Computational Materials Science 92 (2014) 149–156

Contents lists available at ScienceDirect

Computational Materials Science

journal homepage: www.elsevier.com/locate/commatsci

Numerical modeling of laser assisted machining of a beta titanium alloy

Yao Xi [a,b,*], Hongyi Zhan [a], R.A. Rahman Rashid [b,c], Gui Wang [a,b], Shoujin Sun [d], Matthew Dargusch [a,b]

[a] *Centre for Advanced Materials Processing and Manufacture, School of Mechanical and Mining Engineering, The University of Queensland, St Lucia, Queensland 4072, Australia*
[b] *Defence Materials Technology Centre, Level 2, 24 Wakefield St, Hawthorn, VIC 3122, Australia*
[c] *Faculty of Science, Engineering and Technology, Swinburne University of Technology, Hawthorn, VIC 3122, Australia*
[d] *School of Aerospace, Mechanical and Manufacturing Engineering, RMIT University, Melbourne, VIC 3000, Australia*

ARTICLE INFO

Article history:
Received 9 March 2014
Received in revised form 28 April 2014
Accepted 15 May 2014

Keywords:
Laser assisted machining
SPH method
Material constitutive model

ABSTRACT

Laser assisted machining is a promising new machining technology that can be used to assist with the fabrication of components from difficult to machine materials such as beta titanium alloys. To understand the mechanism behind this process, a reliable numerical machining model is needed. This study employed an SPH method to the problem of laser assisted machining of Ti–6Cr–5Mo–5V–4Al alloy. The SPH method has several advantages when dealing with large-deformation problems compared with traditional finite element methods. A laser scanning model was developed beforehand to predict the temperature elevation due to laser heating and the temperature results were used as initial conditions for the SPH/FE machining models. Johnson–Cook parameters and Zerilli–Armstrong parameters of Ti–6Cr–5Mo–5V–4Al alloy were acquired based on experimental data from the Split Hopkinson Pressure Bar (SHPB) test and were implemented in the machining models. The cutting force predictions of machining models using these two material models were discussed in this study. Both conventional machining (CM) and laser assisted machining (LAM) were simulated. The main cutting force predictions and the temperature predictions were compared with experimental results to validate the models.

1. Introduction

Owing to their inherent properties such as high strength to weight ratio, high fracture toughness and excellent corrosion resistance, beta titanium alloys are widely used in the aerospace industry for applications such as landing gear, springs, nacelle and empennage structure [1]. However, the machining cost of beta titanium alloys is very high due to their unique properties such as low thermal conductivity, strong alloying tendency with some material in the cutting tool, and relatively low modulus of elasticity. Thus some advanced machining technologies have been developed to improve the machinability of beta titanium alloys in order to lower the manufacturing cost and increase productivity in order to meet the growing demand for products manufactured from beta titanium alloys. One of these advanced machining technologies being investigated is laser assisted machining (LAM).

The basic idea of LAM is to introduce a laser beam into the conventional machining system as a heat source in order to locally heat and soften the workpiece material before the cutting tool removes the unwanted section. As a result of the laser heating, the yield strength and hardness of the workpiece material is reduced which should allow the material to be machined with lower power consumption and higher material removal rate and therefore greater productivity [2]. This method has been studied by some researchers and is believed to be a promising method to reduce the machining cost of difficult to machine materials. Sun et al. [3] carried out a parametric investigation on laser assisted machining of commercially pure titanium, compared to conventional machining. In this study both a lower magnitude and lower variation of cutting forces and a smoother surface finish were achieved. Dandekar et al. [4] reported a significant machinability improvement for the Ti–6Al–4V alloy during laser assisted machining, with reduced specific cutting energy and improved surface roughness compared to conventional machining. Rahman Rashid et al. [5,6] conducted experimental studies on laser assisted machining of the beta titanium alloy Ti–6Cr–5Mo–5V–4Al. It was found through this work that cutting force can be reduced by up to 15% under LAM when compared with conventional machining, and the optimum feed rate, cutting speed and laser power

---

* Corresponding author at: Centre for Advanced Materials Processing and Manufacture, School of Mechanical and Mining Engineering, The University of Queensland, St Lucia, Queensland 4072, Australia. Tel.: +61 425451005.

E-mail addresses: y.xi@uq.edu.au (Y. Xi), h.zhan@uq.edu.au (H. Zhan), rrahmanrashid@swin.edu.au (R.A. Rahman Rashid), gui.wang@uq.edu.au (G. Wang), shoujin.sun@rmit.edu.au (S. Sun), m.dargusch@uq.edu.au (M. Dargusch).

http://dx.doi.org/10.1016/j.commatsci.2014.05.023
0927-0256/

for LAM of Ti–6Cr–5Mo–5V–4Al alloy was 0.15–0.25 mm/rev, 25–125 m/min and 1200–1600 W, respectively.

Experimental studies of laser assisted machining can be time consuming and expensive because it is a process with complex thermo-mechanical and highly dynamic features, and a large amount of heating and cutting parameters can potentially affect the process dramatically. Therefore, it is essential to have reliable numerical models to conduct parametric studies on laser assisted machining in order to understand the mechanism behind the process and optimize the machining parameters.

Simulation of conventional machining processes have been widely studied by researchers [7–11], and most of this reported work adopted finite element methods. However, as the machining process is a large deformation process with complex physical and chemical features, the traditional finite element method has some difficulties in simulating the machining process due to issues such as mesh tangling and distortion. To overcome these problems, some researchers have introduced a new method in their studies to simulate the machining process, which is the smoothed particle hydrodynamics (SPH) method.

The SPH method is a mesh-free Lagrangian numerical method originally developed in 1977 for astrophysics applications, and has since been applied in mechanics problems over the past three decades. Applying the SPH method to machining models involves several advantages compared to the traditional finite element method. First, the mesh-free SPH method does not have the mesh tangling and distortion problems which usually happen in traditional finite element analyses involving large deformation. Another advantage of the SPH method is that it does not need to use chip separation criterion or predefine the cutting path to allow the chip to separate from the workpiece. In SPH machining models, the chip will naturally separate from the workpiece, and the creation of the new free faces can be directly managed by the SPH method. Limido et al. [12] applied the SPH method to simulate high speed metal cutting. The results of the SPH model were compared with experimental and numerical data in terms of the chip morphology and the cutting forces. The comparison showed that the SPH model is able to predict continuous and serrated chips and also the cutting forces. However, in order to reduce the model size and the computational time, the tool velocity in the SPH model is assumed to be ten times higher than the real velocity, which in reality is valid only for limited situations. Calamz et al. [13] used an SPH metal cutting model to analyze the chip formation and cutting forces with and without tool wear. The tool wear was modeled by the change of the tool geometry. The predicted results were compared with experimental data which showed good agreement for chip formation comparisons. The model correctly predicted the variation of the cutting forces induced by the tool wear but not the magnitude of the cutting forces. In a similar way to Limido's work [12], the tool velocity was also assumed to be ten times higher than the real velocity in this study. Abolfazl Zahedi et al. [14] have also reported an SPH machining model which can be used to study a micro-machining process in a similar way as other reported SPH machining models, this work also simulated orthogonal cutting with a relatively simple shaped workpiece.

Simulation of conventional machining has been widely studied by researchers, but only a few studies have addressed the simulation of laser assisted machining. Singh et al. [15] reported a 3D transient finite element model of a moving Gaussian laser heat source to characterize and predict the heat affected zone of the workpiece material in the laser assisted micro-grooving process. The Gaussian distribution of laser power intensity $P_{x,y}$ at location (x, y) is given by:

$$P_{x,y} = \frac{2P_{tot}}{\pi r_b^2} \exp\left(-\frac{2r^2}{r_b^2}\right) \tag{1}$$

where $r = \sqrt{x^2 + y^2}$ is the distance measured from the laser beam center and r_b is the laser beam radius, $P_{tot} = \eta P_{incident}$, where P_{tot} is the total power absorbed, $P_{incident}$ is the incident laser power, and η is the average absorptivity of the workpiece material. In the center of the laser beam, when the temperature exceeds the melting point the node was assumed to remain in the mesh and the latent heat of fusion was simulated by artificially increasing the liquid specific heat. Corresponding experiments were conducted to validate the model. The experimental results were compared with the predicted results, where a prediction error of 5–15% was found with most of the predicted results falling within 10% of the measured results.

Yang et al. [16] also developed a 3D transient finite element thermal model to predict the depth and width of the heat affect zone in a Ti6Al4V workpiece caused by laser heating. The model was developed using the commercial finite element software ANSYS and the laser beam were simulated by a Gaussian heat source. The material emissivity ε and absorptivity η used in the model were calculated based on the experimental data using Eqs. (2) and (3).

$$\varepsilon = \left(\frac{T_r}{T_s}\right)^4 \tag{2}$$

where T_s and T_r are the sample and its radiance temperature, respectively,

$$\eta = \frac{K\Delta T}{2P_{incident}} \sqrt{\frac{\pi^3 r_b^3 U}{2\alpha}} \tag{3}$$

where k is the thermal conductivity, ΔT is the measured maximum temperature on the top surface of the workpiece material, $P_{incident}$ is the incident laser power, r_b is the laser beam radius, U is the laser scanning speed, α is the thermal diffusivity. To achieve higher model efficiency, a plane of symmetry was used and therefore only half of the workpiece was modeled. Comparisons of the simulated and measured maximum depth and width of the heat affected zone for various laser powers and laser scanning speeds were carried out, and very close correlations between simulation and experimental results were observed.

Shen [17] developed a 3D thermal model using the finite element analysis software ANSYS to predict the temperature distribution in a silicon nitride workpiece during laser assisted milling. The top-hat distribution of laser intensity was used in this study. An approximately uniform heat flux was applied to the elements within an elliptic spot on the top surface of the workpiece. Material removal was taken into account in this study by deactivating the elements that had been removed. Heat generation associated with machining was also considered in the model, however, a later detailed study performed by the author showed that the heat generation associated with machining is negligible compared to the heat flux input from the laser source. The thermal model was validated through experiments, the predicted temperature histories were in good agreement with those measured. The minimum temperature in the cutting zone predicted by the thermal model was used as the initial workpiece temperature for a 2D distinct element machining model which well depicted the brittle behavior of the material removal process of silicon nitride ceramics during laser assisted milling.

In this study, both a traditional finite element method and the SPH method embedded in LS-DYNA were used to simulate the laser assisted turning of the beta titanium alloy Ti–6Cr–5Mo–5V–4Al. A finite element thermal model was developed to predict the cutting area temperature distribution after the laser heated the workpiece material. The laser spot was modeled by an approximately uniform heat flux which was applied to elements within a circular spot on the top surface of the workpiece. A similar method was adopted in Shen's study [17]. The temperature distribution result predicted by