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Computerized Optimization of the Process Parameters in Laser-Assisted Milling

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Abstract

Machining advanced materials, e.g. titanium alloys, usually results in a short tool life. Laser-assisted milling represents an innovative method to enhance machinability with less tool wear and an increased material removal rate. The material is heated locally and thereby softened before machining. This paper describes a thermo-mechanical simulation of a laser-assisted milling process in order to achieve a controlled heat impact. For that purpose the influence of different material parameters on the temperature field was analyzed computationally. The penetration depth of the laser induced heat and the thermally induced internal loads were investigated considering the loss of material and thus of heat during the milling process. Finally, the laser and the milling parameters were adapted for a real laser-assisted process.

Keywords: Laser-assisted milling; titanium; coupled simulation

1. Introduction

Where lightweight constructions and high-performance components are concerned, conventional steel materials are substituted for advanced materials, e.g. composites, aluminum or titanium alloys. Especially in aerospace applications this trend is very distinctive. Presently, aluminum is the most commonly used material in the aircraft industry [1] but the demand for fiber-reinforced composites is stronger than ever [2]. The high potential difference between composites and aluminum alloys results in a severe galvanic corrosion. Therefore, titanium alloys are used in combination with composites because of the minor potential difference. The similar heat expansion of these two materials is advantageous, too [2].

Machining high-strength material usually results in a short tool life due to the high thermal load on the cutter and the high cutting forces. In combination with material removal volumes up to 95% in the aircraft industry [3] the processing times extend that extremely, that a cost-effective machining of these materials is not possible. Machining is a well-proved processing technique, which has been already investigated in detail. A capable and robust process ensures the desired material properties after machining and thus a high quality of the machined part. In the future, there will be no alternative to machining [2]. Therefore, new and innovative processing techniques are needed to...
enhance the machinability of advanced materials [4].

2. Laser-Assisted Hot Machining

Hot-machining is a technique which reduces the tool wear by pre-heating and thus softening the material of the workpiece before machining. Compared to other heat treatment strategies, e.g. plasma, induction or flame heating, laser radiation with its high power density allows heating the material very locally. This reduces the thermal impact on the total workpiece significantly. The workpiece is heated locally above the softening temperature, e.g. 400–450 °C for titanium TiAl6V4 [5], using laser radiation. The cutter mills the softened material before most of the induced heat disperses into the workpiece. Due to the softened material the tool wear is reduced and the material removal rate can be increased. Laser-assisted milling is applicable for rough machining only, because of the small heat affected zone (HAZ) below the milled surface of the workpiece. At the β-transus temperature of 995 °C for TiAl6V4 a phase transformation from α- to β-titanium occurs [1]. A high cooling rate yields to the formation of metastable titanium martensite. The martensite start temperature $\text{M}_s$ of this titanium alloy is at 800 °C [6]. Titanium martensite is a hardened coarse-grained microstructure [1]. The resulting microstructure has to be considered to avoid hot cracks. In the HAZ the microstructure is changed and can cause a change of the mechanical strength and a significant increase of the susceptibility to hot cracks [5].

To find the optimum parameters for the laser-assisted milling two processes and their parameters have to be regarded. Usually the milling parameters are given by the tool manufacturer and the laser parameters have to be adjusted. The maximum feed rate of the hybrid process is limited by the feed rate of the cutter. The resulting temperature field determines the penetration depth of the laser induced heat. The maximum temperature of the material the cutter comes into contact with must not exceed the maximum working temperature of the cutter. This limits the maximum applicable laser power. Generally, the depth of cut given for a milling tool exceeds the heat penetration depth. Therefore, the maximum depth of cut is limited by the laser beam. In the presented article, high feed tools with moderate depths of cut are used. In a laser-assisted cutting process the material should be milled before the induced heat disperses into the material. This will prevent the change of properties in the residual material or moreover a damage of the workpiece by the thermal load. Ideally, the induced heat is removed completely with the chip without heating the tool or the total workpiece. The temperature field in a real workpiece can only be analyzed with high measuring efforts. A finite element (FE) simulation enables to compute the formation of a three-dimensional temperature field. Within a thermo-mechanical simulation the effects on the temperature distribution can easily be analyzed, while varying process parameters in combination with the material removal are considered.

3. Objectives and Approach

Using a thermo-mechanical simulation considering the heat input and the material removal of a laser-assisted milling process the resulting temperature distribution in the workpiece is investigated. The main objective of the following approach is to find the optimum range of laser and milling parameters for the hybrid process.

A comparison of the resulting temperature fields in simulation with and without material removal will show the need of modeling the milling process (and thereby the lost of material and heat) to improve the simulation results. Considering the milling feed rate $v_\text{L}$, which is calculated from the feed rate per insert $f_z$, the heat penetration depth is adjusted to the actual depth of cut $a_p$ by varying the laser power $P_\text{L}$. Also the distance between laser spot and cutter $x_\text{L}$ is adjusted to prevent a thermal overload of the cutter on the one hand side and the heating of the residual workpiece on the other hand side. This approach ensures to find the relation between laser power $P_\text{L}$ and depth of cut $a_p$, which is needed for the process control using CAD/CAM interface [7]. In conclusion the identified range of milling and laser parameters are compared with further experimental results [8].
4. Simulation Build-Up

Based on the Finite Element Method (FEM) the transient computations of the laser-assisted milling process were performed using MSC.Marc and its implemented coupled solver. With this solver the structural reactions (stresses and distortions) resulting from the heat input can be computed instantaneously during the temperature field calculation for every time step [9]. The whole model build-up was preceded by various experiments, which provided numerous measurement values for calibrating the simulation [10]. Thus, verifying the material parameters from appropriate literature, prediction of thermal loads and further boundary conditions were possible. Among other material parameters of titanium the parameters specific heat capacity $c_p$ [11] and heat conduction $\lambda$ were modeled as temperature-dependent (see Figure 1) [12, 13]. Further physical material parameters used in the simulation are given in Table 1.

![Figure 1: Temperature-dependent heat capacity $c_p$ and heat conduction $\lambda$ versus temperature $T$ for TiAl6V4 [11–13].](image)

| Physical material parameters of TiAl6V4 | Spec. heat capacity $c_p \cdot 10^2$ J kg$^{-1}$K$^{-1}$ | Heat conduction $\lambda$ W m$^{-1}$K$^{-1}$ |
|---------------------------------------|---------------------------------------------|----------------------------------|
| Poisson's ratio $\nu$ | 0.28 | |
| Mass density $\rho$ | 4.43 kg/dm$^3$ | |
| Young's modulus (100 °C) | $9.7 \times 10^4$ MPa | |
| Emissivity $\varepsilon$ | 0.56 | |
| Absorption $\varepsilon_{ab}$ | 0.44 | |
| Thermal expansion (100 °C) | $9.2 \times 10^{-6}$/°C | |

In comparison to experimental results an optimal discretization in space and of time could be found regarding modeling effort, computation time and accuracy. At last, the workpiece dimensions could significantly be scaled down without losing quality in the results as verified by comparing simulation models with varying dimensions. The unconsidered part of the FEM model is thermally unaffected. As a result the dimensions were reduced from $150 \times 10 \times 50$ mm$^3$ to $19.2 \times 6.8 \times 8$ mm$^3$ (length $\times$ height $\times$ width), shown in Figure 2. The figure also explains the experimental and simulation setup in principal. The values and ranges of the laser and the milling parameters used in experiments and simulations are given in Table 2.
Table 2: Values and ranges of laser and milling parameters.

| Varied laser and milling parameters | Feed rate $v_L$ | Distance between laser spot and cutter $x_L$ |
|------------------------------------|----------------|--------------------------------------------|
| Feed rate $v_L$                    | 1.6 mm/min     | 0.0 … 5.0 mm                               |
| Laser power $P_L$                  | 400 … 1000 W   | Depth of cut $a_p$                          |
| Spot diameter $d_L$                | 3.0 mm         | Width of cut $a_c$                          |
| Material                           | TiAl6V4        | Material TiAl6V4                            |

The virtual workpiece was meshed by using three-dimensional, first-order arbitrarily distorted bricks. This element type uses trilinear interpolation functions and consists of eight nodes, which are connected to an isoparametric first-order hexahedral. The mesh was highly discretized where the significant heat input is expected (see discretization in Figure 3). While the focus radius is 1.5 mm the length of the element edges is scaled from 0.8 mm in the outer heat zone down to 0.2 mm in the HAZ. This small element size will ensure high result accuracy. Even so the computation time still remains at a moderate level which is because of the reduced workpiece dimensions and thus a smaller amount of elements. For the correct analysis and interpretation of the computation results the points of monitoring were also located in the high discretized region, i.e. in the HAZ. At these points the time and position depending values of temperature are plotted within the post processing.

Although the numerical investigations revealed that a neglect of natural convection and radiation – for this specific problem – will not influence the interested values significantly, both were considered anyhow as they do not increase the computation time. The negligible effect of these factors is due to the characteristic of the laser-assisted milling process, which is highly dynamic with the dominating effects of conduction and specific heat. Thus, related to the small time period between the heat input of the laser beam on the workpiece surface and its removal by the cutter, much more of the absorbed laser energy disperses into the workpiece as it dissipates due to radiation and convection. Next to these boundary conditions the fixture of the workpiece and the laser beam were modeled. The clamping condition is represented by retaining the bottom nodes of the mesh in all their dimensions. For modeling the laser beam, a moving heat source on the surface with a Gaussian heat distribution (face flux) was defined.

The calibration and validation of the model were done by comparing experimental and simulation results of a discrete laser heating process without material removal. The approach of the calibration and validation is orientated on [10], which also presents the experimental results and parameters. Albeit the simulations done in [10] and within this paper differ in their results to a minor degree, the experimental results were matched almost as well by the simulations done in this work.

The reason not to use the same simulation software as in [10] is that MSC.Marc has an implemented element
deactivator, which deletes ascertained elements during the computation to a ascertained point of analysis time. Time and location of the element deactivation can automatically be defined by importing a NC machining file. This describes the cutter path and the milling parameters. The detection of the intersection of the FE mesh and the cutter deactivates automatically the elements, which are located within the cutter path. These elements are no longer factored in the rest of the computation. Thus, the effects of material removal on the heat balance in the workpiece can easily be analyzed.

5. Simulation Results

First, computational investigations were done using a basic parameter set (cf. caption of Figure 4) as a reference for all following simulations. This parameter set was used to analyze the influence of NC machining and thus a considered material removal on the quantity of heat and the temperature distribution in the workpiece. For that purpose, two simulations with the basic parameter set but with and without including the element deactivation were set up. Figure 3 visualizes the points M1 and M2 where the calculated temperature was monitored for the subsequent investigations.

Figure 3: Location of the monitoring points M1 in a depth of 0.7 mm and M2 in a depth of 2.0 mm in the simulation model.

Figure 4 shows the calculated temperature $T$ over the time for 0.0 and 1.5 mm distance between laser spot and cutter $x_L$ respectively in two different depths. A significant influence of the material removal on the resulting temperature is shown. A reduction of the distance $x_L$ results in a decrease of induced heat amount, which is carried away with the chip, and thus a reduction of the thermal load on the workpiece. But even a large distance between laser spot and cutter (e.g. $x_L = 1.5$ mm) highly influences the temperature curve and the total heat input on the workpiece. The percentage deviation of the total heat input between simulations with and without considering NC machining is from 11.7 to 18.5 %. Therefore, the implementation of the material removal mechanism is warrantable and necessary for numerical investigations of the laser-assisted milling process.
Further computations were done by varying the laser power $P_L$ in range between 400 and 1000 W. Figure 5 shows the calculated temperature curves over time and the maximum reachable temperature $T_{\text{max}}$ over the varied laser power $P_L$ in a depth of 0.7 mm. The maximum reached temperature $T$ increases significantly with increasing laser power $P_L$, i.e. the heat penetration depth is depending on the applied laser power $P_L$. This observation is in good agreement with former investigations [10]. The maximum temperatures (e.g. $T_{\text{max},400\text{W}}$) are transferred to Figure 5 (right) and results in a nearly linear dependency of $T_{\text{max}}$ and $P_L$. The maximum cooling rate calculated in simulation is $23 \cdot 10^3 \, ^{\circ}\text{C/s}$ and yields to the formation of titanium martensite during cooling from temperatures higher than $M_S$. Therefore, for the basic parameter set (cf. caption of Figure 4) the material is cut to a depth of 0.7 mm and only to this depth it is admissible to exceed the martensite start temperature ($M_S = 800 \, ^{\circ}\text{C}$). Heating the residual material (depth > 0.7 mm) over $M_S$ has to be avoided. Therefore, $M_S$ is the maximum admissible temperature in the depth of cut (for Figure 5 $a_p = 0.7 \, \text{mm}$) to prevent a irreversible change of the microstructure of the residual material. The corresponding laser power $P_{L,0.7\text{mm},\text{sim}}$ for the given depth of cut was determined to be 583 W. In this way, the material is heated and softened to the depth of cut to reduce the cutting forces without damaging the workpiece by thermal overload. The same approach was done to identify the optimum laser power $P_L$ for each depth of cut in the range of 0.1 to 0.7 mm.

Figure 4: Effect of considering NC machining on the calculated temperature $T$ in two depths (M1: 0.7 mm and M2: 2.0 mm) for two distances $x_L$ between laser and cutter (0.0 mm, 1.5 mm); ($P_L = 625 \, \text{W}$, $d_L = 3.0 \, \text{mm}$, $v_L = 1.6 \, \text{m/min}$, $a_e = 17 \, \text{mm}$, $a_p = 0.7$).

Figure 5: Simulated temperature $T$ in the depth of cut $a_p = 0.7 \, \text{mm}$ with varying laser power $P_L$ (left) and maximum reached temperatures $T_{\text{max}}$ over laser power $P_L$ (right); ($d_L = 3.0 \, \text{mm}$, $v_L = 1.6 \, \text{m/min}$, $x_L = 1.5 \, \text{mm}$, $a_e = 17 \, \text{mm}$).
Afterwards the distance between the laser spot and the cutter $x_L$ was varied in the range of 0 to 5 mm to identify the optimum distance $x_L$ for a laser-assisted milling process. The purpose was to achieve an optimal distribution of heat quantity in the system consisting of workpiece, chip and cutter. The thermal restrictions of this system are visualized in Figure 6. Ideally, only the removed material carries away the heat while the tool and the residual workpiece are less thermally affected by the laser induced heat. The maximum working temperature of the used cutter $T_{\text{max,cutter}}$ is limited to 950°C by the tool manufacture. Thus, the cutter is subject to the restriction not to come in contact with material above $T_{\text{max,cutter}}$. This will prevent a flanking of the coating and a built-up edge effect on the cutter. Therefore, the maximum admissible temperature at the point where the cutter and the surface intersect is 950 °C (see P1 in Figure 6). Furthermore, the residual workpiece must not be heated above $M_S$ (800°C) to avoid irreversible microstructural changes (see P2 in Figure 6). However, in the depth of 0.7 mm (it is also $a_p$) the temperature has to exceed the softening temperature of 400–450 °C but must not rise above $M_S$. Hence, the maximum admissible temperature in the depth of 0.7 mm ranges from 450 to 800 °C (see P3 in Figure 6).

Figure 6: Visualization of the critical points, which are subjected to thermal restrictions during the laser-assisted process: P1 at the surface ($< T_{\text{max,cutter}}$), P2 in a depth of 0.7 mm ($< M_S$) and P3 also in a depth of 0.7 mm ($> \text{softening temperature}$).

Figure 7 shows that the maximum temperature $T_{\text{max}}$ of the material the cutter comes into contact with, at the surface and the depth of 0.7 mm, is decreasing significantly with increasing distance $x_L$. At a distance $x_L$ of 1.2 mm the maximum temperature at the surface $T_{\text{max}}$ is equal $T_{\text{max,cutter}}$ (P1). Therefore, the distance between the laser spot and the cutter has to be set to $x_L > 1.2$ mm and the tool will not exceed $T_{\text{max,cutter}}$. Within the varied range of $x_L$ the temperature in a depth of 0.7 mm does not fall below the softening temperature of 450 °C. In case the described restrictions are fulfilled, Figure 7 illustrates that $x_L$ could range between 1.2 mm and 5.0 mm. Within this distance the softened material can be milled with laser assistance avoiding a thermal overload of the cutter or an irreversible microstructural change in the workpiece. In theory, $x_L$ can be set to 1.2 mm for an ideal heat penetration and low heat impact on the workpiece. However, for experimental investigations $x_L$ should be increased as a precaution to avoid a thermal overload and damage of the tool. Therefore, the distance $x_L$ is set to 1.5 mm for the subsequent investigations.
Figure 7: Maximum temperature $T_{\text{max}}$ the cutter comes into contact with over the distance $x_L$ between the laser spot and the cutter at the surface and in a depth of 0.7 mm ($P_L = 583$ W, $d_L = 3.0$ mm, $v_L = 1.6$ m/min, $a_e = 17$ mm).

6. Validation of the Simulation

Within related works the laser-assisted milling process was investigated experimentally [7, 8]. By microstructural examinations the correlation between the laser power $P_L$ and the resulting depth of the HAZ $h_{\text{HAZ}}$ was experimentally determined. An optimum laser power $P_{L,0.7\text{mm,exp}}$ was found to be 625 W without expecting a microstructural change in the workpiece beyond the depth of 0.7 mm (see Figure 8 (left)). Figure 8 (right) illustrates the consistence of the temperature field in simulation and the measured geometry of the HAZ in experiments. Temperatures above 800 °C ($T_{\text{max}} > M_S$) results in a microstructural change. Therefore, $P_{L,0.7\text{mm,sim}}$ was numerically identified to be 583 W (cf. Figure 5 (right)). The percentage deviation of computational and experimental results is calculated to 6.7 %.

Figure 8: Depth of the HAZ $h_{\text{HAZ}}$ versus the laser power $P_L$ investigated in experiments (left) and illustration of the geometrical dimensions of the computed temperature distribution and the experimentally determined HAZ (right) [8].

Figure 9 illustrates the reduction of the measured process forces during a laser-assisted milling process for the basic parameter set in comparison to conventional milling. The interpolation between the measured values resulted in a percentage reduction of the force in vertical direction ($\Delta F_{Z,\text{exp}}$) of 20.8 % and 13.7 % in X-direction ($\Delta F_{X,\text{exp}}$) in experiments. The process force in Y-direction was nearly uninfluenced and is therefore unconsidered in Figure 9. The computational determined laser power $P_{L,0.7\text{mm,sim}} = 583$ W is also plotted in Figure 9. The application of this
laser power on the measured reduction results in a percentage reduction of the process forces of $\Delta F_{Z,\text{sim}} = 19.6\%$ and $\Delta F_{X,\text{sim}} = 13.0\%$ respectively. The minor difference between the computational and experimental results is illustrated in Figure 9 as the small grey colored corridor. Its width results from the deviation of simulation and experiment. Thus, numerical and experimental results are in good agreement – the simulation setup and the previous approach are validated.

Figure 9: Experimentally determined percentage reduction of the process forces with the aid of laser assistance in comparison to conventional milling over the laser power $P_L$ \cite{8}. Range (grey corridor) of the achievable reduction by application of the experimental identified laser power $P_{L,\text{exp}} = 625$ W and the computed laser power $P_{L,\text{sim}} = 583$ W; ($a_p = 0.7$ mm, $d_L = 3.0$ mm, $v_L = 1.6$ m/min, $a_e = 17$ mm).

7. Conclusion

As a last step after the validation, several simulations were set up, which included the basic parameter set, the determined parameter $x_L$ and a variation of $P_L$. As a result Figure 10 explains for a laser-assisted milling process how to adjust the appropriate laser power $P_L$ for a desired depth of cut $a_p$. With these parameters the material is heated and softened to the depth of cut $a_p$ without influencing the microstructure of the residual workpiece. The previous computational identified laser power $P_{L,0.7\text{mm}} = 583$ W for $a_p = 0.7$ mm is exemplified plotted in Figure 10. This generated database is now useable within a process control via CAD/CAM interface.

Figure 10: Adjusting the appropriate laser power $P_L$ for a desired depth of cut $a_p$ within a laser-assisted milling process ($d_L = 3.0$ mm, $v_L = 1.6$ m/min, $a_e = 17$ mm).
8. Summary and Future Work

The presented work illustrates in detail the approach of establishing a coupled simulation model for laser-assisted milling and its use for determination of optimal process parameters. A comparison of the model with and without considering the NC machining path proves that the implementation of the material removal mechanism is warrantable and necessary for numerical investigations of the laser-assisted milling process. Simulation results are in good agreement with experimental measurements of the reduction of the process forces. Furthermore, a determination of the appropriate laser power $P_L$ for a desired depth of cut $a_p$ during a laser-assisted milling process is possible now.

The next step with respect to the application of the simulation model will consist of experimental investigations to validate the correlation of depth of cut and reasonable laser power by experiments. After the experimental validation of the simulation model other milling conditions (variation of $a_p$ and $v_L$) will be investigated. Finally, the generated database will be used for a CAD/CAM interface to control the hybrid process without influencing the residual workpiece negatively by a thermal overload during the laser-assisted milling process.

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References

[1] M. Peters; C. Leyens (Ed.): Titan und Titanlegierungen, Weinheim: Wiley-VCH, 2009.
[2] M. Meinecke: Prozessauslegung zum fünfachsigen zirkularen Schnupfräsen von Titanlegierungen, RWTH Aachen, Diss. 2009, Aachen: Apprimus, 2009.
[3] B. Denkena; J. Köhler; J. Dege: Optimierte Werkzeuge stellen Schlüssel für wirtschaftlichere Bearbeitung dar, MM – Das IndustrieMagazin, no. 26, 2008, pp. 60–63.
[4] S. Mounsey: Lasers Take Flight, in Laser Systems Europe, no. 5, 2009, pp. 14–15.
[5] U. B. Klossowski: Laserunterstütztes Fräsen von TiAl6V4, RWTH Aachen, Diss. 1998, Aachen: Shaker, 1999.
[6] R. Boyer; G. Welsch; E. W. Collings: Materials Properties Handbook Titanium Alloys, ASM International, Materials Park, OH, 2007.
[7] M. F. Zaeh; M. Baur, R. Wiedenmann: Laserunterstützes Fräsen reduziert Prozesskräfte, MM MaschinenMarkt, no. 5, 2011, pp. 26–28.
[8] M. F. Zaeh; R. Wiedenmann: Prozessuntersuchung zum laserunterstützen Fräsen hochfester Werkstoffe, submitted for publication: wt Werkstattstechnik online, no. 6, 2011.
[9] MSC.Software Corporation (Ed.): Marc 2010 r1 User Documentation, Vol. A: Theory and User Information, USA, 2010.
[10] M. F. Zaeh; R. Wiedenmann; R. Daub: A Thermal Simulation Model for Laser-Assisted Milling, in Laser Assisted Net Shape Engineering (LANE): 6th International Conference, 2010, pp. 353–362.
[11] F. Richter; L. Born: Die spezifische Wärmekapazität von metallischen Werkstoffen: Teil III: NiCr 15 Fe (Inconel 600) und vier weitere Werkstoffe aus der Gruppe der NE-Metalle, Werkstofftechnik, no. 17, 1986, pp. 233–237.
[12] Scientific Forming Technologies Corporation: DEFORM 3D Version 6.1, User’s Manual Material Library, USA, 2007.
[13] VDI-Wärmeatlas: Berlin, Heidelberg, Springer Berlin Heidelberg, 2006.