Study of the Influences of Laser Parameters on Laser Assisted Machining Processes

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Abstract

Hybrid machining processes using additional energy sources such as laser assisted machining (LAM) have increased considerably during the last years. The benefits of LAM for reducing tool wear and cutting forces are well known, especially for superalloys. However, optimal machining results depend on both the laser parameters and the cutting process parameters. It is difficult to find optimal LAM settings due to the complexity of the influencing parameters and their mutual interactions. The aim of the paper is to characterize the laser heating process by detecting how the individual LAM parameters influence working temperature, heat affected zone (HAZ) extension and laser track width. A reliable application requires a localized and controlled continuous heating of the material within the machining zone directly in front of the tool contact area. In this research statistical and technological knowledge is fully involved in the experimental activities. Therefore, a statistical study based on design of experiment (DoE) was carried out in order to investigate the effects of laser process parameters and their interactions. In practice, two-level fractional factorial design and analysis of variance (ANOVA) were applied. The following process parameters were examined: laser power, scanning speed, defocus (the distance between focal point and workpiece surface), temperature controlled by pyrometer, and surface roughness. Furthermore, a Finite Element (FE) model was developed based on experimental results in order to find out the optimal parameters for modeling the laser heating process. Future FE simulations of the laser assisted cutting processes will be carried out using this model of the moving laser source.

Keywords: laser assisted machining (LAM), hybrid machining, design of experiment (DoE), finite element method (FEM)

1. Introduction

Hybrid machining processes such as laser assisted machining (LAM) have increased considerably during the last years [1-8]. In particular, results important for superalloys, e.g. reduction of tool wear and cutting forces are achieved using laser as a heating source [1-3]. However, most research is carried out on turning and micro milling, with the laser focal spot being kept constant [1-5].

Research on laser assisted milling is conducted in the same field [6-8]. In fact, researchers have excluded many important factors such as beam spot diameter, thermal conductivity, reflectivity of workpiece material and the interaction effects between various factors that would affect the LAM performance characteristics differently [9].

Few researchers investigated the interaction between laser beam, surface roughness and workpiece absorptivity [10]. These aspects are the basics of the laser assisted milling process. Indeed, different depths of cut can be machined by LAM and non-homogenous surface roughness can be obtained.

The main objective of this study is to investigate the effects of laser power, scanning speed, defocus distance, surface roughness and temperature in the LAM heating process.
2. Equipment, material and pre-experimental stage

Equipment and material

The tests are performed on a 5-axis milling machine Deckel Maho 125 P. A continuous wave (CW) medium power laser beam is generated by a diode laser Optotools 800 W (λ = 915-980 nm). The laser optics is provided using an f-theta lens and the laser beam is deflected by a mirror, placing the beam perpendicularly onto the workpiece surface (Fig 1). The temperature of the laser spot is controlled by a pyrometer integrated into the laser optics.

The interactions of laser beam and material are investigated on two different kinds of 100Cr6 workpieces (60 x 40 x 6 mm³), with rough and mirror-like surfaces. The temperature in the workpieces is measured by 3 J-type thermocouples which are positioned in three holes (with a diameter of 1 mm) under the symmetry line of the workpiece (at a depth of 3 mm with a distance of 15 mm between the thermocouples, see Fig 1). The measurement signals are amplified (QuantumX MX840A) and recorded by a PC software (Ecatcam-easy).

Tests are performed with the laser spot moving along the center line on the workpiece surface. The design of experiment (DoE) adopted in this paper is described in section 3. At the end of each test run the laser track width is measured.

2.1. Pre-experimental planning

Following the systematic approach to plan designed experiments as proposed in [11] and successfully applied in [12] and [13], two pre-design sheets (i.e. the main and secondary sheets) were prepared and implemented. These two kinds of sheets catalyze the interaction between statistical and technological competences in the pre-design stage (i.e. the pre-experimental planning stage).

The main sheets contain information on the objective of the experimentation, the relevant background, the response variables and the factors (i.e. control, constant factors and nuisance factors). For each factor, the normal operating level, the range, the measurement precision and the relationship to the objective were specified.

On the secondary sheets, the normal level and range as well as the measurement precision were specified for each quantitative control factor. Moreover, the secondary sheets detail the technological relationship between the control factors and the response variables in terms of the expected main effects and interactions.

In this first experimental phase, the aim was to characterize the laser treatment process, i.e. to detect the influence of control factors as regards track width and maximum temperature obtained in the processed material (measured by 3 thermocouples).

3. Experimental design and set-up

3.1. Experimental design

In this screening experimental stage a fractional factorial design $2^{5-1}$ was adopted. In this design (with a defining relation of $I = ABCDE$ and design generator $E = ABCD$) no main effect or two-factor interaction is aliased with other main effects or two-factor interactions, because it is a resolution V design. However, each main effect is aliased with a four-factor interaction, and each two-factor interaction is aliased with a three-factor interaction [14].

The adopted control factors are as follows: power (A), setting temperature (B), laser speed (C), defocus (D) and surface quality (E).

The setting temperature (B) is the target temperature on the workpiece surface and it is selected on the laser controller. C is the speed of the laser beam on the workpiece. The defocus (D) represents the distance between focal point and the processed surface. The qualitative factor E is related to the technical surface of milled and grinded workpieces.

3.2. Set-up

Table 1 summarizes the levels of control factors and their settings.

Table 2 shows the $2^{5-1}$ design matrix. Each treatment was repeated two times (2 replications), resulting in a total of 32 experimental runs. The replications of each treatment were performed to check the response repeatability during this first experimental study.
Table 1. Control factors and their settings

| Control factors | Labels | Low (-) | High (+) | Unit |
|-----------------|--------|---------|----------|------|
| Power           | A      | 300     | 500      | W    |
| Set. temperature| B      | 300     | 500      | °C   |
| Speed           | C      | 1.5     | 3        | mm/s |
| Defocus         | D      | 10      | 20       | mm   |
| Surface         | E      | milled  | grinded  | --   |

Table 2. Matrix for the $2^{5-1}$ design

| Treatment | A | B | C | D | E = ABCD |
|-----------|---|---|---|---|----------|
| I         | - | - | - | + | +        |
| II        | + | - | - | - | -        |
| III       | - | + | - | - | -        |
| IV        | + | + | - | - | +        |
| V         | - | - | + | - | -        |
| VI        | + | - | + | - | +        |
| VII       | - | + | + | - | +        |
| VIII      | + | + | + | - | -        |
| IX        | - | - | - | + | +        |
| X         | + | - | + | - | +        |
| XI        | - | + | - | + | +        |
| XII       | + | + | - | - | -        |
| XIII      | - | - | + | + | +        |
| XIV       | + | - | + | + | -        |
| XV        | - | + | + | - | +        |
| XVI       | + | + | + | + | +        |

In order to reduce the disturbance of any unconsidered noise factor the order of trials was randomized both in the treatments and in their replications.

The data are available on request from the corresponding author.

4. Statistical analysis of results

Since three-factor (and higher) interactions are negligible, the experimental $2^{5-1}$ design enables reliable information to be obtained on main effects and two-factor interactions. The ANOVA method was applied in order to test the statistical significance of the main effects and the two-factor interactions for maximum temperature from each thermocouple and track width. Diagnostic checking was successfully performed via graphical analysis of residuals.

The experimental results for maximum temperature measured by thermocouple 2 (the other two thermocouples provide similar results) and the track width are shown in Fig 2 and Fig 3, respectively, using Pareto charts of standardized effects ($\alpha = 0.05$).

Regarding the maximum temperature measured by thermocouple 2, Fig 4 and Fig 5 show its main effects and interaction effects plots, respectively. The significant effects ($\alpha = 0.05$) are power (A), speed (C) and their interaction (AC).

These results are not unexpected. In fact, plots of the main effect show that the maximum temperature measured by each thermocouple increases when the power (A) increases and decreases when the speed (C) increases. In addition, the interaction plot between power and speed (AC) shows that the level of the power (A) has less influence on the temperature at high level of speed (C).

![Fig. 2. Pareto chart of standardized effects ($\alpha = 0.05$) for maximum temperature measured by thermocouple 2.](image1)

![Fig. 3. Pareto chart of standardized effects ($\alpha = 0.05$) for track width.](image2)

![Fig. 4. Main effect plots for maximum temperature measured by thermocouple 2.](image3)
The analysis of the results measured by thermocouple 3 also points out the statistical significance of other factors (i.e. defocus and surface). This point needs further investigations.

In terms of track width, Fig 6 and Fig 7 show the main effects and the interaction plots, respectively. The significant effects ($\alpha = 0.05$) are power (A), speed (C), defocus (D) and surface (E).

As regards the track width, the plots of the main effect show that its maximum values are obtained when the power (A) is at a high level or the speed (C) is at a low level.

From the technological point of view, it is not the significant influence of defocus (D) and surface (E) that is new, but rather their interaction (DE). Indeed, the interaction plot DE for track width shows that the influence of defocus (D) is higher when the surface (E) is milled.

5. Finite Element modeling

The laser is used for thermal softening of difficult-to-cut materials like Inconel 718. High temperatures should be reached in front of the cutting edge and at a sufficient depth, but the remaining workpiece material and the cutter itself should remain undamaged.

The aim of current cutting experiments is to achieve an optimal temperature field and to find optimal laser positions and motion paths. In addition to the experiments with varying laser parameters and scanning, velocity simulations based on the Finite Element Method (FEM) were carried out in order to calculate the temperature distribution and the characteristic values of the cutting processes (cutting forces, temperature, tool wear, ...)[15].

Prerequisite for a realistic simulation of the laser assisted cutting process is to know the characteristics of the acting laser source. In order to use the CW diode laser and its parameters the workpiece heating is modeled as a heat flux through the surface in the following form:

\[
q(x,y,t) = P_0 e(T) q_0(x,y,t)
\]

with \[\int_{-\infty}^{\infty} q_0(x,y,t) dxdy = I\]

($P_0$ – preselected laser power, $e(T)$ – dependent on temperature absorption coefficient, $q_0(x,y,t)$ – power distribution in the laser spot with radius $r_0$).

Due to the workpiece symmetry only one half of the workpiece must be modeled (size 60 x 20 x 6 mm$^3$, Fig 8). The program MSC.MARC® was used. The laser moves along the symmetry line at a constant velocity $v_o$, at a given time $t$ its position is $x(t) = t \cdot v_o$, $y(t) = 0$. The moving heat source (1) defined by a user subroutine acts on the highlighted area. Further boundary conditions are convective heat transfer to the surrounding air with a heat transfer coefficient of $\alpha = 4$ W/m$^2$K and thermal insulation on the workpiece bottom side.

The MSC.MARC database parameters of the material 100Cr6 are used in the models (Table 3).

In order to demonstrate the method, the results of the experimental treatment II ($P_0 = 500$ W, $T_{cond} = 300$ °C, $v_o = 1.5$ mm/s, defocus 10 mm, milled surface) are presented in the following figures.
The local power distribution $q_0$ in the laser spot (Gaussian or constant) has no significant influence on the temperature at the points of measurement.

Furthermore, as shown in the ANOVA results, no significant influence of the setting temperature (B) could be noticed in the experiments, and, consequently, it was not considered in the simulations.

### 6. Technological interpretation

Fig 7 illustrates that the defocus influence on laser track width is higher on the milled surface. This result can be explained by analyzing the surface texture. According to [10], the specular reflected energy decreases and diffused energy increases at average surface roughness. It is possible that, when the laser spot is defocused at 10 mm on the milled surface, the diffused energy is higher than the reflected one.

Meanwhile, when defocusing the laser spot at 20 mm (less energy density in laser spot), the diffused energy is lower. It may be true that peaks and valleys of milled surfaces trap laser light better when the energy density of the laser spot is lower and its size is larger. On grinded surfaces the influence of defocus is not that distinct because the surface roughness is lower and the diffused energy seems to be rather constant.
7. Conclusion

Analysis results of laser parameters on laser track width showed expected results, but also new ones. Two parameters and their interaction have a strong influence on the laser process: power and laser scanning speed (Fig 2). The other factors, defocus and surface quality, are relatively new. The statistical analysis shows the high influence of defocus on the milled surface in terms of the laser track width (Fig 7).

The study of influence of laser parameters helps to find the best laser parameter setting to improve the machinability of materials during LAM process. In fact, to improve the machinability it is necessary to reduce the mechanical strength. This is achieved when the material is in a proper temperature range. Knowing the temperature distribution into material, related to the factors setting, by FEM simulation (Fig 10), it is possible to choose the best laser parameters setting for LAM. Hence, the machinability would be significantly improved.

Obviously, monitoring of the temperature during LAM (with thermocouples or pyrometer) would be suggested to give feedback or validations to the FEM simulation model.

Thus, FEM modeling can be helpful to define the range of real laser parameters for other material, especially difficult to machine materials (i.e. Inconel 718) for a wider use of LAM technology.

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