Analysis of Laser Assisted Milling (LAM) of Inconel 718 with Ceramic Tools

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Abstract
Laser Assisted Milling (LAM) is a hybrid machining technology which combines conventional milling with a localized laser beam. The laser spot heats the uncut workpiece material in front of the cutting edge. The aim of this technology is to improve the machinability of difficult to cut alloys, like Inconel 718. Hence, the material strength is reduced by high temperatures in the hot cutting process. Indeed, Inconel 718 is widely used in aerospace industry due to its excellent mechanical strength and corrosion resistance at high temperatures. These properties result in poor machinability and high tool wear. In this paper experiments of LAM and conventional milling of Inconel 718 were performed by using ceramic inserts. Methods from the Design of Experiment (DoE) were adopted in order to investigate the influence of laser and milling parameters in the hybrid process. The response variables were measured as tool wear, tool deflection, active machining force $F_a$ and passive force $F_p$. The results showed that machining forces, tool deflection and also tool wear could be reduced by laser heating, especially using enhanced cutting data.

Keywords: Laser beam machining; Nickel; Design of Experiments (DoE).

1. Introduction
Laser assisted milling (LAM) is a hybrid machining technology where the laser heat source is focused on the unmachined section of the workpiece directly in front of the cutting tool [1]. Generally, the aim of laser assisted machining is to improve the machinability of difficult to cut materials such as Titanium, Nickel based alloys and special ceramics [1]. Indeed, the poor machinability of superalloys (i.e. Inconel 718) due to strain hardening, short tool life and low cutting speed limit the manufacturing process [2, 3].

Laser assisted machining can be competitive compared to conventional machining by means of costs per hour and pollution reduction (dry machining process) [4]. Hence, different works presented a successful use of laser assisted machining in turning of Titanium and Nickel alloys [5, 6]. However, few works of LAM are presented because of the complex interactions of milling process with the laser assistance [7]. The following work was developed in order to investigate the influence of the main process factors in LAM and to gain more knowledge about their interaction.

2. Equipment, material and pre-experimental stage
2.1. Equipment and material
In this investigation machining tests were performed on a 5-axis milling center DMU 125P. A continuous wave medium power laser beam is generated by a diode laser Optotools 800 W ($\lambda = 915-980$ nm). The beam is led by a fiber optic cable to a scanner unit moving the laser spot on a certain alternating path. The optics is provided by using an F-theta lens and the laser beam is reflected by a mirror, placing the beam on the workpiece surface (Fig. 1). The machined material is Inconel 718. The workpiece is mounted on a vise anchored to a dynamometer (Kistler 9257B) that records the three orthogonal forces $F_x$, $F_y$, and $F_z$.
The milling inserts are SiAlON based (C6060) and the milling arbor diameter is 40 mm (provided by Sandvik®). Each test was performed using a new cutting edge. During the machining tests, a high speed camera recorded a part of the LAM process and laser interferometry devices (Micro-Epsilon) monitored milling tool deflection in X-Y axis directions. All signals are amplified (QuantumX MX840A) and recorded by a software (Catman-easy). Subsequently the tool wear is measured with an optical microscope (Keyence VHX-600).

2.2. Pre-experimental planning

Before proceeding with experiments, some pretests were carried out in order to find the appropriate range settings for each process parameter. For the investigation the following parameters were kept constant: depth of cut \( a_p = 1 \) mm, radial immersion of cut \( a_e = 7 \) mm, machined path length \( L = 105 \) mm and laser scanning frequency \( f_s = 50 \) Hz. Tool deflection was monitored with two laser interferometry devices mounted on the head of the milling machine. The signals were recorded at a sampling frequency of 9.6 kHz (laser interferometer) and 19.2 kHz (\( F_x, F_y, F_z \)). The machining forces were divided up in the active component \( F_a \), which is calculated from the measured forces \( F_x \) and \( F_y \), representing the resulting force in the cutting plane. The passive force \( F_p \), which is perpendicular to the active force \( F_a \), is directly measured. Due to the kinematics of milling and the discontinuous cut both forces are changing during each tool rotation.

The forces \( F_a \) and \( F_p \) were analyzed in three different points of time during process in each treatment. Here only the results of the third point of time (t3) are reported. This point of time is close to the end of the cutting length and can be related to the tool wear. Another investigated response value is the tool wear. For each test a new cutting edge was used. In order to represent the tool wear, the average flank wear land (VB) and maximum flank wear land VBmax were measured.

3. Experimental design and set-up

3.1. Experimental design

Following the design of experiment approach in this experimental stage, a fractional factorial design \( 2^{5-1} \) was adopted. It is a resolution V design (with a defining relation of \( I = ABCDE \) and design generator \( E = ABCD \)), so no main effect or two-factor interaction is aliased with other main effects or two-factor interactions. However, each main effect is aliased with a four-factor interaction, and each two-factor interaction is aliased with a three-factor interaction [8].

The adopted control factors are the following: laser power (A), cutting speed \( v_c \) (B), feed per tooth \( f_z \) (C), defocus distance (D) and milling mode (E).

The defocus is the distance between laser lens and workpiece surface. Laser spot size is directly dependent on defocus distance. Excluding the control factors, each test was performed under the same experimental conditions.

Table 1 summarizes the levels of the adopted control factors and their settings. Each treatment was repeated two times (2 replications), resulting in a total of 32 experimental runs. The replications of each treatment were performed to provide more consistent response repeatability.

In order to reduce the disturbance of any unconsidered noise factor, but at the same time to avoid technological difficulties related to defocus calibration, the order of trials was partially randomized in terms of treatments and replications. Besides, to compare the results of LAM from DoE with conventional milling a new series of tests was carried out using the same values of process parameters B, C and E.

4. Statistical analysis of results

The ANalysis Of VAriance (ANOVA) was applied in order to test the statistical significance of the main effects and the two-factor interactions for active cutting force \( F_a \), passive force \( F_p \) and for the tool wear VBmax. The analysis was carried out at a confidence level of 95% (\( \alpha = 0.05 \)). Diagnostic checking was successfully performed via graphical analysis of residuals.

The influences of the control factors for machining forces \( F_a, F_p \) and VBmax are shown in Fig. 2-4, respectively, using Pareto charts of standardized effects (\( \alpha = 0.05 \)).

Table 1. Control factors values.

| Control factors | Labels | Low (−) | High (+) | Unit |
|-----------------|--------|---------|----------|------|
| Laser Power     | A      | 500     | 800      | W    |
| Cutting Speed v_c | B   | 500     | 800      | m/min|
| Feed per Tooth f_z | C     | 0.1     | 0.16     | mm   |
| Defocus         | D      | 0       | 10       | mm   |
| Milling Mode    | E      | Down    | Up       | --   |
The main effect of a factor is defined as the change in response produced by a change in the level of the factor. When the difference in response between the levels of one factor is not the same at all levels of the other factors, there is an interaction between the factors.

Regarding $F_a$, Fig. 2, Fig. 5 and Fig. 6 show its main effects and interaction effects, respectively.

The significant terms for $F_a$ are as follows: the main effects of cutting speed (B), feed per tooth (C), milling mode (E) and the two-factor interactions between feed per tooth and defocus distance (CD), cutting speed and milling mode (BE), laser power and defocus distance (AD), laser power and milling mode (AE) as well as cutting speed and defocus distance (BD).

Fig. 3, Fig. 7 and Fig. 8 show the main effects and interaction plots, respectively for $F_p$. The significant terms for $F_p$ are the main effects of milling mode (E), and the two-factor interaction between feed per tooth $f_z$ and defocus (CD), feed per tooth $f_z$ and milling mode (CE) and cutting speed and milling mode (BE).

In terms of $V_{B_{max}}$, Fig. 4, Fig. 9 and Fig. 10 show the main effects and interaction plots, respectively.

The significant parameters for this response variable are the main effects of cutting speed (B), and milling mode (E), and the two-factor interaction between laser power and cutting speed (AB).
5. Experimental results

5.1. Machining forces and tool deflection

For the evaluation the maximum force peak of each single edge engagement was separated forming a maximum force graph, shown in Fig. 11. It demonstrates that the active cutting force \( F_a \) and passive force \( F_p \) in conventional milling show the trend to rise during each test. This occurred with every cutting parameter set. The different modes of laser heating were found to change the value of maximum force peaks, but not the general rising trend. A major influence on the applied maximal forces is the milling strategy. In up-milling mode the mean maximum value of \( F_a \) was found lower than in down-milling. Increasing laser power from 500 to 800 W and the cutting speed \( v_c \) from 500 to 800 m/min diminishes \( F_a \). However, \( F_a \) is higher at \( f_z = 0.16 \text{ mm} \). The laser defocus distance has no significant influence on \( F_a \) (Fig. 5). While in down-milling the active force \( F_a \) was found higher, the passive force \( F_p \) showed an opposing trend, being significantly lower in down-milling (Fig. 7). \( F_p \) is also reduced at increased feed rates and a defocus distance of 10 mm (Fig. 8).

Additionally, the tool deflection was measured in direction of the two perpendicular axes X and Y. As shown in Fig. 12 the average tool deflection is lower in down-milling mode in both directions in LAM compared to conventional milling.

5.2. Tool wear

As regards tool wear a major difference was found between the two milling modes. Fig. 13 shows that in down-milling the main tool wear types are depth of cut notching (DOCN) and a second notch forming on the inserts side which is directed to the milled surface. In up-milling DOCN was not found to be a significant criterion of tool wear. Here the main wear types are chipping, flaking and fracture along the cutting edge. The comparing image Fig. 13 shows that in up-milling mode, tools cutting edge presents V notch wear in the middle of cutting line. Basically like seen in Fig. 9 down-milling was found to have less effect on tool wear in terms of \( VB_{max} \).

High laser power combined with high cutting speed was also found to reduce tool wear. In contrast, high laser power with low cutting speed led to increased tool wear (Fig. 10).

General the higher feed rate shows a strongly increased tool wear. The average and maximum width of flank wear land, \( VB \) and \( VB_{max} \), were measured for comparison. Figure 14 shows the maximum and average values of \( VB \) for conventional and laser assisted processes in down-milling. Apparently the higher feed rate leads to strongly increased tool wear in conventional milling. Using the additional laser heating reduced the wear marks \( VB \) and \( VB_{max} \). A further increase of laser power was found to follow this trend and decreases the tool wear additionally.

Fig. 8. Interaction plots for \( F_p \) at time \( t_3 \) (gray plot: no influence).

Fig. 9. Main effect plot for \( VB_{max} \) [mm].

Fig. 10. Interaction plots for \( VB_{max} \) [mm].

Fig. 11. Force trend in conventional milling and LAM of Inconel 718
6. Technological interpretation

The maximum values of active force $F_a$ were larger in down-milling (Fig. 5). The higher passive forces $F_p$ occurred in up-milling (Fig. 7). These results can be mainly attributed to the different dynamics of both milling strategies. Indeed, in up-milling the edge engagement starts with a heavy rubbing phase. Due to this phenomenon, high passive forces and frictional heat are induced. In milling Nickel based alloys this can cause a strong work hardened layer in this area [10]. Generally, the undeformed chip thickness shows an increasing trend in up-milling. At a certain minimum undeformed chip thickness the edge enters the material and starts cutting a chip [10, 11]. The induced frictional heat is assumed to additionally increase the temperature in the cutting zone. Due to the described self-induced preheating, the material can be removed easier, promoting lower maximal active cutting forces in conventional up-milling process [12].

In down-milling the undeformed chip thickness decreases during each edge engagement. The cutting of the chip starts immediately with the maximum undeformed chip thickness resulting in a high active force peak. In down-milling mode initial rubbing does not occur [12].

The additional laser heating diminishes the material strength, resulting in lower machining forces in both milling modes. In each test a rising trend of active force $F_a$ and passive force $F_p$ was found during cutting (Fig. 11). Thermal effects can be assumed as one reason for the steady increase of machining forces [10]. The major influence on the rising force trend in machining Inconel 718 can be related to growing tool wear and work hardening [3, 10, 13, 14, 15]. Generally, in LAM the slope of this trend is lowered for $F_a$ and altered for $F_p$.

Tool wear types occurring in machining Inconel 718 with ceramic inserts are mainly edge chipping, notching and flank wear [3, 9, 11, 16]. The analysis of tool wear showed that it was significantly lower at a cutting speed of 800 m/min. An approach of explanation can be the contact time. The higher the cutting speed, the shorter is the contact of tool and material, providing less time for heat flow into the tool [3]. The recognized higher forces at $v_c = 500$ m/min are another main influence on tool wear, although it is not clear whether they were the cause or the consequence of the increased tool wear at this speed.

In up-milling the tool is exposed to increased thermal load [11]. Furthermore the described work hardened layer adds a high mechanical load in this area, leading to high tool wear [3]. Additionally, the chips accumulate ahead of the cutting region, generate high temperatures and tend to weld to the cutter at the end of the edge engagement, which reduces tool life [11]. In down-milling, potentially adhering chips are only connected with the cutting edge by a thin strip of material and are usually wiped from the tool upon its re-entry [12]. Machining tests on Inconel 718 with integrated thermocouples showed that the DOCN wear is mainly due to mechanical instead of thermal load [3].

Fig. 10 shows the interaction plot of $V B_{max}$. Particularly, the interaction between laser power (A) and cutting speed (B) point out that increasing the value of cutting speed and laser power reduces $V B_{max}$. Indeed, increasing laser power (heat flow) and cutting speed (softening effect) reduces the mechanical strength of the material. However, increasing the laser power at low cutting speed provokes high tool wear. So the laser heating is detrimental on tool life at low cutting speed. A possible explanation for this phenomenon may be that the heat is not adequately dissipated by the chips.

During machining time the average tool deflection in X and Y axis directions presented a reduction compared with conventional milling. The main reduction in the down-milling mode is more evident in the Y-axis direction. This effect could be directly attributed to the lower tool wear and the softening effect of laser heating on undeformed chip thickness.

The milling tool deflection less because the removed material has lower mechanical strength (i.e. lower cutting forces).
7. Conclusion

This paper presents a statistical analysis of active machining force $F_a$, passive force $F_p$ and tool wear $VB_{max}$ of laser assisted milling (LAM). The following conclusions can be drawn:

- An interaction of material softening, lower tool wear and thermal effect can be assumed. In LAM $F_a$ is reduced due to material softening and lower tool wear and $F_p$ is altered by (thermal) effects.
- Down-milling is recommended for machining Inconel 718 because it reduces the effect of work hardening [3, 10]. Also the kinematics of down-milling is more appropriate for LAM.
- In down-milling the mode laser heating diminishes the tool deflection in X and Y direction.
- Laser assisted milling reduces $F_a$ and $VB_{max}$ at $v_c = 800$ m/min and $f_z = 0.16$ mm (Fig. 11) compared to conventional milling.

Further research and improvement of LAM should be focused on the efficiency of thermal preheating [17].

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