Additive Manufacturing of a Cutting Punch –

Qualification of PBF-LB/M for Processing Tool Steel H13 (1.2344) and Results of 40,000-Stroke Test

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Zusammenfassung Additive Fertigungsverfahren haben in zahlreichen Branchen das Potenzial zur Herstellung hochbelasteter Bauteile nachgewiesen [1, 2]. Der Einsatz als Schneidstempel für Scherschneidverfahren wurde bislang nicht untersucht.

Der vorliegende Beitrag beschreibt die Qualifizierung der Laser-Strahlschmelztechnologie (deutsche Bezeichnung nach [7, VDI3405], nach [8, ISO/ASTM 52900] als Laser-based Powder Bed Fusion of Metals, PBF-LB/M bezeichnet) zur Verarbeitung des Werkzeugstahls H13 (1.2344). Darauf aufbauend wird die additive Fertigung eines Schneidstempels zur Anwendung auf einer Stanzmaschine beschrieben sowie dessen Test mit bis zu 38.088 Hüben in Tiefziehstahl (DX56D, 1.0322) und höherfestem Dual-Phasenstahl (DP600, 1.0936). Die Auswertung der Verschleißuntersuchung hat ergeben, dass die scharfkantige Schneidkante minimal abgenutzt wurde und der Schneidkantenradius sich infolgedessen um 11,5 µm vergrößerte.

Zusammenfassend ist festzuhalten, dass der additiv gefertigte Schneidstempel die Anforderungen vergleichbar zu konventionell Gefertigten erfüllte. Weiterführende Tests bezüglich der Langlebigkeit auf industriell übliche Standzeiten im Bereich mehrerer hunderttausend Hub sind ausstehend.

Abstract Additive manufacturing processes have demonstrated the potential to produce highly stressed components in numerous industries [1, 2]. However, its use as a cutting punch for shear cutting processes has not been investigated to date.

This paper describes the qualification of Laser-based Powder Bed Fusion of Metals (PBF-LB/M) for the processing of the tool steel H13 (1.2344). Based on this, the additive manufacturing of a cutting punch for application on a punch press is described, as well as its testing with up to 38,088 strokes in deep-drawing steel (DX56D, 1.0322) and higher-strength dual-phase steel (DP600, 1.0936). The evaluation of the wear test showed that the radius of the sharp cutting edge increased by 11.5 µm.

In summary, it can be stated that the additively manufactured cutting punch meets the requirements comparable to conventionally manufactured ones. However, further tests with regard to durability are still needed for a final assessment and shall be addressed in future work.

List of symbols

Parameter	Symbol
Power	P
Scanning speed	v
Hatch distance	h
Layer thickness	t
Relative density	ρ
Surface roughness	Sa
Input variables	x_{i}
Expectation response	y
Coefficient	a_{i}
Vector of the experimental response	$\boldsymbol{Y}$
Factor matrix	$\boldsymbol{X}$

List of abbreviations

Term	Abbreviation
Laser-based Powder Bed Fusion of Metals	PBF-LB/M
Laser-powder-based Directed Energy Deposition	DED
Volume energy density	VED
Design of Experiments	DoE
Face Centered Central Composite Design	CCF

Introduction

Additive manufacturing processes have demonstrated the potential to produce highly stressed components in numerous industries [1,2]. Exemplary applications from the aerospace industry include a hybrid injection nozzle manufactured by General Electric Cooperation (USA) or a maintenance opening for aero engines of MTU Aero Engines AG (Germany), so-called “Boroscope boss”. There are also numerous applications of additive manufacturing in toolmaking [1]. However, the use of Laser-based Powder Bed Fusion of Metals (PBF-LB/M) to manufacture a cutting punch for shear cutting processes has not been investigated to date.

This paper describes the qualification of PBF-LB/M for the processing of the tool steel H13 (1.2344). Therefore, results of the parameter study are shown. For the qualification, the PBF-LB/M machine AL3D-METAL 250 from ALPHA LASER GmbH (Munich, Germany) was utilized. Due to its limited build volume of diameter 50 mm with a build height of 50 mm it was not possible to print the cutting punch completely by means of PBF-LB/M. Instead, an additive hybrid manufacturing approach was applied. For that reason, laser-powder-based Directed Energy Deposition (DED) was used to enlarge the cutting punch (cf. Figure 1) so that it fits into the tool holder of the punch press TRUMPF MINIMATIC 100. For DED, the AL FLAK 1200 from ALPHA LASER GmbH was utilized, which is equipped with a cw-mode 1,200 W laser, and the well-known material PLASWELD^{TM} Ferro 44 was processed in this not so highly stressed area of the cutting punch.

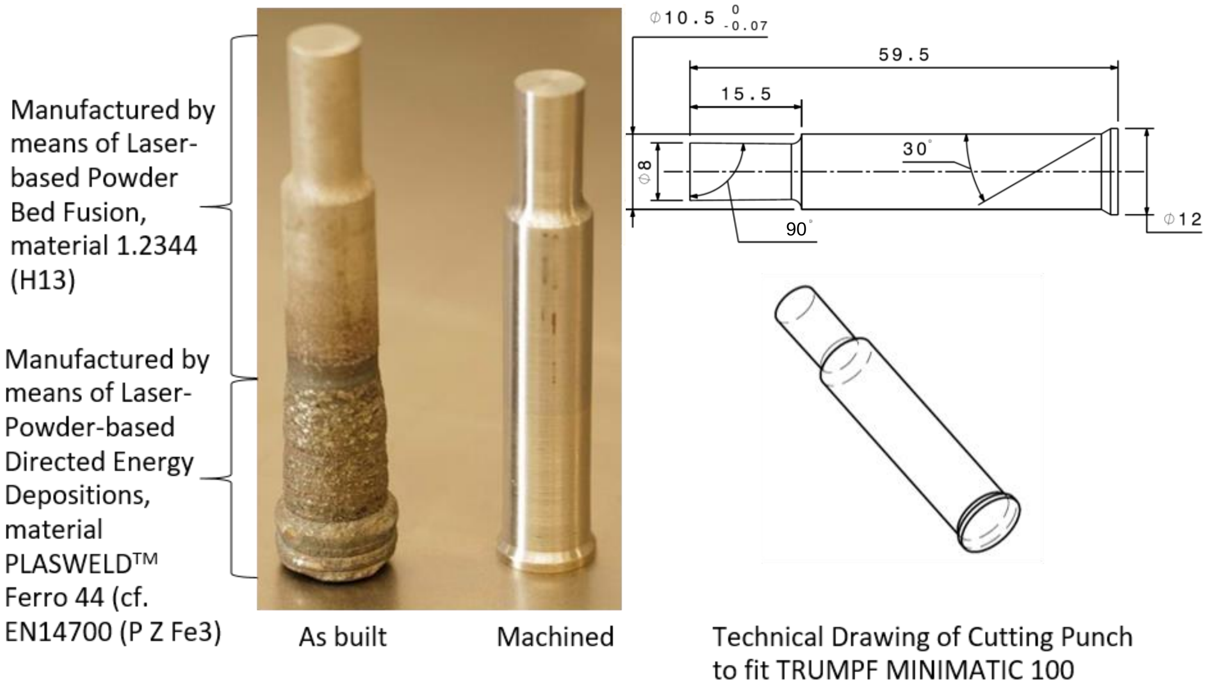

Figure 1: Hybrid printed 8 mm-cutting punch; left: as-built condition and (middle) machined by means of turning and grinding; right: technical drawing of cutting punch

After manufacturing of the cutting punch with a diameter of 8 mm, this tool was tested by applying 800 strokes in deep-drawing steel (DX56D). This was to validate that the printed material is, in general, suitable for the desired application. After successful completion of this pre-test, a 38,088 stroke test was planned. To ensure ideal starting conditions, the punch was reworked and sharpened by means of turning and grinding, thereby the diameter in the area of the cutting edge was reduced to 6 mm. The final grinding process ensures that a surface roughness Ra < 0.8 µm is achieved on the face and lateral surface of the cutting punch. No specific target value for surface roughness is available for the utilized machine type.

With the described starting condition, the punch with a diameter of 6 mm was tested with up to 38,088 strokes in deep-drawing sheet (DX56D) as well as higher-strength dual-phase steel (DP600). The evaluation of the wear test showed that the cutting edge radius changed from 1.1 µm to 12.6 µm. In summary, it can be stated that the additively manufactured cutting punch meets the requirements comparable to conventionally manufactured ones as far as this test can assess. Further tests with regard to durability are planned and necessary for a final assessment.

Experimental Design and Equipment

Within this section, the experimental set-up and the laboratory equipment used are described. Moreover, the specifications of the tool material and the sheet metal materials are introduced.

Materials

Metal Powder H13 (1.2344)

The metal powder to be qualified for PBF-LB/M is the "H13 Hot Work Tool Steel" provided by Oerlikon (Freienbach, Switzerland), cf. Table 1 and Table 2. This powder, with the DIN EN ISO 4957 code 1.2344 (X40CrMoV5-1), was produced by gas atomization and exhibits therefore an almost ideal spherical shape.

Table 1: Chemical composition of H13 powder

Alloying elements in percent by weight [%]					
Fe	**Cr**	**Mo**	**Si**	**V**	**C**
Balance	5.2	1.3	1.0	1.0	0.4

Table 2: Particle size distribution and Hall flow of H13 powder

Particle size distribution and Hall flow				
Nominal	D90 [µm]	D50 [µm]	D10 [µm]	Hall Flow [s/50 g]
-45 +15	50	34	21	≤ 25

Sheet metal – Dual-Phase Steel DP600 (1.0936)

Low-carbon dual-phase steel DP600 has a ferritic basic structure in which a hard martensitic second phase is embedded, often in the form of an island. The embedded phase causes hardness steps in the structure. Depending on the heat treatment, the material can also contain bainite. To increase the formability of dual-phase steels, retained austenite is embedded in the ferritic base matrix. The individual microstructure can be influenced by the cooling process during hot-dip galvanizing. The percentage chemical composition by weight of the dual-phase steel was determined with an optical emission spectrometer and is shown in Table 3. The proportions of the alloying elements in the material are within the tolerance range of the specifications in DIN EN 10346:2015 (2015) [9]. The present material is used for structural and safety components in automotive engineering.

Table 3: Alloy composition of dual-phase steel DP600 determined with an optical emission spectrometer

Alloying elements in percent by weight [%]										
Fe	**C**	**Cr**	**Mo**	**Mn**	**Al**	**Si**	**B**	**V**	**Ni**	**Cu**
Balance	0.154	0.194	0.010	1.97	0.712	0.099	0.001	0.007	0.029	0.031

Sheet metal – Deep Drawing Steel DX56D (1.0322)

The cold-rolled unalloyed steel with the short designation DX56D is used for cold forming due to its very good formability. As a result of its low carbon content and its high ductility, it is well suited for deep drawing. Deep-drawn and stretch-formed components that are difficult to form, such as oil pans, bottom plates or side walls, are made from this material. An examination of the microstructure shows that this deep-drawing steel has a pronounced ferritic microstructure with occasional carbides embedded in it. The material has an A-grade surface. The chemical composition was determined with an optical emission spectrometer and is visualized in Table 4. The proportions of the individual, selected alloying elements are within the respective tolerance range according to the specifications of DIN EN 10130:2007 (2007) [10].

Table 4: Alloy composition of deep drawing steel DX56D determined with an optical emission spectrometer

Alloying elements in percent by weight [%]								
Fe	**C**	**Si**	**P**	**S**	**Mn**	**Ti**	**Cr**	**W**
Balance	0.012	0.002	0.006	0.006	0.095	0.053	0.026	0.011

Additive Manufacturing Equipment

As PBF-LB/M-system, the AL3D-Metal250 from ALPHA LASER GmbH (Puchheim/Munich, Germany) with performance characteristics as shown in Table 5 was utilized.

Table 5: Parameter of the PBF-LB/M-system

Parameter [unit]	**Value**
Laser type, wave length [nm]	Fibre laser, 1,070
Max. Power [W]	250 cw-mode
Scanning speed [m/s]	max. 5
Build platform diameter [mm]	50

For Laser-powder-based Directed Energy Deposition, the AL FLAK 1200 also from ALPHA LASER GmbH was used, cf. Table 6.

Table 6: Parameter of the Laser-powder-based Directed Energy Deposition

Parameter [unit]	Value
Laser type, wave length [nm]	Fibre laser, 1,064
Max. Power [W]	1,200 cw-mode
Weld spot size [mm]	0.2 – 3.5
Rotating speed [1/s]	0.35

Shear Cutting Equipment

The relevant process parameters for carrying out the shear cutting process are shown in Table 7. At the start of the experiment, the cutting edge of punch and die have a sharp-edged condition honed with a glass block. The initial cutting edge radius for each active element is approximately 1 µm to 2 µm. The cutting edge radius of the active elements was recorded before the test using equipment MarWin XC 20, PCV (Mahr GmbH, Germany). Furthermore, the punched out pieces were collected for each sheet of metal. To determine the geometry of the cut surface, the same device from Mahr GmbH was used.

Table 7: Parameter of the shear cutting process

Parameter [unit]	Value
Sheet thickness [mm]	0.8 (DX56D), 1.0 (DP600)
Type of cutting line [-]	Closed
Punch diameter [mm]	6.0 (8.0 only for pre-test)
Shear rake angle [-]	Full-edged, pressing
Stroke per minute [1/min]	300

The feed rate between the cutting operations was selected large enough to prevent mutual interference of the cutting processes due to material hardening. The active tool elements wear out without preferential alignment. A punch press TRUMPF Minimatic 100, Germany was used to carry out the shear cutting process. The press has the following performance characteristics (Table 8).

Table 8: Performance characteristics of the punch press TRUMPF Minimatic 100

Parameter [unit]	Value
Max. force [kN]	150
Max. thickness of sheet metal [mm]	4
Max. stroke per minute [1/min]	300
Tool magazine [-]	9 tools

Qualification of PBF-LB/M for the processing of tool steel H13

Tool steel H13 (1.2344) is often being processed by means of applying pre-heating to the build plate. This leads to a reduction in the temperature difference that needs to be caused by the laser to melt the powder and which has to be cooled down again. Therefore, hot cracks are less likely to occur and the processing of H13 powder tends to be more robust.

Within this contribution, a machine was used that does not offer a pre-heating option. For this reason, a process parameter study was conducted in order to allow for a processing at ambient temperature. In order to decrease the size of the melt pool, a layer thickness of 30 µm was chosen as basis for these tests.

In addition to the layer thickness, many factors influence the quality of the printed samples, including the properties of the metal powder (e.g. grain size distribution and morphology) [4]. The energy input of the laser and its dynamics in terms of scanning speed and distance between the irradiated paths (hatch distance) are significant influencing variables for PBF-LB/M. Often times these factors are summarized in the literature as the formula for calculating the volume energy density (VED) (Formula 1) [11].

$$\boldsymbol{VED} = \frac{\boldsymbol{P}}{\boldsymbol{v} \cdot \boldsymbol{h} \cdot \boldsymbol{t}} \qquad \text{Formula 1}$$

VED is defined as the ratio between laser power P and the product of scanning speed v, hatch distance h and layer thickness t. Thus, it expresses the amount of energy introduced per volume. To find out the ideal set of parameters VED itself is not enough. The parameters in the equation for VED must each be kept in a suitable range and thereby form the so-called parameter window.

Design of Experiment

Design of Experiments (DoE) was used in order to allow for an efficient and systematic parameter identification. For this study, data analytic software MODDE Pro 13 (Sartorius AG, Umeå, Sweden) was used. As a DoE method, Face Centered Central Composite Design (CCF) was utilized. CCF is based on a complete, two-stage experimental test plan and is supplemented with a fractional factor plan. The CCF can be thought of as a cube where each axis represents a factor that is varied.

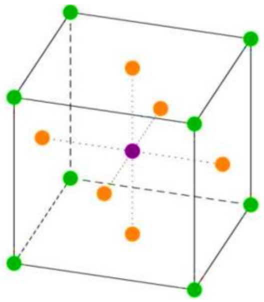

Figure 2: Illustration of Face-Centered Central Composite Design (CCF), following Siebertz et al., 2017 [3], green: form cube-shape, orange: additional experiments in star-shape, purple: additional experiment in cube’s center

Following Siebertz et al. [3], the base values for the two-stage experimental design are depicted by green dots (cube-shape, cf. Figure 2), supplemented by additional experiments indicated by orange dots (star-shape in Figure 2). The central point of reference is denoted by the purple dot at the cube's center. In the CCF, the star-shaped points are centered on the outer surfaces of the cube. The CCF experimental plan in the form of a design matrix is shown in Table 9.

Table 9: Matrix of the CCF, two-stage experimental test plan: first Test No. 1 to 8, second Test No. 9 to 15;
+: upper limit value, -: lower limit value, 0: middle value

Test No.	A	B	C
1	–	–	–
2	+	–	–
3	–	+	–
4	+	+	–
5	–	–	+
6	+	–	+
7	–	+	+
8	+	+	+
9	–	0	0
10	+	0	0
11	0	–	0
12	0	+	0
13	0	0	–
14	0	0	+
15	0	0	0

This CCF approach shortens the test plan compared to a full-factorial design from 27 experiments (3 factors, 3 stages) to a total number of necessary trials of 15. The result of the CCF with three input variables is a second-order polynomial with one constant term, three linear terms, three interaction terms, and three quadratic terms, as follows [3]:

$$\boldsymbol{y = a_0 + a_1x_1 + a_2x_2 + a_3x_3 + a_{11}x_1^2 + a_{22}x_2^2 + a_{33}x_3^2 + a_{12}x_1x_2 + a_{13}x_1x_3 + a_{23}x_2x_3}$$

Formula 2

Whereas, x_1, x_2 and x_3 are the input variables and y is the expectation response. The coefficients a_0, a_1, … a_{23} can be calculated from the vector of the experimental response $\boldsymbol{Y}$, i. e. the measured density, and the factor matrix $\boldsymbol{X}$.

$$\boldsymbol{a = (X_t \cdot X)^{-1} \cdot X_t \cdot Y}$$

Formula 3

Input and output variables

The input variables (Table 10) originate from the VED and were varied according to the chosen CCF. Hereby, the choice of the boundary limits is important and was derived from literature [5, 6].

Table 10: Limits of process parameter input variables

Input variables	Symbol	Lower limit	Upper limit	Unit
Laser power	P	110	160	W
Scanning speed	v	1,000	1,600	mm/s
Hatch distance	h	0.045	0.06	mm

Output variable	Symbol	Unit
Relative density	ρ	%

Experimental specimen dimensions

To evaluate parameters, specimen with cubical dimensions of 8 x 8 x 8 mm³ with a 0.8 mm thick bar, cf. Figure 3, were manufactured according to the various combinations of processing parameters shown in Table 11 using the AL3D-METAL 250 machine. The 0.8 mm thick bar allows for an impression of material properties in rather filigree part areas directly next to the bulky rest of the cube specimen.

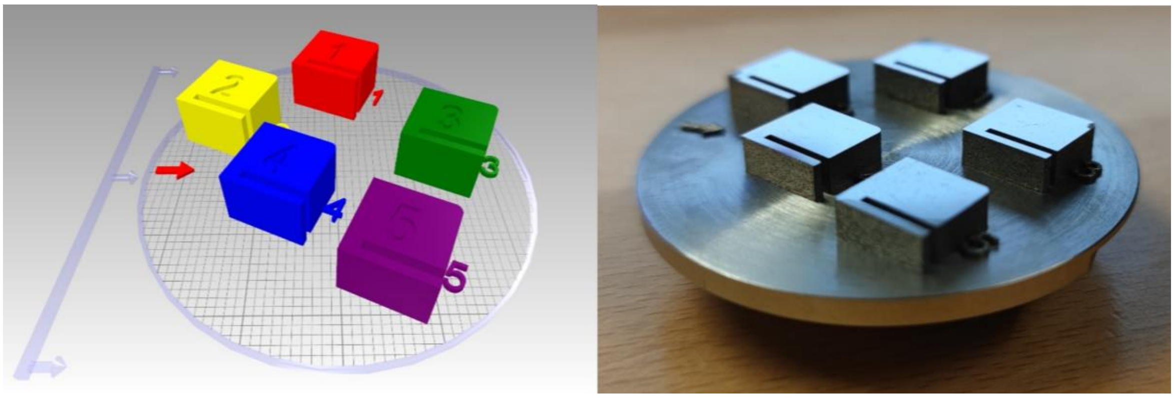

Figure 3: Left: 5 specimen cubes representing different sets of parameters in the AL3D-OS print preparation software; right: cubes in printed form after polishing; arrow indicates protective gas flow direction

To analyze the relative density, the samples were wet-separated using a separating machine (Secotom-15, Struers, Denmark) and prepared on a grinding and polishing device (Labopol-25, Struers, Willich Denmark). First, the surfaces to be measured were roughly pre-sanded using a 200 µm grinding disc. Second, the polishing was done with the help of 9 and 3 µm diamond suspensions on the respective polishing discs.

Evaluation of Relative Density

The assessment was conducted using a VHX-7000 digital microscope from Keyence, Japan. A motorized table of the microscope allows the entire cross-section to be analyzed by stitching the pictures together. The images were taken using the ZS20 objective lens at a 50x magnification with coaxial illumination and then subjected to automatic area measurement using the microscope's internal software. The software detects pores based on the white-black threshold and subtracts them from the total area of the region to be extracted. The marked areas were then manually checked and spots with dust, scratches or water traces were removed. The result is a two-dimensional section of the volume and can thus be interpreted as a relative density in percent and used for optimization. Figure 4 provides an example.

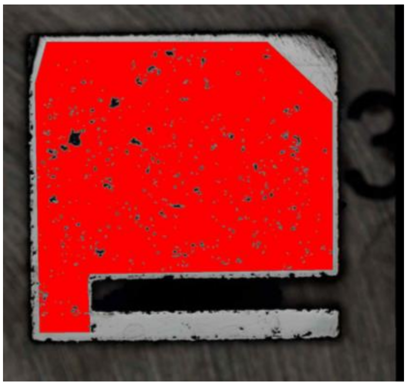

Figure 4: Example of a density measurement based on sample no. 3 (cf. Figure 3, left) resulting in a relative density of 97.99% within the red evaluation area

Results and Discussion

Additive Manufacturing

As a result of the parameter study, tool steel H13 can be processed with a relative density of more than 99.99%. This should result in mechanical properties comparable to conventionally manufactured H13. The results of the printed test cubes are summarized in Table 11.

Table 11: Overview on experimental results of the manufactured test cubes

	Input variables				**Output variable**
No.	P **[W]**	v **[mm/s]**	h **[mm]**	**VED [J/mm³]**	ρ **[%]**
1	110	1,000	0.045	81.2	99.717
2	160	1,000	0.045	118.5	99.930
3	110	1,600	0.045	50.9	97.985
4	160	1,600	0.045	74.1	99.959
5	110	1,000	0.060	61.1	99.599
6	160	1,000	0.060	88.9	99.948
7	110	1,600	0.060	38.2	95.748
8	160	1,600	0.060	55.6	99.829
9	110	1,300	0.053	53.2	99.622
10	160	1,300	0.053	77.4	99.909
11	135	1,000	0.053	84.9	99.991
12	135	1,600	0.053	53.1	99.815
13	135	1,300	0.045	76.9	99.957
14	135	1,300	0.060	57.7	99.939
15	135	1,300	0.053	65.3	99.689

To better visualize the ideal parameter set window a contour plot can be used (Figure 5). With the help of MODDE 13 it was possible to derive the ideal set of parameters for the

H13 tool steel by approximation of the optimizer, which is a part of MODDE 13 Software. The optimizer uses desirability functions for each response and searches for the combination of factor settings that predicts a result as close as possible to the desired target. For this study, a laser power P of 136 W, scanning speed v of 1,133 mm/s and hatch distance h of 0.049 mm was found to be ideal according to the applied algorithms within the MODDE 13 software. It seems likely that rounding of these values will lead to similar results due to limited machine accuracy.

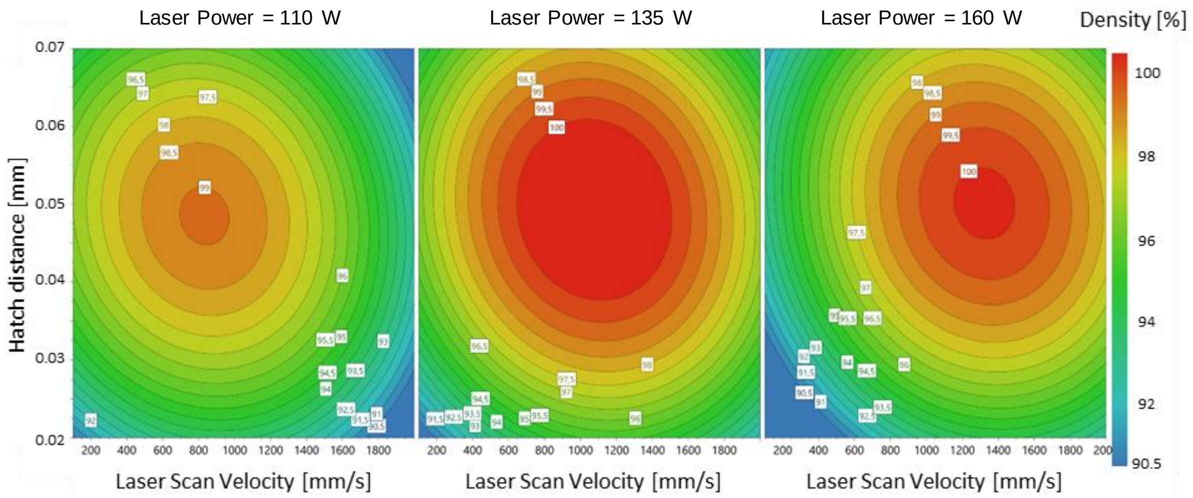

Figure 5: Contour plots illustrating density (color scale) as a function of scanning speed and hatch distance at power settings of 110 W, 135 W and 160 W

Shear Cutting

Pre-test

Based on the promising results described in the section above, the cutting punch was produced by PBF-LB/M, enlarged by Laser-powder-based Directed Energy Deposition (cf. Figure 1), mechanically finished and tested in a two-step-procedure. First, the hybrid manufactured 8 mm-cutting-punch (cf. Figure 1) was tested on a TRUMPF Minimatic 100 for 800 strokes. After this pre-test, the punch was analyzed by visual inspection and it was found that no visible wear, such as an edge breakout, was existent. A presentation of the results is omitted. As a result of this pre-test, the diameter of the front part of the cutting punch was reduced to 6 mm.

Wear and tear investigation

After 24,750 shear cutting operations using the material DX56D and the 6 mm-punch, no noticeable wear or breakout could be detected on the cutting edge of the hybrid manufactured cutting punch. In order to increase the punch load, the material DP600 was used in the further tests. The microscope images (cf. Figure 6) show that no breakout occurred at the cutting edge of the punch using a DX56D for strokes 1 to 24,750 and DP600 for strokes 24,751 to 38,088.

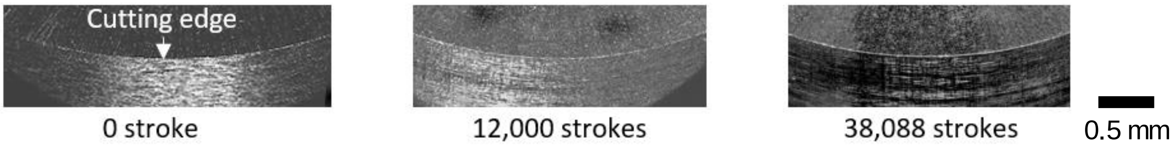

Figure 6: Microscope images of the cutting edge at three different stroke counts

In order to determine the process-specific abrasive tool wear, the cutting edge of the punch was measured tactilely. The increase in cutting edge rounding is illustrated in Figure 7. After 38,088 cutting operations, the cutting edge radius has increased by 11.5 µm. Thus, the recorded process-specific abrasive tool wear is within the usual range.

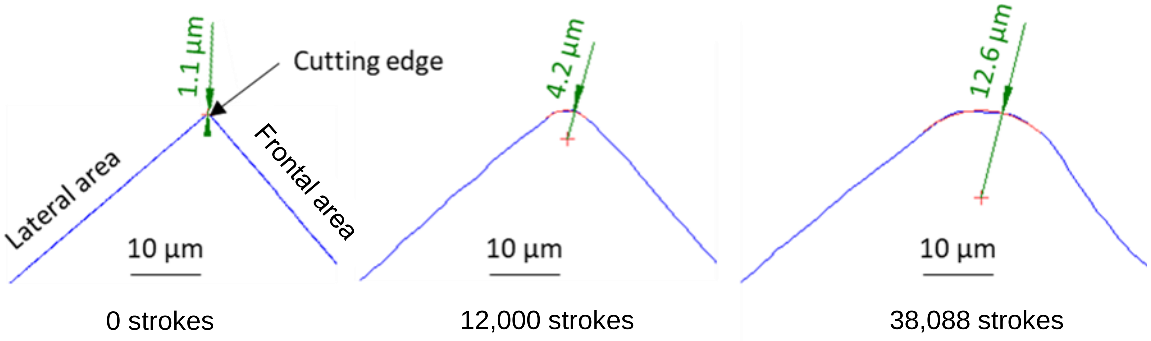

Figure 7: Left: sharp-edged cutting edge; center: tool wear after 12,000 strokes; right: tool wear after 38,088 strokes

Conclusion and future work

Additive manufacturing, specifically using the H13 tool steel, has demonstrated potential for the use as shear cutting punch. The results from the 38,088-stroke-test are promising, with the cutting edge radius increasing by 11.5 µm from its initial condition. Notably, no other damages were observed on the punch, indicating the robustness and durability of the additively manufactured material.

The success of this study suggests further investigations that additive manufacturing can be a viable alternative to traditional manufacturing methods for producing cutting punches, especially when considering the wear resistance and longevity demonstrated. Extended wear tests, beyond the 38,000 strokes, could provide more insights into the durability and potential lifespan of these punches.

Acknowledgement

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