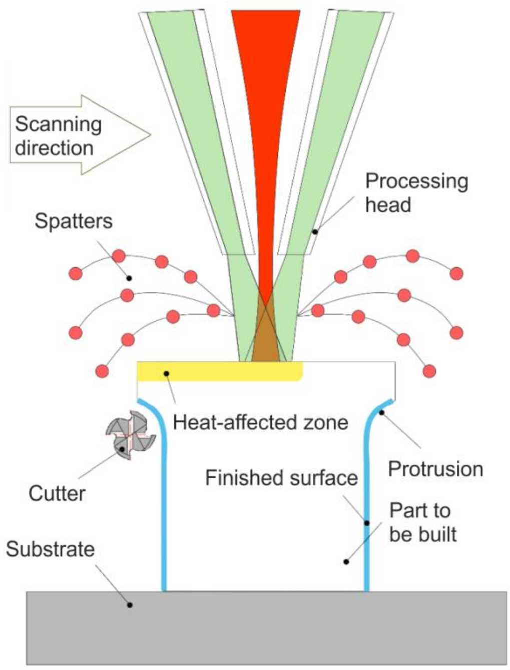

Figure 3. Concept of a provisional protrusion on top of each section to protect finished surfaces from the heat-affected zone, local distortion, and spatters

2.3. Experimental setup

A prototype machine for combined DMD and milling from the Swiss company GF Machining Solutions was used for the experiments. It bases on a five-axis machining centre type Mikron HPM 450U. Company HMT provides the laser deposition system. It consists of two processing heads with 1 and 3 mm nominal laser spot size, which can be exchanged automatically with milling tools. Laser, powder, gas, and cooling water are supplied by a retractable docking mechanism. The laser source emits a laser power of 1000 W at a wavelength of 1070 nm. As deposition material, steel powder type 1.4404 with a grain size distribution of 45 to 106 µm was used. The tool path was prepared with in-house CAM software and consists of three offset contour paths for the rocket nozzle. DMD process parameters are listed in Table 1.

Table 1 DMD process parameters for steel 1.4404

Parameter	Value
Laser power P [W]	800 to 1000
Scan speed v [mm/min]	351 to 492
Powder flow rate m_t [g/min]	8.2
Hatching distance d [mm]	1.1
Layer height Δh [mm]	0.9

3. Results and discussion

3.1. Rocket nozzle fabrication

With the alignment method as described in section 2.1, a rocket nozzle with a nominal height of 130 mm and a desired oversize of 0.6 mm was fabricated. The buildup time was 3.5 h with an average powder catchment efficiency of 41 %, leading to an actual build rate of 3.3 g/min. A 3D scan of the as-built part is shown in Figure 4 and reveals the dimensional accuracy: The thickness ranges between 0.56 mm and 0.81 mm at the outer surface, and is 0.9 mm at the top edge. Few spatters from the DMD process are visible.

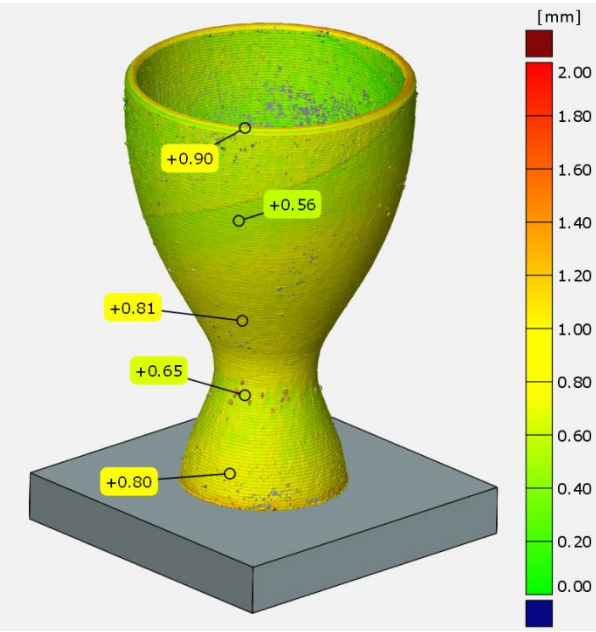

Figure 4. 3D scan of the as-built nozzle, made from steel 1.4404

Milling of the outer surface to its nominal geometry was prepared with the CAM software Autodesk PowerMill and required a removal of 112 g of material. Since accessibility is not constrained for the outer surface, milling could be performed with a ball-end cutter with a diameter of 12 mm. The finished surface does not show any defects as depicted in Figure 5. With the high accuracy of the as-built DMD part, changes to the CAD geometry or to the coordinate system of the machine were not necessary, and the outer surface could be milled in one roughing and one finishing operation. However, milling of the interior of the combustion chamber, which is the cavity below the bottleneck, becomes impossible when the nozzle is fabricated in one step.

Figure 5. Rocket nozzle after finishing of the outer surface

3.2. Combined processing for inner surfaces

Transferring the process of DMD with subsequent milling to the inner surfaces of the nozzle imposes constraints regarding accessibility. Due to the bottleneck, there exist undercuts that cannot be reached by a milling tool after the additive buildup. Thus, the geometry needs to be split up into various sections that are built and milled individually, applying the concept of provisional protrusions. Swarf milling from top with a ball-end cutter and a certain lean angle δ provides a maximum of flexibility. Figure 6 illustrates the geometrical constraints: With a minimum width b of a gap between two inner surfaces of a pocket, the cutting depth h_c can be reached with a cutting diameter d_1 and a shaft diameter d_2 of the tool, applying a safety clearance c. However, the achievable cutting depth decreases due to the protrusion with an oversize u_{pr} and a height h_{pr}.

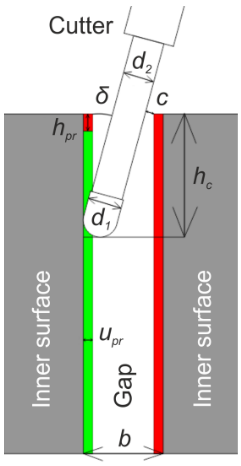

Figure 6. Accessibility of inner surfaces of a pocket for a ball-end cutter, considering a protrusion at the top

Combined processing for a given part geometry is therefore a trade-off between the cutter diameter determining the metal removal rate, the required protrusion size, and the number of sections, with each section height smaller than the cutting depth for a smooth transition.

The maximum cutting depth is plotted in Figure 7 as a function of the nominal pocket width for different tool diameters, considering the tool holder size and the maximum tool length. Ball-end cutters with a long shaft come from company Fraisa (tool number P7544). The lean angle δ is fixed to 15° for acceptable cutting conditions. The protrusion size is u_{pr} = 1 mm according to the maximum DMD oversize, with a height of h_{pr} = 2 mm. The graph shows that the achievable cutting depth depends linearly on the gap width. For a width smaller than 6 mm, the gap is not accessible for standard cutters. Mostly, two to four different tools are applicable for the same width. For a minimum total processing time, a tool needs to be selected that leads to the best trade-off between metal removal rate and the additional time that is required to switch between DMD and milling for the necessary number of sections.

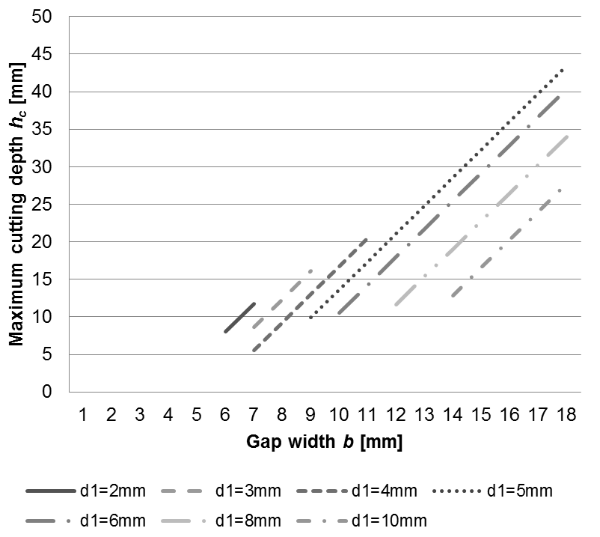

Figure 7. Maximum cutting depth as a function of the gap width for different tool diameters

The concept of provisional protrusions is validated by the fabrication of massive cylinders in a combined process, since they reduce the effort of CAM programming and are easier to analyse compared to a hidden pocket. Figure 8 shows the single steps to fabricate two adjoining sections: The first section is made by DMD with an intentional oversize (a) and milled to its nominal diameter of 18 mm, leaving a protrusion with u_{pr} = 1 mm and h_{pr} = 6 mm (b). Adding the second section by DMD (c) and removing the oversize by milling, a smooth, accurate transition between both sections could be achieved (d). The protrusion protects the previous section successfully from spatters and thermal distortion; solely annealing colours appear.

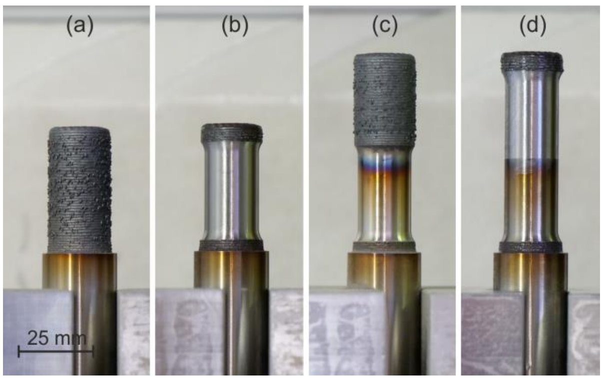

Figure 8. Alternating DMD and milling to fabricate a cylinder: Buildup of the first section (a), milling and leaving a protrusion (b), buildup of the second section (c), milling and removing of the previous protrusion (d)

4. Conclusion and outlook

Combined processing brings together the advantages of a high buildup rate of DMD and the accurate surface finish of milling. However, alignment of the laser beam, powder stream, and TCP is crucial for a precise additive buildup. With the concept of provisional protrusions, parts with cavities such as a rocket nozzle could be fabricated in multiple steps of DMD and milling with a smooth surface transition. An accurate DMD process allows a small oversize for near-net shape fabrication and thus a small cutting volume for finishing, which is important for high-strength materials. An analysis of the accessibility reveals the influencing factors for the production time during combined processing: A smaller gap requires a smaller cutter diameter to achieve a constant cutting depth, leading to a lower metal removal rate. Alternatively, a bigger cutter can be used, leading to a smaller cutting depth and thus to an increasing number of sections that need to be built and milled alternatingly.

A drawback of combined processing is the effort for CAM programming and the cutting time, which increase significantly for challenging geometries that comprise narrow, deep, and overhanging inner surfaces. Such high expenditures may be only justifiable for parts with high requirements and that are not producible with other manufacturing technologies. In future, the presented use case of a rocket nozzle shall be developed further, with the combustion chamber as cavity that is made by alternating DMD and milling.

Acknowledgements

The authors would like to acknowledge the contribution of the funding agency Innosuisse (grant number 25498) and of the companies GF Machining Solutions, GF Precicast, ABB Turbo Systems AG, and Autodesk.

References

[1] Kaierle S, Overmeyer L, Alfred I, Rottwinkel B, Hermsdorf J, Wesling V and Weidlich N 2017 Single-crystal turbine blade tip repair by laser cladding and remelting *CIRP Journal of Manufacturing Science and Technology* **19** 196-199

[2] Sealy M P, Madireddy G, Williams R E, Rao P and Toursangsaraki M 2018 Hybrid processes in additive manufacturing *Journal of Manufacturing Science and Engineering* **140** 6 060801

[3] Sartori S, Moro L, Ghiotti A and Bruschi S 2017 On the tool wear mechanisms in dry and cryogenic turning additive manufactured titanium alloys *Tribology International* **105** 264-273

[4] Flynn J M, Shokrani A, Newman S T and Dhokia V 2016 Hybrid additive and subtractive machine tools - research and industrial developments *International Journal of Machine Tools and Manufacture* **101** 79-101

[5] Eisenbarth D, Borges Esteves P M, Wirth F and Wegener K 2019 Spatial powder flow measurement and efficiency prediction for laser direct metal deposition *Surface & Coatings Technology* **362** 397-408

[6] Brown S W, Przyjemski A G, McPherson M B, Steinberg J H, Corbin, D and Reutzel E W 2018 Insights into powder flow characterization methods for directed energy distribution additive manufacturing systems *Proceedings of the 29th International Solid Freeform Fabrication Symposium* 1976-1988

[7] Ibaraki S, Sawada M, Matsubara A and Matsushita T 2010 Machining tests to identify kinematic errors on five-axis machine tools *Precision Engineering* **34** 387–398

[8] Eisenbarth D, Soffel F and Wegener K 2019 Effects of direct metal deposition combined with intermediate and final milling on part distortion *Virtual and Physical Prototyping* **14** 2 130-134