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Comparative analysis of variants of the CYCLAM-technique

Alexander F. H. Kaplan, Ramiz S. M. Samarjy, Jesper Sundqvist

Luleå University of Technology, Department of Engineering Sciences and Mathematics, 971 87 Luleå, Sweden

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Abstract

When a laser beam develops a quasi-steady state boiling front in a metal, the ablation pressure can eject the melt in a controlled manner. This droplet-jet can be applied for controlled deposition, to feed additive manufacturing. Melt ejection from a waste part even enables efficient recycling to immediately print a new part, termed CYCLAM. Several technique variants are possible, which are here presented, assessed and compared for the first time. A simplified model identifies constraints from melt ejection and beam reflection directions. One promising variant is selective surface drop ejection, e.g. on electronic parts.

Keywords: additive manufacturing; remote cutting; recycling; boiling; model; metal; waste; high speed imaging; criteria; environment.

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1. Introduction

Additive Manufacturing, AM, (also termed 3D-printing) of metal parts is based on feeding of powder or wire that is melted along a path, e.g. by a laser beam (then denoted LAM). Since these metal consumables have to be separately produced, they cause additional costs and environmental impact. In addition, the portfolio of commercial wires and powders is limited. The range can be extended by powder mixing or by (powder) metal-cored wires.

Recently an alternative technique has been demonstrated by Samarjy and Kaplan (2017) and by Kaplan and Samarjy (2017) that enables to even apply metal sheets or other forms of massive metal as the feeding material, which means a literally unlimited range of available metal alloys. One option of this technique is to apply waste metal for feeding, which enables highly efficient recycling in terms of low environmental impact, costs and use of resources, as will be studied and discussed in the present paper. The technique of recycling by laser-induced boiling to feed additive manufacturing is termed CYCLAM, Kaplan and Samarjy (2017). Note that for the sake of simplicity, in the following we use the acronym even when applying new material as the feeding sheet.

Normally, additive manufacturing of metal parts is carried out either by preplaced powder (termed Powder Bed Fusion, PBF, or Selective Laser Melting, SLM) or by feeding of powder or wire (termed Direct Energy Deposition, DED, or Direct Metal Deposition, DMD). Favoured energy sources are laser beams, electron beams or electric arcs. Wire arc additive manufacturing, WAAM, enables high building rates but the limited precision usually requires post-machining, becoming a hybrid approach, see Karunakaran et al. (2010). Ding et al. (2015) have demonstrated strategies for overlapping tracks of WAAM. The most applied metals are Ti-alloys, stainless steel and Ni-alloys, particularly driven by medical, aerospace and turbine applications. Typical for AM are anisotropic grain growth and in turn material properties, as shown by Keist and Palmer (2016) for DED of Ti-alloys. The potential and limits of Laser Metal Deposition, LMD, with respect to accuracy and performance are described by Brueckner et al. (2017). PBF was recently studied in more detail by Computational Fluid Dynamics, CFD, of the melt flow and by High Speed Imaging, HSI, particularly by Khairallah et al. (2016).

Different are drop-on-demand-techniques, DOD, where typically a small feeding sample is molten and ejected as sequential drops through a nozzle, e.g. for printing of electronic thin films. Dong et al. (2006) studied by HSI the drop and satellite separations. Drops were also generated by laser melting of wire followed by gravity-driven detachment, as observed by HSI by Bizjan et al. (2017). Luo et al. (2012) studied such technique for soldering.

The here presented CYCLAM-technique is based on accelerating melt in a controlled manner by laser-induced boiling. This mechanism, that governs keyhole laser welding but also laser remote cutting, was recently studied and understood in more detail by Eriksson et al. (2013) and by Pocorni et al. (2017). One main insight, that the laser beam generates melt waves that preferably travel along the beam direction, i.e. downwards in welding and cutting, inspired its controlled use for the CYCLAM-technique of Samarjy and Kaplan (2017). Drops are ejected downwards in an unwanted manner as root spatter in welding but deliberately during laser Remote Fusion Cutting, RFC, as observed by Wagner et al. (2013). In laser Remote Ablation Cutting, RAC, see Lutke et al. (2012), the melt is driven upwards, layer by layer grooving into the metal. RAC is limited to thinner sheets than RFC. Gas-assisted laser cutting is here avoided because of the jet impact on AM. Essential for CYCLAM is the fluid mechanic behaviour of the accelerating and detaching melt, along with its subsequent incorporation during AM. HSI is a powerful observation method for the melt flow, which was applied by Samarjy and Kaplan (2017), Dong et al. (2006), Eriksson et al. (2013) and Pocorni et al. (2017), as is CFD, e.g. by Pocorni et al. (2017) for studying the melt film front in RFC. Here variants of the CYCLAM-technique are presented and compared for the first time.

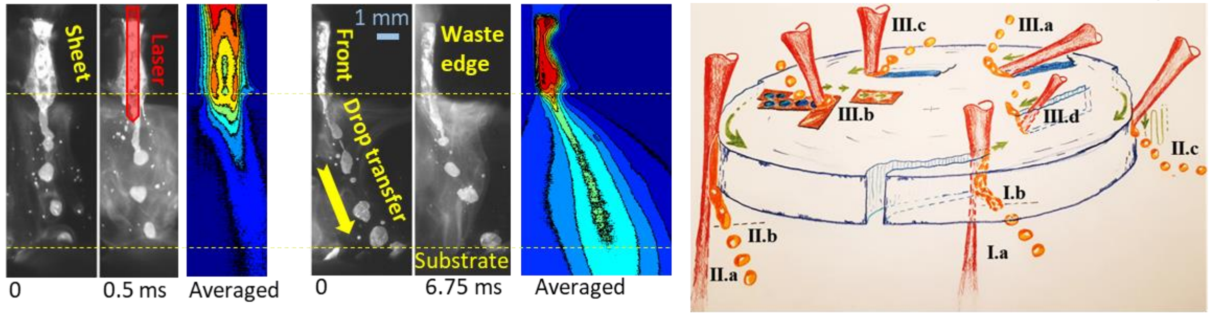
2. Methodological approach

Three variants along with six options for the CYCLAM-technique are proposed and defined, highlighting their differences. The concepts are assessed and compared concerning their potential and limits in terms of environment, recycling, costs, precision, performance, geometrical constraints and practical aspects. With respect to their technical opportunities and limitations, the technique variants are experimentally observed by HSI (for details see Samarjy and Kaplan (2017)) and analyzed by involving a simple mathematical process model. Depending on the technique variant, the processing front on the waste sheet has a different shape, which determines the direction of ejection of the melt as well as the directions of reflections of the laser beam. These key domains can be identified by drop- and ray-tracing. The front shape is approximated by a polynomial, based on the beam diameter. For the technical, environmental and economic analysis, six important aspects are defined, for discussion and comparison. In addition, key properties can be derived based on fundamental estimations of the process performance with respect to thermophysical properties of a chemical element, combined with process parameters and market prices.

3. Presentation, comparison and discussion of variants and options of the CYCLAM-technique

The main variants of the CYCLAM-technique under investigation are I. cutting through the gauge of a sheet, II. edge machining by ejection downwards at the edge of a sheet, III. surface ablation by driving drops upwards from a surface. These variants, denominated I.a, II.a and III.a ('.a' for regular), are distinguished through their different interaction region of a waste sheet or part to be processed by the laser beam, to generate the drop transfer.

Variant I, where drops are ejected underneath a sheet, from laser RFC, was applied first, to demonstrate CYCLAM. Based on laser-induced boiling, the melt is driven down a quasi-steady state *cutting* front that progresses through a metal sheet. Figure 1(a) shows high speed images and the greyscale-averaged melt jet. *Pros:* For sheets with constant thickness, cutting through the sheet is a very robust, self-adjusting process; the cut kerf enables clear, symmetric guidance of the melt; already proven to work properly. *Cons:* Not applicable, if the gauge is too large or varying; cannot be very selective; cannot machine off a part (surrounding material needed); the aspect ratio kerf width to thickness has fluid-mechanic limitations, when it comes to downscaling and precision.



(a) I.a Cutting through (b) II.a Edge machining (c)

Fig. 1. Two subsequent high speed images and a greyscale- and time-averaged plot of the mass flow [a.u.], view from the front between the waste sheet and substrate (both low C-steel Hardox, 3.2 mm thick; fibre laser, beam power 10 kW, beam diameter 680 µm, speed 3 m/min); (a) CYCLAM-technique variant I.a: cutting through, (b) II.a: edge machining (lateral beam displacement to the disc edge 0.5 mm inwards); (c) sketch of the beam incidence (green arrow: movement) and drop transfer from a waste metal disc, for the variants/options I-III/a-d.

Variant II applies the same technique but at the *edge* of a sheet, which is here termed *machining*. The conditions become asymmetric, see Fig. 1(b). The lateral position of the laser beam relative to the edge is an extra parameter, to carefully adjust. It was demonstrated that the resulting edge topology can be equally processed by a second run, as proof of feasibility to e.g. convert a whole disc radially inwards, layer-by-layer. *Pros:* Natural access from the side, e.g. for sheets and discs; can fully remove a part in a systematic manner; more options than for cutting; good access, e.g. for HSI and for ejection. *Cons:* Can be sensitive to lateral positioning; difficult to avoid beam transmission; risk for less robustness than cutting, because of less determined melt guidance conditions.

Variant III (not demonstrated yet) instead ejects drops from a *surface* upwards, again by a quasi-steady-state boiling front. Placing one track of *ablation* beside the other, a surface can be removed, then layer-by-layer into depth. The technique enables to remove surface layers and domains in a selective manner, too. *Pros:* Selective material transfer, even for coatings (e.g. PCBs); the drop-per-pulse-variant can enable systematic pixel-like raster removal of a surface and volume (voxel-, maxel-scheme); the grooving-option can guide the melt, like cutting; surface ablation provides the highest degree of creativity. *Cons:* Geometrical constraints for laser beam access as well as for AM-part building; less clearly defined ejection edge than for I,II, except when opting for grooving.

Options for these regular variants are possible; I.b,II.b: bridge transfer by continuous melt flow transfer, II.c: oscillating edge machining, applying III.a for II, down the edge, III.b: pw laser beam (not cw), aiming to detach one drop per laser pulse, III.c: backwards drop-driving instead of forward for III.a (laser tilting), III.d: grooving of a multi-track channel into depth, can be 3D. The geometrical conditions for the technique variants and options are illustrated in Fig. 1(c), when processing a waste disc. Figure 2(a) shows the different routes for the here proposed CYCLAM variants and options but also the main routes for established AM.

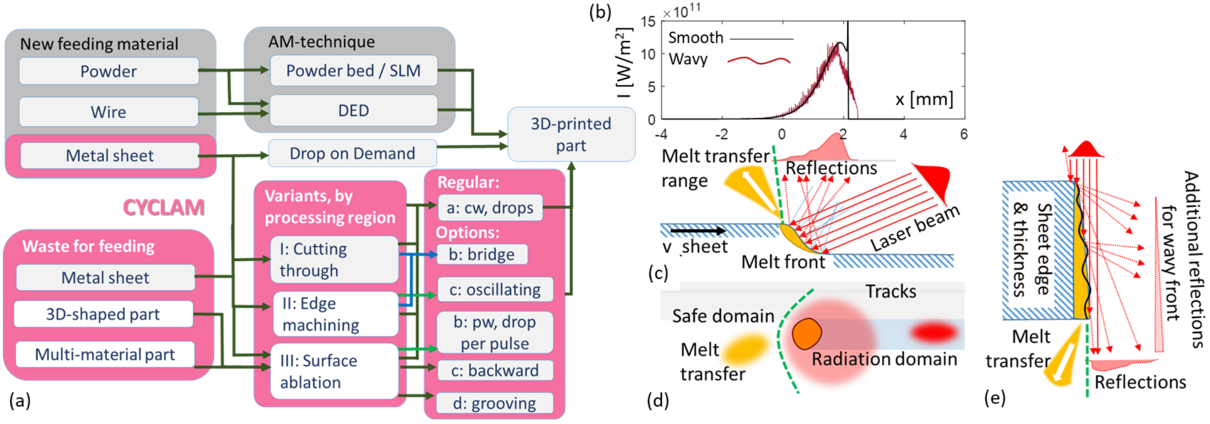


Fig. 2. (a) established AM-techniques, for metals (grey); here proposed routes for the variants and options of the CYCLAM-technique (cyclamen color); (b) calculated (steel, front length 2 mm, height 100 µm) horizontal reflection distribution I(x) upwards from an either smooth or wavy front as illustrated in (c) for variant I.a, surface ablation; (d) same, top view when modelling the processing front, showing resulting directions / domains of the drop flight and of the reflected laser beam, (e) similar for variant II.a: edge machining, side view.

For *cutting* or for *edge machining*, I.b,II.b, instead of drop ejection the melt transfer can take place by a direct *bridge flow* from the waste sheet to the AM-part. HSI has revealed that a 2-4 mm long melt column flows off the processing zone before breaking into drops. So far, bridging did not overcome this Plateau-Rayleigh instability.

For the *edge machining* variant, II, instead of a processing front over the whole thickness a transient erosion mechanism downwards can be imagined, similar to variant III, *oscillating* down a thicker edge. While the initial variant II.a has the disadvantage of accurate lateral positioning plus beam transmission losses, for II.c the beam can avoid these drawbacks by a more controlled manner to shear the melt off, in an oscillating up-down-sequence.

For *surface ablation*, *variant III*, several options are possible. Processing by a pw- instead of a cw-laser beam has the potential to eject, for proper parameters, exactly *one drop per pulse*, enabling a drop-on-demand technique, III.b. Different beam angles of incidence can offer the options to drive the drops either forward in travelling direction or *backward*, III.c. Apart from geometrically selective removal, the removal of surfaces or grooves and other 3D-geometries can be imagined. Grooves would resemble cutting with respect to clear guidance and flight direction accuracy of the drops. In the following, selected *key aspects* are briefly assessed for the variants I-III.

Environmental impact: Established recycling routes, see Reck and Graedel (2012) or Awasthi and Li (2017), cannot avoid impact from transport and several steps of processing, including manufacturing of the new product. CYCLAM offers among its various routes an ideal scenario that a manufacturing company converts a returned product out of service directly to a new product, via CYCLAM. Independent of the variant, this ideally requires merely the power consumption of the laser, resulting from wall plug efficiency, process absorptance and process efficiency for melting. The minimum energy required for melting (heated up to boiling temperature), can be derived from the thermophysical properties of the respective metal, e.g. for steel 1,5 kJ/g energy needed, Al 2,7 kJ/g, Au only 0,43 kJ/g. Preheating can further lower these limits, by 25-45%. From variants I,III waste remains.

Recycling potential: While the variants I,II are suitable for recycling of homogeneous metals (variant I mainly for sheets of constant gauge), III is applicable for almost any waste product with respect to shape and composition, as long as geometrical access is possible. III offers highly selective recycling, e.g. of Cu-layers on PCBs, indicated in Fig. 1(b), for III.b. Recycling of layers <10-100 µm thin (e.g. Ni, Au) might require modified approaches.

Costs: According to the above mentioned limited need for resources like processing steps or transport, also the

costs can ideally be kept very low, reduced to the laser system that carries out the CYCLAM-process, plus post-processing, if needed, or combination with other materials and manufacturing steps. The costs mainly arise from the laser and manipulation system. The investment widely can be planned proportional to the building rate, aiming at very high uptime. Basically the costs for the three variants I-III remain very similar. Transmission of a portion of the laser beam in variants I,II, or breaks (from path or pulse duty cycle) in variants II,III will cause higher costs.

Building rate - performance: The performance with respect to building rate can to some extent be chosen as a trade-off in relation to investment, layout and planned production volumes, limited by the above mentioned factors.

Precision: So far only rather coarse tracks were demonstrated (1-2 mm width and height, Samarjy and Kaplan (2017)), while downscaling by smaller beam focusing and higher speed can be expected. Among the different variants, cutting, I, is limited by fluid-mechanics to drive the melt out of a deep, narrow kerf (aspect ratio), as is known from fiber laser cutting. Edge machining, II, was so far less robust and less precise than cutting, but does not have its fluid-mechanic constraints. Surface ablation III has the additional option of drop-per-pulse, promising with respect to controllability and precision. Pulse-per-drop, III.b, can directly determine drop size and precision.

Geometrical constraints: Freedom of design of the resulting part and of its placement is constrained by the limited space between the ejection/deposition angle range at the one hand and the waste sheet, system and beam propagation range at the other hand. Edge machining provides much space in contrast to surface ablation and to bridging. From the mathematical model, the geometrical constraints (domains to avoid, for the growing part) from the deposition range and beam incidence/reflection domains are shown in Fig. 2(b)-(e), for two examples. The ablation front in Fig. 2(c) causes a reflection distribution of Fig. 2(b), separated from the deposition area, Fig. 2(d).

4. Conclusions

(i) From comparison, cutting is the simplest and most robust variant to get started with, requiring a flat sheet.
(ii) Provided optimization, the edge machining variant enables systematic conversion of one homogeneous material into a new part; the geometrical conditions offer advantages.
(iii) Surface ablation, not yet demonstrated in this context, offers the widest variety of options and creativity, including selective recycling of different metals; this technique can be most constrained in geometry.
(iv) For all techniques, control of the fluid mechanics and understanding of the limits will determine the potential with respect to precision, geometry and building rate.

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