A 3D FEM-based model of laser heating for selection of process parameters in laser-assisted machining of Ti6Al4V

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Abstract

An appropriate selection of the laser parameters is critical in realizing the potential of laser-assisted machining (LAM) for hard-to-cut materials. This work presents a 3D FEM-based model of the laser heating in Ti6Al4V to select the laser parameters by analysing the effect of the laser-tool gap, laser scanning speed, and laser power on the temperature of the workpiece in the cutting zone. The model accounts for moving a continuous laser heat source with Gaussian intensity distribution and is implemented in Abaqus/explicit with the help of a VDFLUX subroutine. The results suggest that the laser-tool gap plays a significant role in heating the entire cutting region. Regardless of power and scanning speed, the laser-tool gap must be sufficient enough to allow heating of the cutting region, which depends on the material's thermal diffusivity. The scanning speed, which is the same as the cutting speed, showed heating of the entire cutting region only at lower values, suggesting that the LAM process could be inefficient at higher cutting speeds. The laser power should be sufficient enough to heat the material, but it can be minimized by choosing an optimal value of the laser-tool gap. The study demonstrates that through an appropriate selection of the laser parameters, the entire cutting zone can be heated to temperatures between 500-300 °C, desired in the machining of Ti6Al4V.

Keywords: Laser-assisted machining, finite element method, laser heating model

1. Introduction

Titanium alloys are widely used in aerospace and biomedical applications due to their high specific strength, corrosion resistance, and biocompatibility. Despite these advantages, their machinability is poor, owing to their low thermal conductivity and hardness. Accordingly, traditional machining of Ti-alloys becomes a less productive and costly process [1]. Therefore, laser-assisted machining (LAM) has grown as one of the promising approaches in the last decade. In LAM, thermal softening of workpiece due to laser heating reduces cutting force and tool wear and increases productivity [2, 3]. Therefore, LAM is an effective process for machining of difficult-to-machine materials. However, the choice of appropriate laser parameters such as laser power, spot diameter, scanning speed, and the laser-tool gap is crucial in LAM. For a given cutting conditions, it is essential to select an optimum combination of the laser parameters to heat the entire cutting zone above a certain temperature for material softening.

LAM has been studied by researchers with both modelling and experimental approaches. Rajagopal *et al.* [4] is one of the earliest who suggested using LAM for aerospace alloys like Inconel 718 and Ti6Al4V by performing experiments and studied the effect of laser power on cutting force and tool wear. Sun *et al.* [5] observed a 27-55 % reduction in cutting forces by changing laser-tool gap for Ti-alloy in their experimental study. Further, Wiedenmann *et al.* [6] suggested an optimum set of laser parameters for milling of titanium alloy. While modelling LAM, laser heating is incorporated in the model by assigning initial temperature to the workpiece by Lesourd *et al.* [7]. The model was extended by Germain *et al.* [8] by incorporating temperature field induced by laser as an initial condition in their model. Further, Yang *et al.* [9] developed a Gaussian moving laser heat source model using the finite element method (FEM) to predict the heat affected zone (HAZ) in a workpiece made of Ti-alloy. They found that both the depth and width of heat affected zone increase with an increase in laser power and decrease with an increase in laser scanning speed and spot diameter. Ayed *et al.* [10] performed a 2D simulation of laser-assisted orthogonal cutting of Ti-alloy based on FEM and found that a 4-55 % reduction in cutting forces by varying laser power and laser-tool gap. Further, Zamani *et al.* [11] performed 3D simulation of laser-assisted side milling of Ti6Al4V and observed 25-60 % reduction in the cutting forces.

Based on the literature survey, it is understood that an optimum set of laser parameters for a moving Gaussian laser heat source to get a required temperature field on the workpiece is a challenging task. It is also interpreted that experimental studies for such a multi-parameter optimization problem will be cumbersome. Hence, the development of a 3D model of moving laser heat source is a prime need for in-depth analysis of temperature field in a workpiece material. Therefore, the proposed work focuses on analyzing the effect of the laser parameters such as laser power (p), laser scanning speed (v), and laser-tool gap (l_g) on the temperature field in Ti6Al4V workpiece. For this purpose, a 3D model based on FEM is developed in Abaqus/explicit^{TM} by incorporating a moving Gaussian laser heat source through a VDFLUX subroutine. The model is described in Section 2. In Section 3, results predicted by the model are discussed. Lastly, important conclusions and future directions based on the work are listed in Section 4.

2. Model description

Laser-assisted machining (LAM) can be considered as a two-step process, laser heating process and machining process. In this work, only the laser heating process is modelled to understand the effect of various laser parameters on temperature distribution in workpiece. The understanding of the temperature distribution with the proposed model will be helpful to select optimum laser parameters in LAM.

2.1. Physical and mathematical description

The model consisting a continuous laser heat flux moving over top surface of 20 mm x 10 mm x 6.5 mm Ti6Al4V workpiece along with associated coordinate system is schematically shown in Fig. 1. A virtual tool is considered at the edge of the workpiece to define laser-tool gap, depth of cut, and tool-tip (point A in Fig. 1). In the model, laser heat source is considered as a surface heat flux, *q(x,y),* with Gaussian distribution (see Eq.1). It starts moving from origin *o* along x-direction with scanning speed (v). α is the absorptivity of the workpiece.

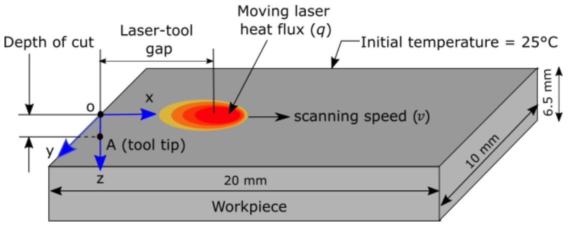

Fig. 1. Schematic of moving laser heat source model.

$$q(x,y) = \frac{2\alpha P}{\pi b^2}\exp\left(-\frac{2(x^2+y^2)}{b^2}\right) \tag{1}$$

The conduction heat transfer in the workpiece is modelled using the 3D transient heat conduction equation given by Eq.2. The thermal-physical properties of workpiece, such as density (ρ), conductivity (k) and specific heat (c) are considered to be temperature dependent [9].

$$\frac{\delta^2 T}{\delta x^2}+\frac{\delta^2 T}{\delta y^2}+\frac{\delta^2 T}{\delta z^2}=\frac{\rho c}{k}\left(\frac{\delta T}{\delta t}-v\frac{\delta T}{\delta x}\right) \tag{2}$$

The initial condition is given by Eq.3. Further, the natural boundary condition to account the surface heat flux neglecting the convection and radiation mode of heat transfer is given by Eq.4.

$$T(x,y,z,0) = 25\ ℃ \tag{3}$$

$$-k\frac{\delta T}{\delta z} = q(x,y) \tag{4}$$

2.2 Numerical approach

A finite element model based on the theory described in Section 2.1 is developed in Abaqus/explicit^{TM}. The moving surface heat flux with Gaussian distribution is implemented in the model through VDFLUX subroutine written as a FORTRAN script. The temperature dependent thermo-physical properties of Ti6Al4V are assigned to the workpiece [12]. Further, the workpiece is discretised with 3D heat transfer elements. The minimum element size in the heat flux region is taken is 50 μm for smooth temperature distribution. The model is then solved using dynamic/explicit scheme.

3. Results and discussion

In this work, the cutting region is assumed as the uncut chip area formed with feed 0.2 mm and depth of cut 0.5 mm. The main objective is to achieve thermal softening in the entire cutting region. It is understood from literature survey that the temperature of 250-300 ℃ in the cutting zone causes enough thermal softening of Ti6Al4V [13]. Consequently, the range of laser parameters is selected to achieve temperature around 300 ℃ in the cutting zone. Accordingly, for 1 mm laser beam diameter, laser power is varied in the range of 500 W to 1500 W, laser-tool gap is varied in the range of 6 mm to 14 mm, and laser scanning speed is varied in the range of 200 mm/s to 400 mm/s. In the simulations, the temperature in the cutting region is measured along the depth of workpiece for the set of laser parameters.

3.1 Model validation

For validation purpose, a numerical simulation with laser power 678 W, beam diameter 4.4 mm, and laser scanning speed 17.35 mm/s is performed. Temperature distribution due to laser heating at the time of 0.5 s is shown in Fig. 2. At 0.5 s, the laser spot is moved 8.675 mm distance from the origin (see Fig. 2). It is observed that the temperature reaches to the maximum value of 2278.5 ℃ at the laser spot. The temperature gradually reduces along all the three directions. However, it is noted that heat conduction depth increases from the laser splaser asisot to the origin. Therefore, it is inferred that to achieve the required cutting depth in LAM, the laser-tool gap is a crucial parameter. Further, the temperature distribution and the maximum temperature predicted by the model agree well with the numerical results of Yang et *al.* [9]. The maximum temperature predicted by the proposed model is deviated by less than 1 % as compared to the results in [9].

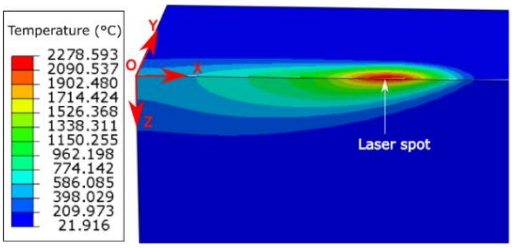

Fig. 2. Simulated temperature contour of laser heating

3.2. Evaluation of an optimum laser-tool gap (l_g)

As discussed in Section 3.1, laser-tool gap is one of the crucial process parameters in LAM. For a given laser power and laser scanning speed, temperature in cutting zone substantially varies with a change in the laser-tool gap. Here, the temperature variation at the tool-tip is analyzed for different laser-tool gap and plotted in Figs. 3 and 4. It is observed that the temperature rapidly increases at the beginning, it attains a maximum, and then gradually decreases, with an increase in the laser-tool gap. Accordingly, an optimum laser-tool gap should be maintained to attain a maximum temperature at the tool-tip under given laser parameters. The optimum laser-tool gap changes with both the laser power and the laser scanning speed. However, it is noticed that the effect of laser scanning speed on the optimum laser-tool gap seems to be more dominant than laser power. For instance, the optimum laser-tool gap increases from 3 mm to 6 mm, when the laser scanning speed increases from 200 mm/s to 350 mm/s (see Fig. 4). Further, it is also noted that the maximum temperature at the tool-tip increases with an increase in laser power and a decrease in laser scanning speed.

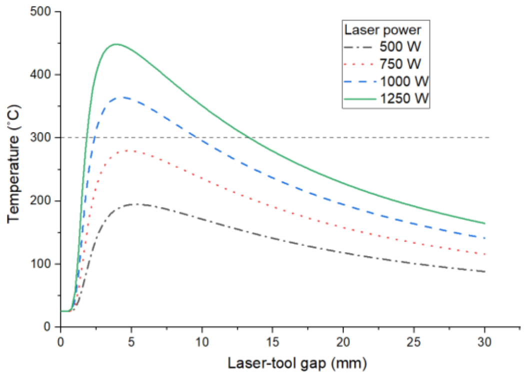

Fig. 3. Variation of temperature at the tool-tip with laser-tool gap at different laser power.

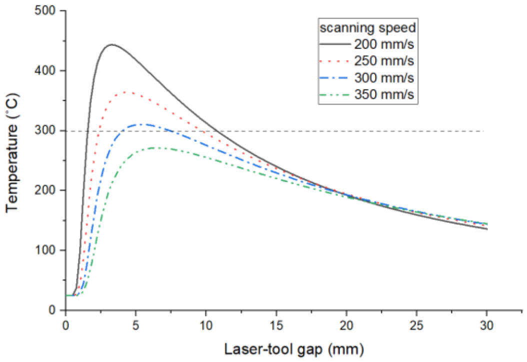

Fig. 4. Variation of temperature at the tool-tip with laser-tool gap at different laser scanning speed.

3.3. Effect of laser-tool gap (l_g)

To understand the effect of the laser-tool gap on temperature distribution, the gap is varied from 6 mm to 14 mm at laser power of 1000 W and laser scanning speed of 250 mm/s. For the various laser-tool gaps, the temperature distribution along the depth (z-axis) of the workpiece at the origin *o* is plotted in Fig. 5. It is observed that the temperature monotonically reduces along the depth of workpiece. Further, it is noted that the temperature gradient increases with decrease in the laser-tool gap. This may be due to poor thermal conductivity of Ti6Al4V. For instance, temperature reduces by 200 ℃ for the laser-tool gap of 6 mm and by 75 ℃ for the laser-tool gap of 14 mm. Furthermore, for a given laser-tool distance, the rate of temperature reduction increases along the depth of workpiece. Consequently, the temperature at the origin reduces greatly as compared to at the depth of 0.5 mm, when laser-tool gap increases from 2 mm to 14 mm. Based on the observations, it is inferred that, for required thermal softening in cutting zone, the laser-tool gap should not be more than 10 mm. Because, for the laser tool-gap below 10 mm, the temperature at the depth of 0.5 mm is above 300 ℃.

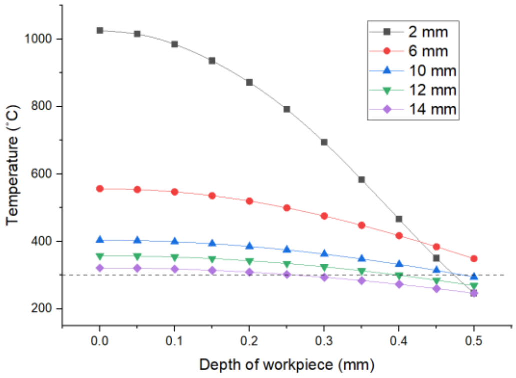

Fig. 5. Variation of temperature along the depth of workpiece at origin for different laser-tool gap.

3.4. Effect of laser scanning speed (v)

In this section, the effect of laser scanning speed on the temperature distribution along the depth of workpiece is analyzed. For this purpose, the laser scanning speed is varied from 200 mm/s to 400 mm/s. Based on the results discussed in Section 3.3, the temperature is analyzed at a laser-tool gap of 10 mm and laser power of 1000 W. The temperature variation for different laser scanning speed is depicted in Fig. 6. It is observed that the temperature monotonically decreases with an increase in the laser scanning speed. Because, laser-workpiece interaction time decreases with an increase in the laser scanning speed. Further, at the given laser-scanning speed, temperature reduces at faster rate for higher depths. Therefore, the effect of laser scanning speed on temperature is more pronounced at higher depths than near the origin. However, the rate of reduction of temperature along the depth of workpiece is almost identical for all laser scanning speeds. Based on the observations, for required thermal softening in the cutting zone, the laser scanning speed should not be more than 250 mm/s. Because, at higher speeds than 250 mm/s, the temperature at 0.5 mm depth is below 300 ℃.

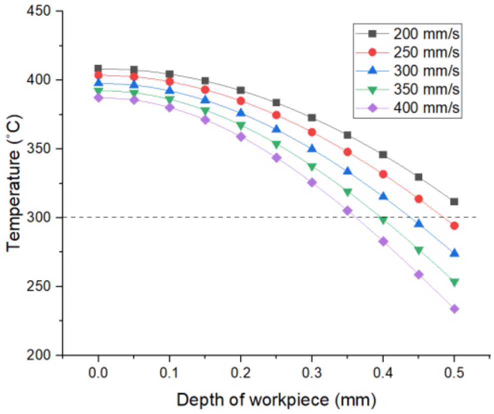

Fig. 6. Variation of temperature along the depth of workpiece for different laser scanning speed

3.5. Effect of laser power (P)

While analyzing the effect of laser-tool distance and laser scanning speed, the laser power was fixed at 1000 W. However, laser power is one of the crucial laser parameters in controlling maximum temperature in the cutting zone. Therefore, to understand the effect of laser power on temperature variation along the depth of workpiece, the laser power is varied from 500 W to 1500 W. The laser scanning speed and laser-tool distance is fixed at 250 mm/s and 10 mm, respectively based on the results obtained in Section 3.3 and 3.4. The temperature variation along the depth of workpiece for different laser powers is shown in Fig. 7. It is observed that the temperature increases with an increase in the laser power due to increase in heat flux. Further, the temperature along the depth of workpiece reduces at identical rate, for all laser powers. It is inferred that, for required thermal softening in the cutting region, the laser power should be more than 1000 W. Because, at lower powers than 1000 W, temperature in the cutting zone is much below 300 ℃.

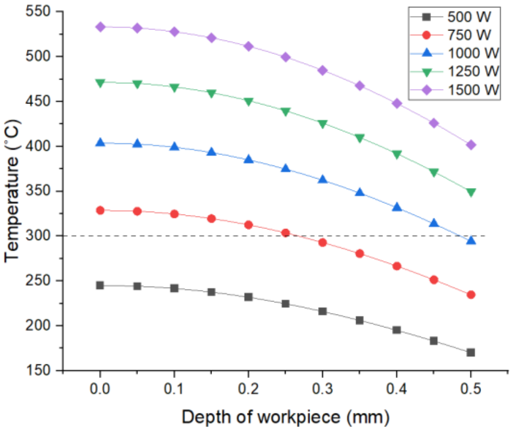

Fig. 7. Temperature distribution along the depth of workpiece for different laser power.

3.6. Selection of optimum parameters

As discussed in Section 3.1-3.5, the temperature in the cutting zone primarily depends on laser power, laser scanning speed, and laser-tool gap. Therefore, the selection of an optimum set of parameters required through investigation of these parameters. The minimum thermal softening temperature and cutting depth were set to 300 ℃ and 0.5 mm, based on the literature. The results obtained in the work are well applicable for cutting depths below 0.5 mm. Based on the work, it is observed that laser-tool gap below 10 mm with laser scanning speed below 250 mm/s and laser power above 1000 W, produce required temperature in the cutting zone. The simulations can be extended to any combination of depth of cut and cutting speed to choose an optimal value of laser-tool gap for minimal laser power.

4. Conclusions

This work presents an approach to select operating laser parameters viz. power, scanning speed, and laser-tool gap in laser-assisted machining of Ti6Al4V using a 3D finite element model of laser heating. In the simulation, the temperature variation along the depth of the workpiece in the cutting zone is analyzed for different laser parameters. It is observed that the temperature decreases along the depth of workpiece for all the laser parameters. However, the rate of reduction of temperature along the depth of workpiece is different for different parameters. Further, it is noticed that the temperature gradient increases with decrease in laser-tool gap due to poor thermal conductivity of Ti6Al4V. Furthermore, lower laser scanning speed increases laser-workpiece interaction time and hence increases temperature in the cutting zone. Finally, it is concluded that the laser-tool gap below 10 mm with laser scanning speed below 250 mm/s and laser power above 1000 W, produce required temperature in the cutting zone of Ti6Al4V workpiece.

Acknowledgement

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