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Machinability improvement of titanium alloy (Ti–6Al–4V) via LAM and hybrid machining

Chinmaya R. Dandekar [a], Yung C. Shin [a,*], John Barnes [b]

[a] Center for Laser-based Manufacturing, School of Mechanical Engineering, Purdue University, West Lafayette, IN 47907, USA
[b] Lockheed Martin Aeronautics, Advanced Development Programs, 86 S. Cobb Dr., Marietta, GA 30063-0660, USA

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ABSTRACT

Titanium alloy (Ti–6Al–4V) is one of the materials extensively used in the aerospace industry due to its excellent properties of high specific strength and corrosion resistance, but it also presents problems wherein it is an extremely difficult material to machine. The cost associated with titanium machining is also high due to lower cutting speeds (<60 m/min) and shorter tool life. Laser-assisted machining (LAM) and consequently hybrid machining is utilized to improve the tool life and the material removal rate. The effectiveness of the two processes is studied by varying the tool material and material removal temperature while measuring the cutting forces, specific cutting energy, surface roughness, microstructure and tool wear. Laser-assisted machining improved the machinability of titanium from low (60 m/min) to medium-high (107 m/min) cutting speeds; while hybrid machining improved the machinability from low to high (150–200 m/min) cutting speeds. The optimum material removal temperature was established as 250 °C. Two to three fold tool life improvement over conventional machining is achieved for hybrid machining up to cutting speeds of 200 m/min with a TiAlN coated carbide cutting tool. Tool wear predictions based on 3-D FEM simulation show good agreement with experimental tool wear measurements. Post-machining microstructure and microhardness profiles showed no change from pre-machining conditions. An economic analysis, based on estimated tooling and labor costs, shows that LAM and the hybrid machining process with a TiAlN coated tool can yield an overall cost savings of ~30% and ~40%, respectively.

1. Introduction

Titanium and its alloys have high strength to weight ratios, good temperature and chemical resistance, and relatively low densities, which make them ideal for applications in the aerospace industry. Ti–6Al–4V is a common alloy of titanium and is generally classified as "difficult to machine" because of its thermo-mechanical properties. The primary challenge when machining titanium is overcoming the short tool life that typically prevents people from using high cutting speeds. Several explanations for the poor machinability of Ti–6Al–4V are available in the literature [1–3]. Titanium has low thermal conductivity, which impedes heat transfer out of the cutting zone while creating high cutting zone temperatures. Titanium shows high chemical affinity towards the cobalt binders that are found in most cutting tool materials. The interface between titanium chips and cutting tools is usually quite small, which results in high cutting zone stresses. Lastly, there is a strong tendency for titanium chips to pressure-weld to cutting tools. Due to all these issues, the choice of cutting tool material has been limited to carbide tools [1,2].

In order to ensure good tool life, cutting speeds for Ti–6Al–4V are often limited to 60 m/min [2,4]. There are several ways to improve the machinability of titanium. These include the use of standard coolants or lubricants [2] and cryogenic cooling [5,6], the use of alternate cutting tool materials [7] such as coated carbide cutting tools (AlSiTiN coating), which doubled the tool life in terms of cutting time as compared to that of uncoated carbide tooling and permanently or temporarily altering the workpiece material properties during machining. Temporarily altering workpiece material properties, alternate cutting tool material and LN_2 coolant usage to improve machinability is addressed in this study, through the hybrid (HYB) machining method; a combination of laser-assisted machining (LAM) and cryogenic cooling of the tool.

LAM is based on the idea of lowering the cutting forces during machining, by systematically lowering the material yield strength through the use of localized heating. Titanium is such an alloy that shows reduced material strength at elevated temperatures where an almost 60% reduction in strength is realized around 500 °C [8]. There have been previous studies on LAM of titanium [9–12], but no tool life improvement has been reported with LAM.

* Corresponding author.
E-mail address: shin@ecn.purdue.edu (Y.C. Shin).

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Another earlier study by Sun et al. [9] studied the effects of laser beam arrangement of a 2.5 kW Nd:YAG laser, laser power and cutting speed on the cutting forces, chip formation and the machined surface at maximum cutting speeds of 93 m/min. The results indicated a reduction in the cutting forces with the feed force reducing the most with an increase in the laser power. Further results indicated a smoother surface finish due to the lower stresses observed during LAM as compared to conventional machining while the hardness values of conventional machining were higher than those of LAM. Germain et al. [10] in LAM of titanium alloy with a 2.5 kW Nd:YAG laser, found an almost 50% reduction in the cutting forces, a slight reduction in the fatigue strength of the machined samples and attributed this to the inferior microstructure and residual stress state achieved after LAM. No systematic analysis was performed to model and control the temperature distribution generated due to the localized heating in order to optimize the process in terms of achieving favorable surface finish, microstructure and hardness profiles of the machined surface. Extending their respective studies on LAM of titanium, Germain et al. [11] and Yang et al. [12] constructed 3-D slab based models to predict the heat-affected zones during laser heating in titanium. Both studies have stated that the thermal model can be used to determine the laser parameters so as to minimize the heat-affected zone and to control the sub-surface integrity of the workpiece.

Laser-assisted machining has been successful in solving numerous problems associated with a wide range of materials including ceramics [13–16], metals [17–19] and particulate metal matrix composites [20]. Rozzi et al. [21,22] developed a transient 3-D thermal model capable of predicting the temperature distribution in the workpiece undergoing LAM. Utilization of this model allows the user to systematically optimize the cutting conditions to obtain favorable results in terms of higher material removal rate, improved surface integrity and reduced tool wear.

In numerical studies the primary focus has been on predicting the chip formation process and the cutting forces in machining of titanium. Amongst 2-D studies, Umbrello [23] conducted 2-D FEM machining simulations of Ti–6Al–4V alloy to predict the cutting forces and chip formation, while Bäker et al. [24] studied the adiabatic shearing phenomenon in chip formation through the use of ABAQUS. Li and Shih [25] conducted 3-D FEM modeling of machining Ti–6Al–4V using Third Wave System's AdvantEdge© focusing on the prediction of cutting forces, temperature and the curling of the chip. In another study on FEM of titanium, Klocke et al. [26] addressed some of the challenges involved in modeling of machining for practical applications, to assist in the selection of the right cutting parameters. One of their suggestions was to utilize the modeling outputs of stresses, relative velocities, temperature and strains to arrive at the possible tool wear rate.

The goal of this study is to maximize material removal rate (MRR) while also maximizing tool life through modeling and experiments. The 3-D transient thermal model developed in the authors' group [21,22] to predict the temperature field in cylindrical workpieces during the LAM process and a 3-D FEM machining model are used to optimize the machining conditions. Although the thermal model has been validated for many materials, it is once again validated with an infrared camera to increase the confidence of the material properties used. The 3-D FEM model is implemented to predict the tool life and subsequently optimize the machining conditions in terms of cutting conditions and cutting tool material. Based on this analysis, hybrid machining (HYB) is attempted with laser heating of workpiece and cryogenic cooling of the tool to achieve high speed machining. Machinability tests were conducted and the results analyzed, including a preliminary economic analysis comparing conventional machining, LAM and HYB. During LAM one challenge is to maintain the machined workpiece temperature below 880 °C, since there is a phase transformation from the α phase to β phase above this temperature [8]. This transformation must not occur in the machined workpiece since it will reduce the resulting structural integrity and hence microstructural analysis and hardness measurements were also conducted to determine the suitable machining conditions.

2. Experimental setup

The machining experiments for this project were conducted on a laser-assisted machining setup, which is comprised of a 20 Hp Jones and Lampson CNC turret lathe and a 1.5 kW CO_2 Coherent Everlase S51 laser. A standard coolant was not used for any of the machining experiments. Instead, cutting tools were cooled with liquid nitrogen (LN_2) for some of the tests to evaluate the hybrid machining (HYB) process. Argon gas was introduced to the cutting zone to prevent oxidation of the laser-irradiated surface and contamination of the laser optics.

The methodology involved in hybrid machining is two-folds, wherein the workpiece is irradiated with the laser while simultaneously cooling the cutting tool. The laser irradiates a circular spot on the workpiece, which is 55° upstream of the cutting tool in the radial direction and 2.5 mm upstream of the tool in the axial direction. These lead distances can be changed and allow the workpiece to be preheated before it is cut. A schematic of the HYB experimental setup is provided in Fig. 1. This process combines the benefits of both approaches in improving the machinability of titanium, resulting in significant improvement. The setup for hybrid machining necessitates the modification of the tool holder to incorporate the cooling of the rake face as shown in Fig. 1. A reservoir cap was included to provide the necessary cooling of the tool. It has two openings, one at the top of the cutting tool and the other to the side of the cutting tool, these openings constitute as the inlet and outlet

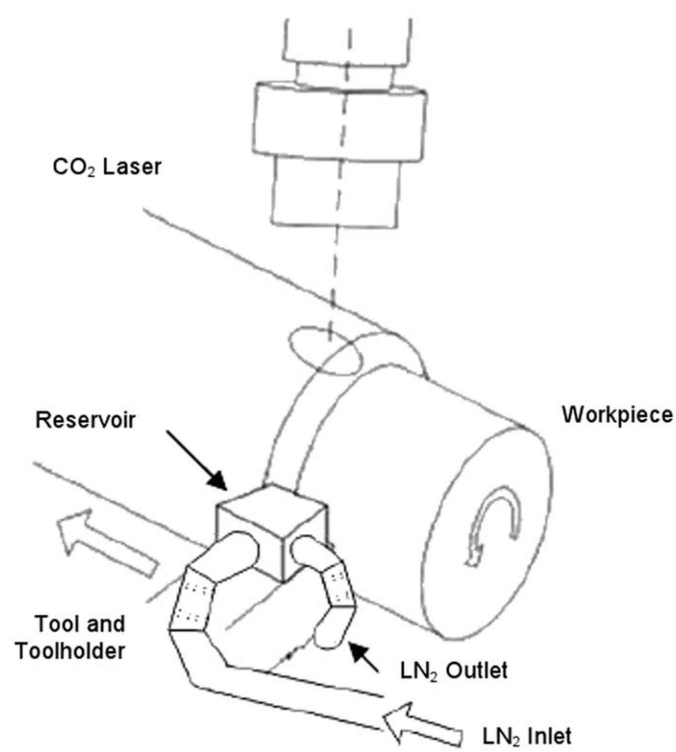

Fig. 1. Schematic of hybrid machining experimental setup with CO_2 laser.