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Towards near-net shape micro-machining of aerospace materials by means of a water jet-guided laser beam

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Abstract

Guiding light with a thin, cylindrical water jet provides a range of advantages in laser machining such as reduced heat affected zone, cleaner kerfs, focused light over several centimeters in depth and improved material removal rate (MRR). Pushing the technology further requires a thorough understanding of its behavior, which adds the behavior inherent to water jets to the already complex parameter space of laser machining. In an attempt to simplify process description and to estimate the expected performance, a semi-empirical approach was selected based on physical considerations and experimental observations. The proposed model is fitted using a database of milling and drilling experiments on aerospace nickel alloys and thermal barrier coating (TBC) ceramic materials. It is then tested to mill shapes with controlled depth and angles using arbitrary sets of machining parameters. The experimental results are discussed. The obtained experimental data has provided a strong contribution to both the theoretical understanding and the exploration of actionable optimization measures for the Laser MicroJet® process.

Keywords: laser; water jet; ablation; drilling; modelling

1. Introduction

The Laser MicroJet® (LMJ) technology (Richerzhagen, 1994) combines the accuracy of a hair-thin (25 to 100 microns) cylindrical pure water jet with the robust throughput of Nd-YAG lasers ranging from 20 to 200 W, the principle is shown in Fig.1.(a) and Fig.1.(b). The LMJ is well suited for applications in domains such as diamond cutting, watch making and silicon wafer dicing. Over the recent years it has proven itself effective for rough cutting and finishing of polycrystalline diamond (PCD/Co) and monocrystalline diamond (MCD) cutting tool inserts (Richmann et al., 2015). It also receives considerable interest from the aerospace and energy sectors (Danford M., 2016) for cutting and drilling tough to machine materials such as nickel based superalloys and the more demanded SiC/SiC ceramic matrix composites (CMC).

Compared to the increasingly used pico-second and femto-second laser systems, the LMJ's main strength is to provide a long (10 to 60 mm) effective processing depth of field, see Fig.1.(c). To capitalize on this advantage and offer ever more versatility, the ability to cut and drill needs to be improved upon by adding 2.5D free shape machining capabilities.

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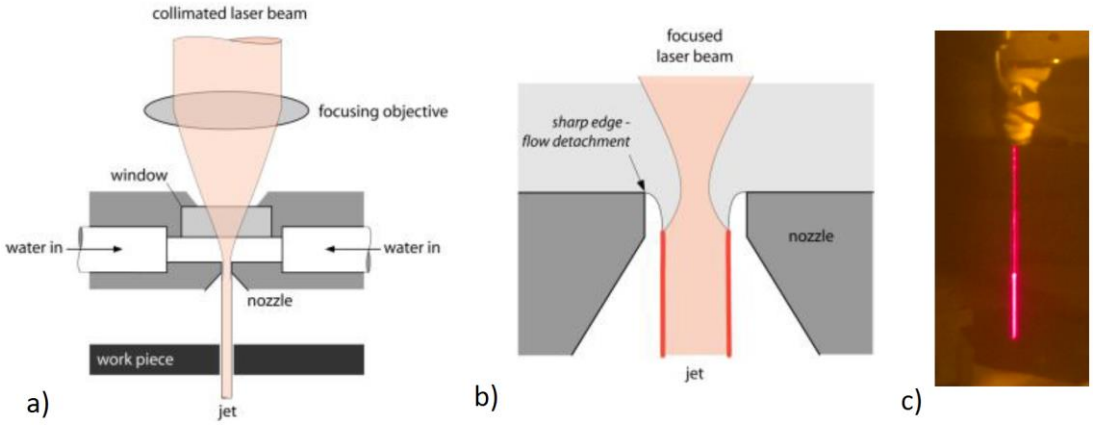

Fig. 1. (a) Principle of the Laser MicroJet®; (b) Detail:, focused and guided laser; (c) Effective depth of field (several cm)

Such an application can be partially solved by using suitable CAD/CAM strategies combined with fast response of systems (axis controller, Q-switch operation). Nevertheless the particularities of the LMJ need to be accounted for so as to provide accurate freeform shaping with repeatable performance.

Indeed the LMJ shares challenges encountered in abrasive water-jet machining, specifically in 2.5D operations (milling, pocketing…) such as water splash-back and hydrodynamic instabilities.

Hereafter, a two parts investigation is presented. First a semi-empirical model is proposed with the aim to estimate process performance and provide a basis to single-out the water jet behavior. Second, experimental investigations are conducted on simple pockets, with the aim to control depth and side-wall angle. This in turns leads to the investigation of process modifications, with an expected drastic increase in versatility for the LMJ.

2. Semi-empirical model

The main interaction between the LMJ tool and the workpiece has been fully observed in 2015, whereby in collaboration with EMPA and Fraunhofer-ILT an effort for analytical description of the “lift-off” (Fig.2) phenomenon has been initiated.

(Images courtesy of EMPA)

Fig.2. (left) Jet stagnation contact point before laser pulse ; (right) Jet lift-off during laser pulse ablation

This effort was supported by a large parametric study of the ablation of nickel based superalloys. In order to leverage the resulting database, a semi-empirical model is devised with the objectives of reducing the parameter space shown in Table 1 to usable performance estimates.

Table 1. Engineering parameters considered in the database

Parameter name - Symbol– (unit)	Min Value	Max Value
Laser Average Power – P_L – (W)	10	120
Laser Pulse Rep. Rate – f – (kHz)	6	24
Laser Pulse Duration (FWHM) – tp – (ns)	100	500
Jet Nozzle Diameter – d_n – (micron)	50	100
Jet Water Pressure – P_w – (bar)	100	400
Machine Axis Velocity – v – (mm/s)	0.75	20
Machine Line StepOver – S_o – (micron)	1	105
MATERIAL DATA	-	-

Note: MATERIAL DATA is an umbrella term in which are included the density ρ; thermal diffusivity D; the boiling temperature Tv; the heat of fusion Lm and vaporization Lv; the specific heat Cp; as well as reflectance R and optics transmission T as [0-1] values.

The model is built around the well-known energy balance approximation (Stafe M. et al., 2014), as well as the 1D thermal diffusion parameters defined by equation (1). They are used to define two volume parameters as material removed per pulse estimated with energy (MRP_e) and material removed per pulse estimated thermally (MRP_{th}) as shown in equation (2) and (3). The definitions using volumes provide an intuitive link to process performance. In the literature, they are often used in the form of Fluence and Fluence Threshold (Cabalin L.M., Laserna J.J., 1998).

$$\delta_{th} = 2 * \sqrt{(D * t_p)} \tag{1}$$

$$MRP_e = \frac{T*(1-R)*\frac{P_L}{f}}{\rho*(C_p*T_v+L_m+L_v)} \tag{2}$$

$$MRP_{th} = \pi * (0.4 * dn + \delta_{th})^2 * \delta_{th} \tag{3}$$

$$MRP_{fit} = DistributionPulses * PressureParameter * MRP_e * e^{-0.1*\frac{MRP_e}{MRP_{th}}} \tag{4}$$

Two other parameters are defined graphically in Fig.3. They are the dimensionless pulse distribution, and the dimensionless pressure parameter. They include considerations on water pressure, plasma pressure and machining parameters such as velocity, tool step over and jet width.

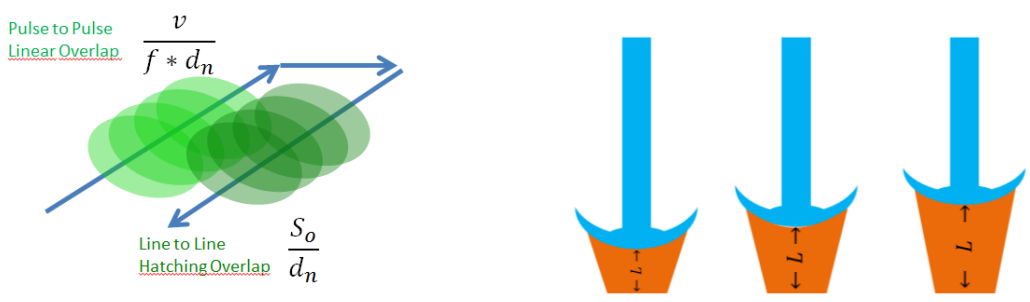

Fig.3. (left) dimensionless Distribution of Pulses; (right) dimensionless PressureParameter

The resulting model described by equation 4 estimates the Material Removed per Pulse (MRP_{fit}) by fitting it to the database, the fit is shown in Fig.4. It scales with the energy delivered and an exponential term describing the saturation phenomena commonly observed in laser ablation. From 8 independent engineering parameters, it provides an estimation of the process performance over a wide range of operating values. The resulting fit follows experimental tendencies satisfactorily as evidenced in Fig.4.

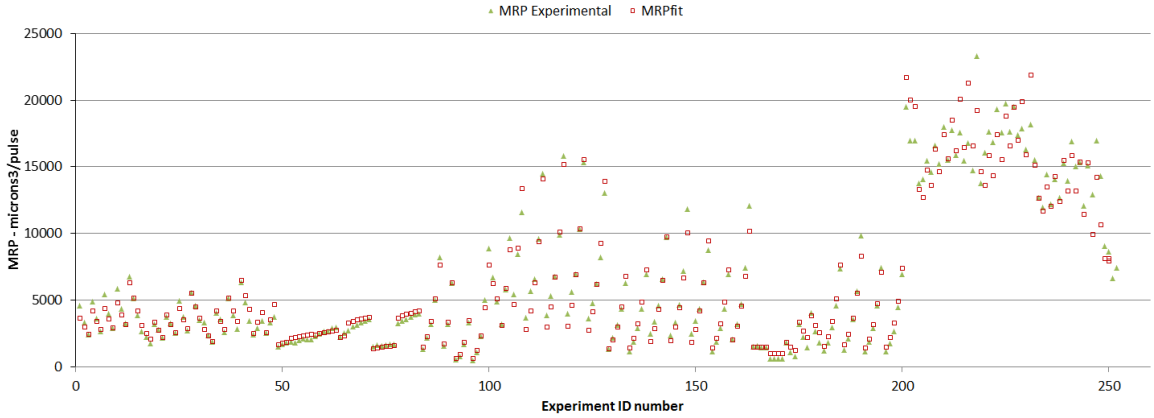

Fig. 4. Database Fit

In the following the model is used to generate pockets with expected depth and wall angle.

3. Machining simple pockets

3.1. Square pocket with an angle

The shape chosen in this study has been selected with the following experimental observations in mind:

- Process behavior in plane.
- Process behavior in inclines.
- Process behavior near walls.

To achieve these objectives, the shape chosen has a wide flat bottom and wide forward angled wall (35°), it also provides significant parallel and transverse wall dwelling as shown in Fig.5. The selected tool path is shown as overlay. The stepped approach for the angled wall is simple in nature and gives a rough approximation of the final desired shape.

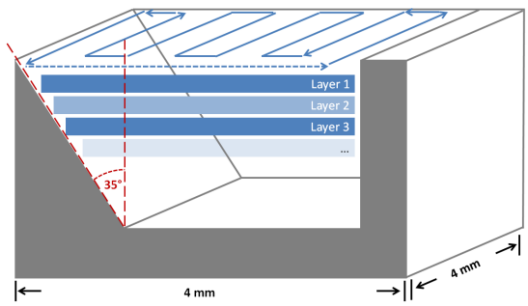

Fig.5. Geometry used in the study

The Model Input and Output for NC-code used for the pocket are described in Fig 6. The function of the predictive model in this particular case is to provide a “near net-shape” starting point for depth and angle, by calculating the necessary step size per layer before any machining occurs, thus reducing drastically the need for experimental optimization.

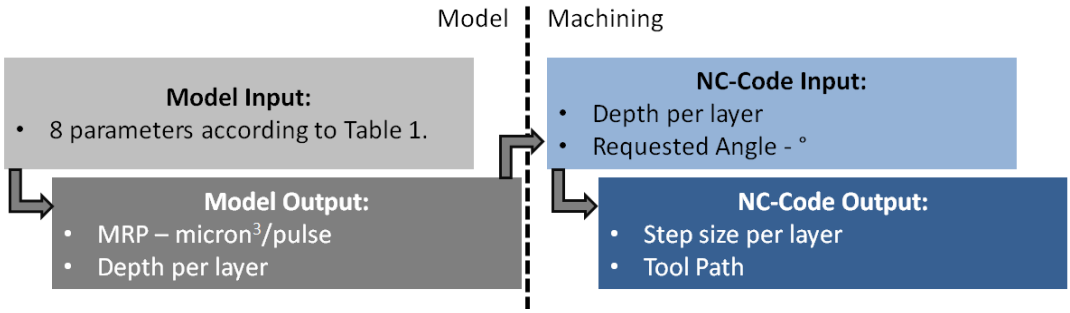

Fig. 6. Contribution of the model to near net shape machining

3.2. Results

The resulting shape shown in Fig.7 provides several valuable observations. First, the wall angle fits the requested angle by less than 1° of error, which acts as a proof of concept for the model. The LMJ displays, as expected, a strong performance for vertical ablation with a contained spot size, as evidenced by the trough appearance of the steps for the wall angle. This makes the stepped strategy adequate for roughing but not for smooth wall machining, as the step must be smaller than the jet size but adapted to the layer thickness.

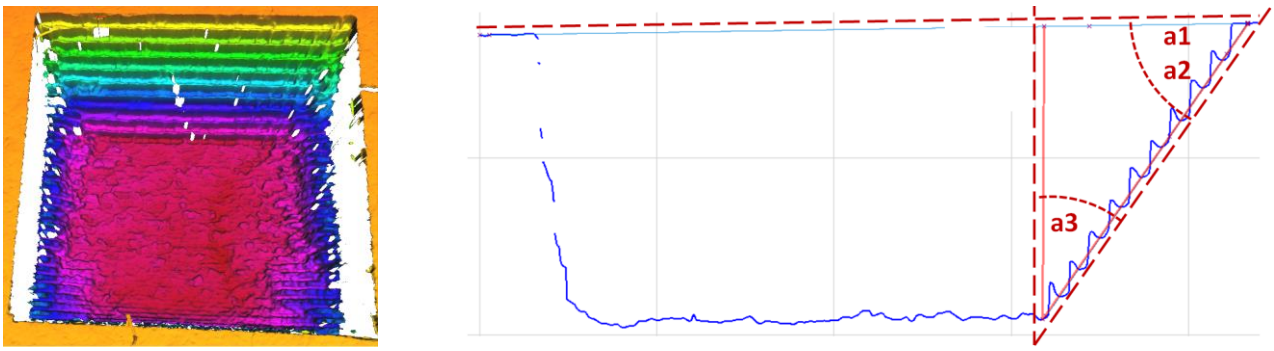

Fig. 7. (left) shape obtained experimentally; (right) angle measurements: a3 = 34.4° (Error of +/- 0.5°)

Second, the process shows an evident variability in performance as shown by Fig.8 (left). The difference from the performance expected by the model indicates a water jet specific effect. Moving the head closer to the workpiece during processing led to a recovery of performance. Mist accumulation on the head is generally present. This water drips towards the head exit and disturbs the light guiding ability of the jet. In the particular case of a closer working distance the back flow from the pocket provides a counter acting force to the dripping of such accumulated mist, thereby mitigating the effect and conserving the process performance (Fig.8 (right)).

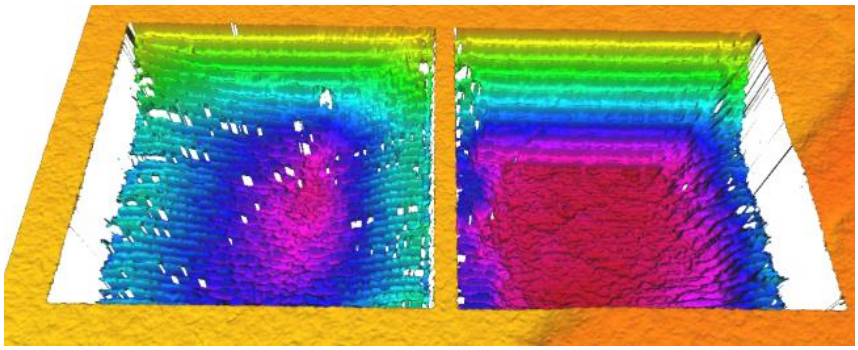

Fig. 8. (left) head to workpiece distance 25mm; (right) head to workpiece distance 10 mm

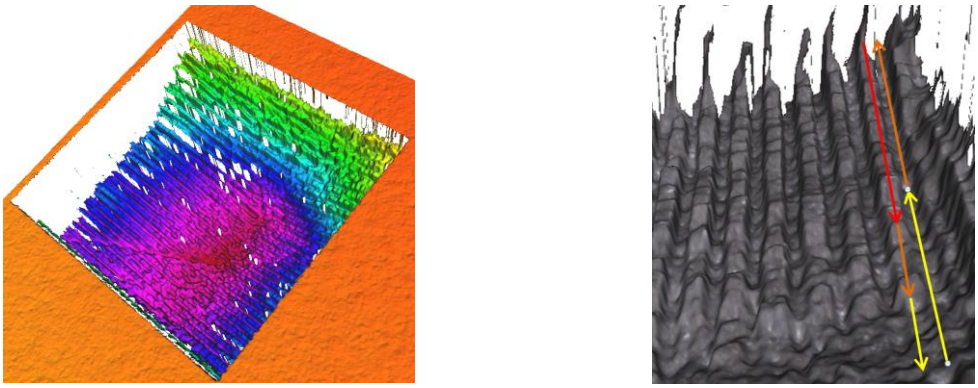

Fig. 9. (left) strong mist effect ; (right) detail of the wall effect.

In all experiments, a conspicuous wall-effect can be observed as evidenced by Fig. 9. As the LMJ tool moves closer to a wall, a gradual reduction of performance is observed (Yellow to Orange) arrows. When moving back away from the wall, the process is less effective but performance is gradually recovered (Red to Yellow) arrow. This is evidenced by a characteristic “trough and ridge” structure. A ridge corresponds to a comparatively lower performance, while a trough corresponds to a comparatively higher ablation performance. The observed asymmetry of the phenomenon (tool moving towards or from the wall) suggests an accumulation effect ascribed to water misting and water back-flow.

4. Outlook

The present study was based on simple machining trajectories and concepts (meander, layering) and the use of a semi-empirical performance estimate. It has successfully used predicted aspects of free-shape machining such as depth and controlled angle and has evidenced the wall effect and its main causes during 2.5D shape machining with the LMJ.

Methods such as overshoot hatching combined with fast Q-switch actuation can work around the effect, thus providing satisfying results as shown in Fig.10. However in such cases all parameters are optimized experimentally for a specific shape. Any variation in the geometry would require further optimization work.

Mastery of the jet behavior is therefore the next step to enable effective, versatile, arbitrary shape machining.

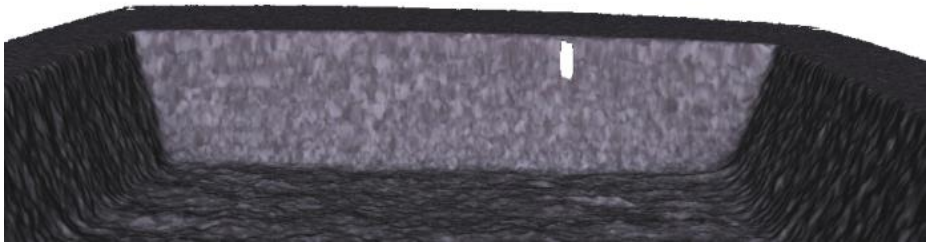

Fig. 10. No wall effect when pocketing a cermet. 500 microns, accuracy +/- 10 micron. Ra = 1.1 micron.

The short-term goal of free-shape machining using the Laser MicroJet® will be achieved by:

1. Controlling the jet behavior near walls
2. Developing process knowledge and prediction
3. Implementation of predictions into a CAD/CAM solution

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