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Post-processing of additively manufactured cutting edges by laser ablation

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Abstract

In the packaging industry, cutting dies are used to process paper based material. The dies are mainly manufactured via steel strip principle, which consists of many manual steps and is difficult to automate.
Laser material processing represents a promising approach to simplify manufacturing. This study realized additively manufactured cutting edges post-processed by laser ablation to achieve a defined final profile shape. First verification shows that laser ablation appears to be attractive for finishing of additively manufactured cutting edges.

Keywords: additive manufacturing; laser ablation; post-processing; hybrid production; cutting edge; angle of incidence

1. Introduction

Cutting dies are used to process paper based material in the packaging industry [1]. Processing of cardboard mainly uses the knife cut principle [2]. During flatbed die cutting, the die cutter performs a linear movement with its installed cutting die (Fig. 1). The cutting die penetrates the material to be processed with its knife-like cutting edge and separates it.

For conventional manufacturing of cutting dies, steel strips with standardized dimensions of 23.8 mm in height and 0.71 mm in width are integrated into multiplex boards [3]. The contours of the cutting geometry are mechanically pre-cut and steel strips are manually driven into the wooden substrate.

The standard cutting angle for a double-sided chamfer is 54° with an angular tolerance of +0°/ -2° [4]. This angle is manufactured by chipping. Further requirements regarding height of cutting lines exist.

To avoid numerous conventional manufacturing steps, laser material processing appears to be a promising alternative to automatically realize flexibly built cutting edges derived for specific applications. With Selective Laser Melting (SLM), manufacturing of arbitrarily formed structures is possible [5]. During the cyclic process a thin layer of single-component powder is applied, completely melted by the energy of the laser, solidified and fused with the previous layer. Finally, the lift table is lowered by a layer thickness of 30 µm up to 60 µm [6] and the process repeats.

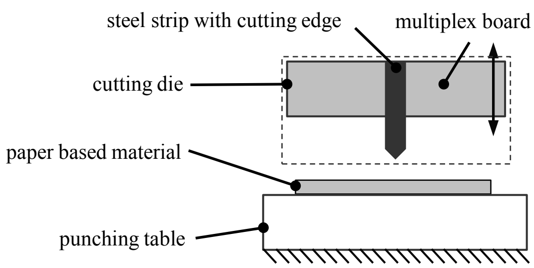

Fig. 1. Principle of flatbed die-cutting.

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SLM is suitable for the manufacturing of functional components, has an optimal material utilization, and opens up new possibilities for the design of products.

However, a disadvantage is the resulting surface morphology in terms of final profile shape and surface roughness [7]. The so-called stair-case-effect [8,6], due to the rather large layer thickness, limits the achievable surface quality. In addition to that, loose or partially melted powder particles may stick to the surface [7,9].

To comply with tolerances, post-processing of SLM built cutting edges is required. Thus, laser ablation is used. This technology enables processing without cutting forces [10], which is important for high cutting lines. Profile shapes, for example different angles in one cutting edge, seem to be freely designable with laser as tool. The laser beam diameter is usually smaller than the finest resolution of conventional chipping tools, so that more precise results are possible.

During laser ablation material is removed from a surface using high-intensity laser pulses [11]. The irradiated energy of each pulse is absorbed by the solid and an evolving thermal wave propagates into the material. This heat development causes melting and evaporation of the material [12].

Typically, the laser beam is orthogonally guided over the surface. Positioning pulses next to each other results in an ablated layer. Consecutively ablated layers form an ablated volume. Typical layer thicknesses range from 1 µm to 5 µm [13].

Layer-wise laser ablation leads to an approximate parallel shift of the surface. This is particularly pronounced on rough, uneven surfaces, such as those generated by SLM. The ablated volume can be controlled with sensors, which monitor each layer. However, this is not usual and cost intensive. A specific correction of the profile shape and simultaneous smoothing of the surface is consequently impossible using the present approach with orthogonal laser beam guidance.

A new approach for post-processing of additively manufactured structures by laser ablation is developed and tested in the present study. The laser beam should be guided as parallel as possible to the SLM surface during processing. The ablating laser is orientated towards the target profile shape. The actual uneven and rough profile shape is not considered.

The aim is to build up near-net shape SLM profiles on conventional sheet metal which subsequently are accurately laser ablated to target profile shape using different angles of incidence (Fig. 2). Both target profile shape and required surface roughness shall be reached in one process step.

For this purpose, the influences of angle of incidence and pump current on cutting edges are investigated. Furthermore, three different scanning patterns are tested. Finally, optimized parameters for post-processing are deduced and verified.

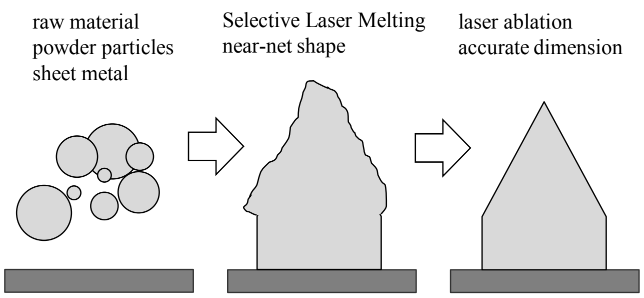

Fig. 2. Workflow schematic.

2. Material and Methods

For the welding process, powder and conventional sheet material must have low and similar carbon content for good welding properties. As powder material, commercially available tooling steel 1.2709 (maraging steel) is chosen. It has a carbon content of 0.02 %, is hardenable and its powder grain size is between 20 µm and 50 µm. The stainless steel 1.4301 also has a low carbon content of maximum 0.07 %. This steel is chosen as the substrate material with a thickness of 3 mm, width of 30 mm and length of 40 mm.

Additively manufactured profile shapes of the cutting edges are derived from the line standard [4]. This profile has a height of 1 mm, a width of 0.71 mm as well as a nominal cutting angle of $\varphi_N = 54°$ in data preparation (Fig. 3). The specimen are 26 mm long. In order to make sure that the profile shape is larger than the target and can be post-processed, an allowance of 0.2 mm is added to the cutting edge in CAD data. Preliminary tests show that an allowance of 0.2 mm is expedient. The reference plane of ablation is set on top of it. Layers to be ablated and the reference plane are 90° relative to the target profile shape.

Standard preformed metal sheets are fixed on the building platform to prepare the SLM process. Thus, they cannot be pushed away by the recoater or be deflected by absorbed laser energy. Cutting edges are additively manufactured on a commercially available SLM machine with a 200 W continuous wave fiber laser and focal spot diameter of 80 µm. Laser parameters are set to a scan speed of 800 mm/s, laser power of 180 W and a hatch distance of 0.1 mm with a layer thickness of 30 µm to achieve a ≥ 99.9 % dense specimen.

After the SLM process, specimens are fixed in the ablation machine. For laser ablation a ns-pulsed fiber laser with 200 W average output power and a focal spot of 60 µm is used. The laser setup consists of 8 axes, 5 CNC and 3 optical, for precise positioning and ablation.

In preliminary tests parameters for orthogonal laser ablation have already been determined on an even SLM specimen. The focus of the investigation is on surface roughness and ablation rate. Therefore, a pulse length of 120 ns, repetition rate of 160 kHz and scan speed of 4,000 mm/s as well as track distance of 25 µm is constantly set for the following ablation.

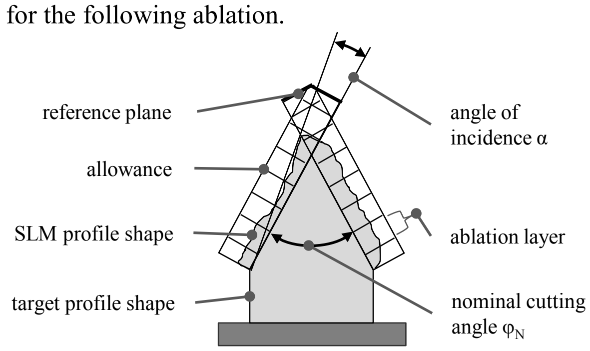

Fig. 3. Definition of terms for cutting edges.

Near-net shape cutting edges are post-processed under variations of parameters, which Table 1 presents.

Table 1. Laser parameter for post-processing of SLM profiles.

angle of incidence α in °	pump current in %	scanning pattern
0 – 27	30 – 80	random, crossed, profile parallel

Different angles of incidence α, which are measured from the orthogonal of the reference plane, from 0° to 27° are chosen. Pump currents are set in a range between 30 % and 80 %. The investigation is additionally carried out under consideration of three scanning patterns: random, crossed and profile parallel (Fig. 4). If not explicitly mentioned, laser ablation is conducted with a random scanning pattern. A segment of 4 mm length is ablated with each combination of parameters on both sides of the cutting edge.

One has to take into account that an angle of incidence of 0° causes a shadowing of the laser beam by the part, resulting from the caustic of the laser beam. At an angle of incidence larger than 0° there is no shadowing.

The post-processed cutting edges are evaluated regarding cutting angle and surface roughness. To measure cutting angles 3D images of profile shapes are taken by a confocal laser scanning microscope. Evaluation is based on seven cross sections per single cutting edge. Additionally, 2D cross sections are made by an optical microscope. The surface roughness S_a is measured according to ISO 25178 [14] with six measuring points each. Consolidation of these results yields optimized parameters to be transferred to demonstration.

3. Results and Discussion

SLM specimens have been successfully built up on the 3 mm metal sheets (Fig. 5a). As expected, cutting angles and surface roughness do not meet requirements. An exemplary cross section is shown in Fig. 5b, in which a cutting angle of $\varphi = 51°$ and a surface roughness of $S_a = 8.5$ µm are shown.

Selected results of laser ablation are shown below. No measurable cutting edge has been formed using a pump current of 80 % with an angle of incidence of at least 15°. Therefore, measuring points are missing in the following two figures.

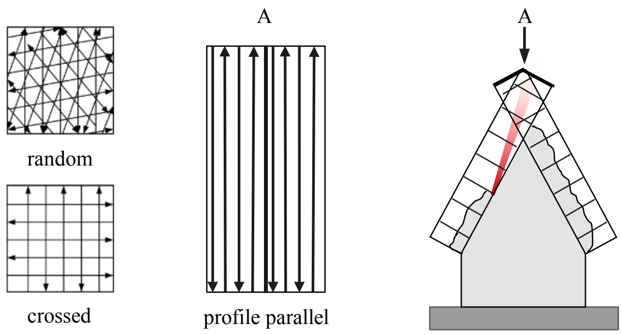

Fig. 4. Evaluated scanning patterns.

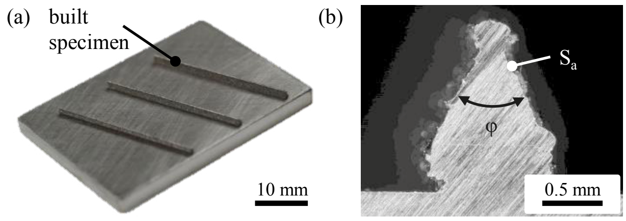

Fig. 5. (a) Built linear specimen; (b) Cross section of SLM built specimen.

Dependency of the resulting cutting angle on the angle of incidence and pump current is illustrated in Fig. 6. For simplification the deviation of the cutting angle from the target value $\varphi_N = 54°$ is shown. It is obvious that with increasing pump current the target angle is achieved at a smaller angle of incidence. Tolerated cutting edges are achieved for angles of incidence between 6° and 20° regardless of the pump current (process line).

Dependency of the resulting surface roughness on the angle of incidence and pump current is shown in Fig. 7 as second criterion. Surface roughness decreases with a smaller angle of incidence. It scatters greatly at the considered pump currents at angles of incidence above 20°. The highest surface quality results from angles of incidence smaller than 7° regardless of the pump current.

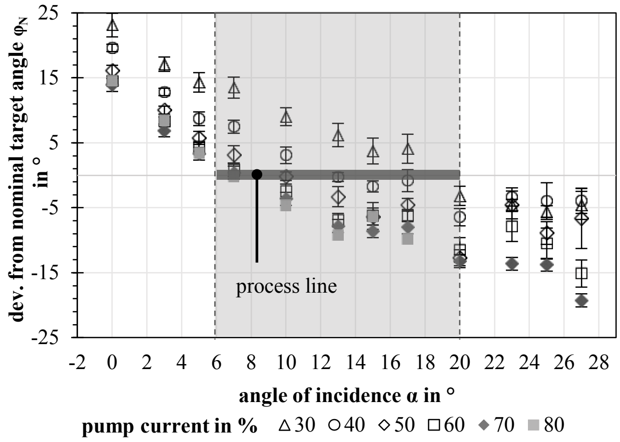

Fig. 6. Dependency of cutting angle on angle of incidence and pump current.

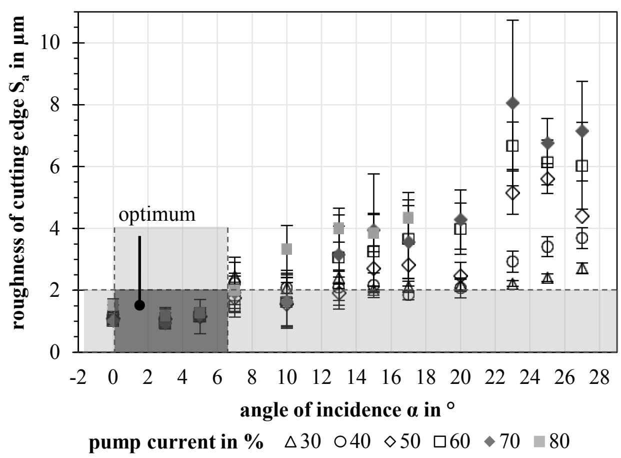

Fig. 7. Dependency of roughness on angle of incidence and pump current.

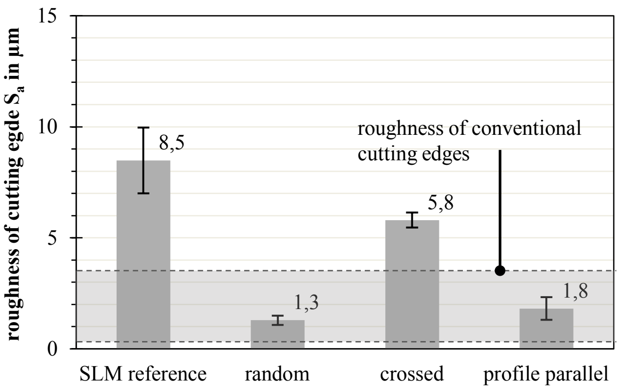

Fig. 8. Impact of scanning pattern on surface roughness.

The larger the angle of incidence the more ablation behaves similarly to orthogonal processing in which single pulses are placed next to each other leading to rougher surfaces. This effect is increased by higher pump currents. As soon as the angle of incidence falls below 7°, laser ablation again takes place approximately parallel to the edge. In that area the laser smooths the surface in addition to shaping it.

The impact of different scanning patterns on the surface roughness of cutting edges is presented in Fig. 8. Cutting edges are ablated with an angle of incidence of 8° and a pump current of 50 % as these parameters produce a cutting angle within the tolerated range. Reference values are both roughness of additively and conventionally manufactured cutting edges. Conventional roughness has been measured at several different cutting edges and shows a range of S_a between 0.3 µm and 3.5 µm. The highest surface quality is realized with the random pattern (S_a = 1.3 µm) followed by the profile parallel pattern (S_a = 1.8 µm). The surface structure is homogenous due to laser vectors that impact the resulting surface with various angles respectively parallel in each layer. In contrast, the crossed scanning pattern causes a surface roughness of S_a = 5.8 µm. The cutting edge is characterized by grooves that are induced by orthogonal laser vectors. Both random as well as parallel scanning patterns achieve surface roughness comparable to conventional cutting edges.

Considering the presented results as well as further geometric and time-based criteria, optimized parameters are determined. These are a random scanning pattern combined with a pump current of 77 % for maximized productivity and an angle of incidence of 0° for lowest surface roughness and smallest cutting radius. To achieve the desired cutting angle by this combination, the orientation of the reference plane has to be adapted accordingly.

For verification a linear line with target cutting angle of 45° has been laser ablated (Fig. 9).

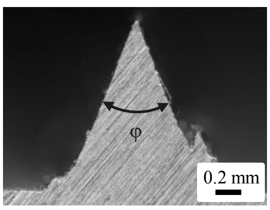

Fig. 9. Cross section of post-processed cutting edge for verification.

For this specimen surface roughness and the cutting angle are within the tolerance range. A surface roughness of S_a = 1.3 µm and a cutting angle of φ_{45} = 43.7° ± 0.4° are measured.

4. Conclusions and Outlook

Post-processing of additively manufactured cutting edges has been successfully demonstrated. It is possible to build on 3 mm sheet metal substrates and to achieve target profile shapes within tolerances. The main influencing factors on cutting angle are the angle of incidence and pump current. A dimensionally accurate profile shape generation and surface finishing is possible in a single process step without additional sensor technology by means of oblique laser ablation.

Subsequently, the potential to produce undercuts by this method which cannot be conventionally manufactured needs to be evaluated. Next to linear contours, the procedure has to be validated for curved and rectangular ones. The relation between the optimum angle of incidence and the angle of aperture should be considered in further investigations.

An entire laser-based process has been realized. This approach holds potential for implementation of an integrated process chain for additive manufacturing.

Acknowledgements

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