New Production Technologies in Aerospace Industry - 5th Machining Innovations Conference (MIC 2014)

Modelling and Simulation of Laser Assisted Milling Process of Titanium Alloy

Changyi Liu*, Yuhao Shi

*Nanjing University of Aeronautics & Astronautics, 29 Yudaqjie Street, Nanjing 210016, China
* Corresponding author. Tel.: +86-25-8489 5781; fax: +86-25-8489 5781. E-mail address: liuchangyi@nuaa.edu.cn

Abstract

High power thermal source such as laser beam has been applied for softening the difficult-to-machine materials when it is combined with conventional machining processes, such as milling. Analytical model and finite element method (FEM) model for the simulation of the laser assisted milling process are presented. In the analytical model, the general solution of the temperature distributed for a moving heat source in a semi-infinite body is calculated. The impact of the initial temperature to the cutting forces are taken into account, based on Johnson-Cook material constitutive law. In the FEM model, Johnson-Cook material constitutive law and Johnson-Cook material failure criteria have been implied within the material model. Sequentially thermo-mechanical coupling FEM approach is adopted. Gauss laser beam heating process is modelled as heat flux load scanning along the workpiece material surface and the temperature field with respect to time has been simulated. Then the temperature distribution about a series of discrete time steps has been taken as the initial temperature condition to the corresponding machining process simulation steps. Finally, the laser assisted titanium alloy milling simulation results of the analytical model, the FEM model, and the published experimental results have been compared. That shows the FEM model predicting cutting zone temperature, stress, and cutting forces accurately and elaborately, while the analytical model predicting cutting forces and cutting zone temperature efficiently to a certain accurate extent.

1. Introduction

In order to improve the machinability of the difficult-to-cut materials such as titanium alloy and heat resisting alloy, high power thermal sources, e.g. laser beam, have been combined with conventional machining processes. In laser assisted machining (LAM) process, the material is heated by a laser prior to the material removal location, and the heat energy transferring to the cutting deformation zone leads to the temperature elevation, material softening. As a result, the yield strength, hardness and strain hardening of the workpiece reduce and deformation behaviour of the materials changes to be machined more easily [1]. The process may yield higher material removal rates, reduced man and machine hours per part, increased tool life, an increased ability to precisely control part geometry, and substantial cost savings [2].

Demitrescu et al. [3] confirmed that for small brittle chips formed through preheating turning of AISI D2 steel with diode laser. As the temperature of the basic material rises, flow stress decreases and consequentially the chip can flow along the tool without breaking. This was also confirmed by Sun et al. [4] through laser assisted machining of titanium alloy.

Modelling the LAM processes helps to get a better understanding of this complex process, and the relationship between process parameters and the resultant temperature, strain, stress, and cutting forces etc. The retrieved models can be briefly classified as analytical, numerical,
experimental, intelligence algorithms based, and hybrid modelling approaches.

There have been plenty of literatures focusing on the analytical modeling of conventional machining processes. Merchant, Shaw and others had studied the actual machining operations in terms of basic mechanical quantities [5, 6]. Altintas et al. [7] developed the cutting force coefficients method that calibrate these coefficients which imply the influence of the material properties and geometries on the cutting forces through cutting experiments.

Most of the modeling efforts for the LAM have been primarily directed towards predicting the temperature distribution in the workpiece during machining [8]. Laser conduction heating of solid surfaces was introduced and analytical approaches for temperature field in the irradiated region was presented for the appropriate boundary and heating conditions [9].

However, to the best knowledge of the authors, the analytical models to predict cutting forces during LAM process are seldom published. In literature [10], the impact of cutting speed and initial temperature of the preheated laser beam on the cutting forces were taken into account, and laser-heat assisted titanium alloy milling simulation was carried out.

FEM is a powerful approach to establish a numerical model for LAM process simulation. Both the thermal process and mechanical process could be modelled and simulated simultaneously, and the elaborate temperate, stress, strain with respect to time and space could be solved and visualised. Using finite element method, a thermal model for a moving Gaussian laser heat source has been developed to predict the depth and width of the heat affected zone on the Ti6Al4V alloy workpiece [11]. A thermo-mechanical FEM model for the laser-assisted machining process, which consider the thermal boundary conditions (convection and radiation) by applying the convection heat transfer coefficients and the emissivity to all elements with external contact, has been set up [12]. Adopting the smoothed particle hydrodynamics (SPH) method and FEM to simulate the thermally assisted machining of Ti6Al4V, a 2D model was used to investigate the chip formation process while a 3D model was used to study the cutting force [13].

With the interest in LAM, the material constitutive model must represent the accurate characteristics of the material, especially while being subjected to high temperature. Johnson and Cook developed the basic form of the constitutive law that the power intensity and represents the integral average of the temperature, and $\Delta$ is the beam diameter.

One of the important parameters influencing the effects of laser-material interactions is the absorptivity of the material for laser radiation. It can be defined as the fraction of incident radiation that is absorbed at normal incidence. [8]. The average absorptivity of the Ti6Al4V plate workpiece was selected as 0.34 [11].

The laser beam is moving relative to the workpiece during LAM process. Hence, calculation of temperature distributions around the moving source of laser beam becomes important. For a point heating source moving with a constant velocity $v_r$ in the x-direction, with point source as

In this paper, an analytical model and FEM model are presented to model and simulate laser assisted milling process of the titanium alloy. The analytical model allows a quick and efficiently prediction of the process and FEM model simulates the processes precisely and elaborately. In the analytical model, the temperature of the workpiece cutting deformation zone preheated by the laser beam scanning is calculated and the temperature of a point relative stationary to laser source is assumed to be constant in the quasi steady state. While in the FEM model, the heat transfer process of the traveling laser preheating is simulated with respect to time and results in the temperature field distribution along discrete time intervals. Then the corresponding milling process step simulates the work material deformation interaction with milling tool under the initial temperature condition input from the heating model results and achieved the stress and strain field distribution. The heating and the cutting analysis steps are performed in turn sequentially with given time intervals to implement the entire process simulation of the LAM.

2. Model

2.1. Analytical model

2.1.1. Laser heat source and workpiece temperature distribution

The laser beam is abstracted and simplified to a base mode Gaussian beam perpendicularly directed at the top surface of the workpiece. The laser beam intensity which strikes the surface of a workpiece is expressed as [18]

$$I = I_0 e^{-(r^2 + r^2)/4R_o^2},$$

where $I_0$ is the laser beam intensity at the center (W/m²), $R_o$ is the laser beam spot radius. The intensity of the heat flux applied on the top surface can be calculated from the total power of the applied Gaussian beam through an integral average of the Gaussian beam intensity profile over the beam spot size using the following equation:

$$P_o = \frac{1}{\Delta} \int I_0 e^{-(r^2 + r^2)/4R_o^2} \, dr \, dy$$

where $\Delta$ is the beam spot area $\pi R_o^2/4$, $P_o$ is the average power intensity and represents the integral average of the intensity profile, and $\Delta$ is the beam diameter.
origin, the three-dimensional heat transfer can be rewritten as [8]

\[ \frac{\partial T(z, y, z, t)}{\partial z^2} + \frac{\partial T(z, y, z, t)}{\partial t} = \rho c_a \frac{\partial T(z, y, z, t)}{\partial t} \]

where \( T \) is the temperature at a location after time \( t \), \( a \) is the thermal diffusivity of the material, \( \zeta = x - v_y t \).

In this analytical model, the steady state temperature of the workpiece was concerned. The method introduced in literature [19] and [20] has been applied to calculate the general solution of the quasi-steady state conditions for moving heat sources.

The resultant temperature has been used to set the initial temperature of the cutting zone. Since the milling tool has the same velocity with the laser beam, the particular point in the cutting zone has approximate constant temperature on the steady state. The average temperature of a certain point in the cutting zone is set as the initial temperature during the analytical cutting forces calculation.

2.1.2. Shear banding material constitutive model
The shear banding material constitutive is the key to build complete analytical cutting force model. In this paper the Johnson-Cook (JC) material model is applied to describe the material softening during elevated temperature, and the material strengthening during large plastic strain and rapid plastic strain rate. The temperature risen affects material stress and the stress rate [21].

Failure accumulation in the JC model does not directly degrade the yield surface. The model defines the strain at fracture as [15]

\[ \varepsilon_{\text{fracture}} = \left( D_1 + D_2 \exp(D_3 \sigma) \right) \left( 1 + D_4 \ln \left( \frac{\dot{\varepsilon}}{\dot{\varepsilon}_{\text{ref}}}ight) \left( 1 - D_5 \dot{T} \right) \right) \]

where \( \sigma \) is the ratio of the stress to the effective stress, i.e. \( \sigma^* = \frac{\sigma}{\bar{\sigma}} \). Fracture occurs when the damage parameters \( D \) exceeds the value 1.0. The evolution of \( D \) is given by the accumulated incremental effective plastic strains divided by the current strain at fracture \( D = \sum (\Delta \varepsilon^*) / \varepsilon_{\text{fracture}} \). Titanium alloy Ti6Al4V failure strain parameters are set as literature [15] defined \( D_1 = 0.090, D_4 = 0.014, D_2 = 0.270, D_3 = 3.870, D_5 = 0.480 \).

2.1.3. Cutting forces model for general tool description
To suit the model to general milling tool geometry, flat end milling tools with corner radius and ball end milling tools are described concordantly. Some helical flute flat end milling tools have a corner radius \( r_c \), typically \( r_c < D_m / 2 \) (tool diameter \( D_m \)). While \( r_c = D_m / 2 \), flat end milling tools transform to ball end milling tools with ball radius \( r_b \). In this paper, the uniform model has been setup to simulate milling tool with different corner radius.

Discretizing the corner part of the bottom cutting edge along \( z \) direction (see Fig. 1), the cutting depth of every element is \( h = f_z \sin \alpha \sin \phi \) (feed rate \( f_z \), tool rotational angle \( \phi \)). To the cylinder part (side cutting edge) \( \kappa = 0 \); to the corner radius part or ball end \( \kappa = \arcsin\left( r - (D_m - r) / r_b \right) \). The cutting force elements on the bottom cutting edge are [22]

\[ dF_x = K_n f_z \sin \kappa \sin \phi dz + K_m dz / \cos \kappa \cos \beta \]

\[ dF_y = K_n f_z \sin \kappa \sin \phi dz + K_m dz / \cos \kappa \cos \beta \]

where \( K_n, K_m, K_r, K_w \) are cutting force coefficients where subscripts \( r, t, c, e \) denotes radial, tangential, cutting and edge effecting respectively; \( \beta \) is the helical angle of the milling tool flute. For titanium alloy, the cutting forces coefficients were from reference [14]. The integration of these element forces achieves the cutting forces on tools.

2.2. FEM Model
2.2.1. Laser heat source model
The laser beam scans the surface of the workpiece along a certain direction to heat the material. Milling tool performs the cutting process behind the laser spot with a constant distance. Laser power \( P_w \), with absorptivity \( A \), has been loaded to the workpiece material as heat flux load, with scanning speed \( v_f \), the distance between the position of laser spot on the workpiece and the position of cutting tool \( L \).

After setting the material heat exchange properties, initial temperature and boundary temperature, the solving of the heat process is separated to a series of time steps, each step is simulated as a quasi-steady state heat process and the workpiece initial temperature boundary of the consequent mechanical simulation step is achieved.

2.2.2. Material constitutive law
During LAM processes, titanium would be heated by the laser beam and the temperature of the cutting deformation zone material would be elevated higher than the condition without laser heating. Johnson-Cook material model describes the material softening during elevated temperature, and the material strengthening during large plastic strain and rapid plastic strain rate. JC material model [21] is expressed as

![Fig. 1 Corner radius of the milling tool](image-url)
\[ \sigma = (A + Be^c)(1 + C \ln \dot{\varepsilon})(1 - T^{m}) \]

where \( \sigma \) is the flow stress resistance, \( A, B, C \) and \( m \) are the strain strengthening, strain rate hardening and thermal softening constant respectively, \( \dot{\varepsilon} \) and \( \dot{\varepsilon} \) are the strain and strain rate respectively. \( T^* = (T - T_0)/(T_{melt} - T_0) \), \( T_{melt} \) is the melting temperature of Ti6Al4V, \( T_0 \) is ambient temperature.

The five JC model parameters \( A, B, C, n, \) and \( m \) adopted in the following FEM model are determined by the regression-analysis procedure under a constant strain-rate of \( 10^3 \) s\(^{-1} \) at an initial temperature varying from 700-1100°C at intervals of 100°C. The parameters could be estimated to be: \( A = 782.7 \) MPa; \( B = 498.4 \) MPa; \( n = 0.28 \); \( C = 0.028 \); and \( m = 1.0 \).

2.2.3. Laser assisted milling process model

The geometrical model of helical flute flat end milling tool, which has diameter 10 mm, helical angle 30°, rake angle 15°, flank angle 6°, has been built up first. Then the cutting tool geometrical model was input to FEM preprocesser, set as rigid-thermal material, divided to discrete 3D solid elements. Workpiece material was set as Johnson-Cook model and to use Johnson-Cook crack model as the failure criteria of the chip separating from workpiece.

In order to compare the traditional milling process and LAM process, the two different conditions have been simulated respectively. They have the same geometries and basic processing parameters. However, the former does not employ laser assistant, just in ambient temperature. The conventional milling workpiece is divided to thermo-mechanical solid elements that means thermal analysis and mechanical analysis coupling synchronously.

The LAM process has been simulated using sequential coupling approach. Laser beam could be a strength heat source; also the cutting process would translate some material plastic deformation potential energy and friction to heat energy that could be a relatively weak heat source. These two kinds of heat sources would integrate during the machining process, so it is a typical thermo-mechanical coupled problem. Naturally, this problem could be solved through simulation based on the thermo-mechanical coupling elements. Unfortunately, when laser beam as a heat load added to the former traditional milling model, the simulation could not be performed. The reason might be that the FEM software could not carry out this strong coupled problem properly in the current edition.

Therefore, an expedient way is to simulate the laser heating process and cutting process sequentially. That could be a weak coupled simulation. The entire time of the LAM process is separated into small intervals. The temperature field of every time interval was simulate, as the initial temperature field of the consequent machining process step. The heat process step and the machining process step have been performed interlacedly.

3. Simulations

3.1. Simulation results

Temperature distribution and milling forces of titanium Ti6Al4V under conventional and LAM conditions have been simulated using both the analytical model and FEM model presented previously. Machining parameters are set as feed speed \( v_f \) 6.66 mm/s, cutting tool diameter \( D_m \) 10 mm with three flutes, radial cutting depth \( a_r \) 5 mm, axial cutting depth \( a_p \) 1 mm, cutting speed \( v_c \) 130 m/min, the distance between cutting tool axis and laser beam center \( L \) 28.5 mm. Laser scans in front of the cutting zone, with the identical speed \( v_f \) and direction. Laser beam with 1000W power heats the Ti6Al4V workpiece with ambient temperature.

Fig. 2 depicts the temperature distribution of a point at workpiece surface on the laser scanning path. Fig. 3 displays the 3D temperature field when the time \( t = 5.728 \) s. The laser beam centre has the maximum temperature of 1080°C, and the point in front of the cutting zone has the temperature of 326°C. The front vicinity of the cutting zone has been preheated to 300°C~350°C or higher. Also, the LAM simulation result were compared with experimental result from literature [23], having the equivalent process parameters \( v_c \) 130 m/min, \( a_r \) 5 mm, \( a_p \) 1 mm, and \( v_f \) 6.66 mm/s, where workpiece temperature of the laser beam centre and the point in front of the cutting zone are almost 1340°C and 420°C respectively for 1000W laser power.
Fig. 4 illustrates the stress distribution field comparison between traditional milling and laser assisted milling. The result demonstrates the thermal stress during LAM is more significant than traditional machining process and the laser assisted heating can reduce the stress impact to the cutting zone caused by cutting edge penetration from more than 800 MPa to less than 400 MPa. Consequently, the maximum of the cutting forces will be depressed effectively.

3.2 Comparison with experimental results

Simulated feed forces during conventional milling and laser assisted milling processes have been compared with experimental results from literature [23].

The simulated conventional and LAM milling feed forces using the presented analytical model and FEM model, and the comparison with experimental results are depicted in Fig. 5. Both the simulated and experimental results show that the feed force reduce dramatically. The average of maximum feed force of analytical simulation, FEM simulation and experiment are 145 N, 120N and 136 N respectively, therefore the average errors of analytical and FEM simulation to experiment are 6.6% and 11.8%, within 15%.

4. Conclusions

An analytical cutting force model and FEM model for heat assisted milling titanium alloy process have been presented. The JC material model is applied to describe the heat softening and mechanical hardening of titanium alloy consistently in both of the models. The temperature distribution during the laser beam scanning is analytically calculated using the general solution of the quasi-steady state for moving heat sources in a semi-infinite body in the analytical cutting forces model.

In the FEM model, temperature distribution of the workpiece through laser beam scanning process is
simulated and taken as the preheated initial temperature boundary of the cutting process. Thermal simulation and mechanical machining simulation are interfaced performed in the FEM model to implement the sequentially thermo-mechanical coupled simulation of the entire LAM process.

The simulated temperature and cutting forces are in good agreement with the published experimental data. The simulation demonstrates that for the Ti6Al4V laser-heat assisted milling operation, the flow stress maximum is decreased in the cutting zone. The analytical model suits for the LAM temperature and cutting forces prediction with efficient time and computer resource consumptions; while the FEM model suits for the elaborate simulation with more accurate, detailed and visual temperature, strain, stress results.

Acknowledgements

This work was supported by the Nanjing University of Aeronautics & Astronautics Fundamental Research Funds [grant number NS2013048].

References

[1] Sun, S., Brandt, M., Dargusch, M. S., 2010. Thermally enhanced machining of hard-to-machine materials-A review. International Journal of Machine Tools & Manufacture 50, p. 663-680.

[2] Chryssoulis, G., Afantitis, N., Karagiannis, S., 1997. Laser Assisted Machining: An Overview. Journal of Manufacturing Science and Engineering-Transactions of the ASME 119, p. 766-769.

[3] Dumitrescu, P., Koshy, P., Stenekes, J., Elbestawi, M. A., 2006. High-power diode laser assisted hard turning of AISI D2 tool steel. International Journal of Machine Tools and Manufacture 46, p. 2009-2016.

[4] Sun, S., Brandt, M., Dargusch, M. S., 2010. The effect of a laser beam on chip formation during machining of Ti6Al4V alloy. Metallurgical and Materials Transactions A: Physical Metallurgy and Materials Science 41, p. 1573-1581.

[5] Merchant, E., 1945. Mechanics of the Metal Cutting Process. I: Orthogonal Cutting and a Type 2 Chip. Journal of Applied Physics 16, p. 267-275.

[6] Merchant, M. E., 1945. Mechanics of the Metal Cutting Process. II: Plasticity Conditions in Orthogonal Cutting. Journal of Applied Physics 16, p. 318-324.

[7] Budak, E., Altintas, Y., Armarego, E. J. A., 1996. Prediction of Milling Force Coefficients From Orthogonal Cutting Data. Journal of Manufacturing Science and Engineering-Transaction of the ASME 118, p. 216-224.

[8] Dahotre, N. B., Harimkar, S. P., Laser Fabrication and Machining of Materials. 2008: Springer US.

[9] Yilbas, B., Shuja, S., Laser Surface Processing and Model Studies. 2013: Springer Berlin Heidelberg.

[10] Liu, C., 2014. Cutting Force Model for Heat Assisted Titanium Alloy Milling. Advanced Materials Research 887-888, p. 1191-1194.

[11] Yang, J., Sun, S., Brandt, M., Yan, W., 2010. Experimental investigation and 3D finite element prediction of the heat affected zone during laser assisted machining of Ti6Al4V alloy. Journal of Materials Processing Technology 210, p. 2215-2222.

[12] Zamani, H., Hermani, J-P., Sonderegger, B., Sommitsch, C., 2013. 3D Simulation and Process Optimization of Laser Assisted Milling of Ti6Al4V. Procedia CIRP 8, p. 75-80.

[13] Xi, Y., Bermingham, M., Wang, G., Dargusch, M., 2014. SPH/FE modeling of cutting force and chip formation during thermally assisted machining of Ti6Al4V alloy. Computational Materials Science 84, p. 188-197.

[14] Johnson, G. R., Cook, W. H., A constitutive model and data for metals subjected to large strains, high strain rates and high temperatures, in Proceedings of the Seventh International Symposium on Ballistics. 1983: Hague, Netherlands. p. 541-547.

[15] Johnson, G. R., Cook, W. H., 1985. Fracture characteristics of three metals subjected to various strains, strain rates, temperatures and pressures. Engineering Fracture Mechanics 21, p. 31-48.

[16] Davies, M. A., Burns, T. J., 2001. Thermomechanical oscillations in material flow during high-speed machining. Philosophical Transactions of the Royal Society of London Series A-Mathematical Physical and Engineering Sciences 359, p. 821-846.

[17] Karpat, Y., 2011. Temperature dependent flow softening of titanium alloy Ti6Al4V: An investigation using finite element simulation of machining. Journal of Materials Processing Technology 211, p. 737-749.

[18] Sowdari, D., Majumdar, P., 2010. Finite element analysis of laser irradiated metal heating and melting processes. Optics & Laser Technology 42, p. 855-865.

[19] Hou, Z. B., Komanduri, R., 2000. General solutions for stationary/moving plane heat source problems in manufacturing and tribology. International Journal of Heat and Mass Transfer 43, p. 1679-1698.

[20] Zimmer, K., 2009. Analytical solution of the laser-induced temperature distribution across internal material interfaces. International Journal of Heat and Mass Transfer 52, p. 497-503.

[21] Lee, W.-S., Lin, C.-F., 1998. High-temperature deformation behaviour of Ti6Al4V alloy evaluated by high strain-rate compression tests. Journal of Materials Processing Technology 75, p. 127-136.

[22] Engin, S., Altintas, Y., 2001. Mechanics and dynamics of general milling cutters. Part I: helical end mills. International Journal of Machine Tools and Manufacture 41, p. 2195-2212.

[23] Sun, S., Brandt, M., Barnes, J. E., Dargusch, M. S., 2011. Experimental investigation of cutting forces and tool wear during laser-assisted milling of Ti-6Al-4V alloy. Proceedings of the Institution of Mechanical Engineers, Part B: Journal of Engineering Manufacture 225, p. 1512-1527.