High speed machining of titanium alloys

Barnes, John; Shin, Yung; Brandt, Milan; Sun, Shoujin

https://researchrepository.rmit.edu.au/esploro/outputs/9921857772401341/filesAndLinks?institution=61RMIT_INST&index=null

Barnes, J., Shin, Y., Brandt, M., & Sun, S. (2009). High speed machining of titanium alloys. Materials Science Forum, 618-619, 159-163. <https://doi.org/10.4028/www.scientific.net/MSF.618-619.159>
Document Version: Published Version

Published Version: <https://doi.org/10.4028/www.scientific.net/MSF.618-619.159>

COR-10120511

VIT

CSIRO

EMAIL: libdoc@rmit.edu.au
Document Delivery Services
GPO Box 2476
Melbourne, Victoria 3001
Australia

ATTN:	SUBMITTED:	2012-10-17 10:52:22
PHONE: 03 9925 2441	PRINTED:	2012-10-17 12:10:08
FAX: 03 9925 2513	REQUEST NO.:	COR-10120511
E-MAIL: libdoc@rmit.edu.au	SENT VIA:	ISO
	EXPIRY DATE:	2012-11-04
	EXTERNAL NO.:	1977814

COR	Core	Copy	Journal
-----	------	------	---------

TITLE:	MATERIALS SCIENCE FORUM.
PUBLISHER/PLACE:	Trans Tech Publications Aedermannsdorf, Switzerla
VOLUME/ISSUE/PAGES:	618-619 159-163
DATE:	2009
AUTHOR OF ARTICLE:	Barnes,JE; Shin, YC; Brandt, M; Sun,S
TITLE OF ARTICLE:	HIGH SPEED MACHINING OF TITANIUM ALLOYS
ISSN:	0255-5476
SOURCE:	University of Newcastle/INNOPAC
MAX COST:	\$25.00
COPYRIGHT COMP.:	Fair Dealing - S49
NOTES:	Abbreviated Title: Mater. sci. forum.; Key Title: Materials science forum.
DELIVERY:	E-mail attachment: libdoc@rmit.edu.au
REPLY:	Mail:

This document contains 6 pages. You will be invoiced for \$16.50. This is NOT an invoice.

High Speed Machining of Titanium Alloys

John E. Barnes^{1,a}, Yung C. Shin², Milan Brandt³ and Shoujin Sun³

¹ Lockheed Martin Advanced Development Programs, 86 S. Cobb Dr.,
Marietta, GA, 30063 USA

² Purdue University, School of Mechanical Engineering, W. Lafayette, IN, 47907, USA

³ IRIS, Swinburne University of Technology, Melbourne, Australia

^a john.e.barnes@lmco.com

Keywords: machining, titanium, laser

Abstract

Removal rates for machining titanium alloys are an order of magnitude slower than those for aluminum. The high strength and hardness coupled with the relatively low elastic modulus and poor thermal conductivity of titanium contribute to the slow speeds and feeds that are required to machine titanium with acceptable tool life.

Titanium has extremely attractive properties for air vehicles ranging from excellent corrosion resistance to good compatibility with graphite reinforced composites and very good damage tolerance characteristics. At current Buy to Fly ratios, the F-35 Program will consume as much as seven million pounds of titanium a year at rate production. This figure is nearly double that of the F-22 Program, which has a much higher titanium content. As much as 50% of the final cost of titanium parts can be attributed to machining. Specifically, in this task, we are working to improve the material removal rate of titanium to reduce cost.

Lockheed Martin is evaluating the potential to use lasers to heat the material ahead of the tool to reduce its strength. Coupled with other technologies that can improve the tool life and prevent the titanium material from welding to the tool, there is hope for a practical solution using similar milling machines to those which exist today, if not a simple retro-fit option.

This presentation will present the current progress of this project and its potential impact to the Joint Strike Fighter.

Introduction

Titanium and its alloys have high strength to weight ratios, good temperature and chemical resistance, and relatively low densities, which makes 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. In order to ensure good tool life, cutting speeds for Ti-6Al-4V are often limited to 60m/min.

Several explanations for the poor machinability of Ti-6Al-4V are available in the literature [1,2,3]. 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.

Titanium alloy Ti-6Al-4V (hereafter called Titanium) is an α - β alloy which is primarily comprised of the stronger α phase. At temperatures above 880°C, the α phase transforms to β . This transformation must not occur in the machined workpiece because it will reduce the resulting

structural integrity [4,5]. The strength of Titanium is largely affected by temperature. As shown in Figure 1, a 60% reduction in strength is realized around 500°C. This temperature-dependence will be exploited in LAM (laser assisted machining).

The goal of this project is to maximize material removal rates (MRR) while also maximizing tool life. A 3-D transient thermal model was developed to predict the temperature field in cylindrical workpieces during the LAM process. The predicted tool life is presented in comparison with experimental results.

For this technology to be readily accepted by industry, however, it is necessary to demonstrate its potential in milling operations. While laser turning is a relatively simple concept to implement in practice, the same is not the case for laser milling due to the nature of the cutting process and the complexity of delivering a laser beam ahead of the cutting tool [6-10]. Phase 2 of this project is to establish a laser milling cell and investigate both the cutting process itself and the integration of the laser beam with the milling tool.

Figure 1. Strength and elongation of Titanium as a function of temperature [4].

Procedure

The machining experiments for this project were conducted on a laser-assisted machining setup, which is comprised of a 20 Hp Jones and Lamson CNC turret lathe and a 1.5kW CO2 Coherent Everlase S51 laser. A standard coolant was not used for any of the machining experiments. Instead, cutting tools were cooled with Liquid Nitrogen (LN2) for some of the tests to evaluate a “hybrid machining” process. Argon gas was introduced to the cutting zone to prevent oxidation of the laser irradiated surface and to prevent contamination of the laser optics.

The laser irradiates a circular spot on the workpiece, upstream of the cutting tool in the radial direction and 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. The lead distance is chosen so that both the temperature gradient across the cutting tool and the temperature of the resulting workpiece are minimized. A schematic of the LAM experimental setup is provided (Figure 2).

Figure 2. Schematic of the LAM set up.

Results

Experiments have shown a 60% improvement in material removal by heating the material at an optimized temperature (Figure 3) as predicted by modeling. Empirical results were obtained without cutting fluid at the same tool life. Largely, this means that 60% more material can be removed at the same tool life without the environmental issues involved with discarded cutting fluid.

Figures 3 and 4. Volume of material removed as a function of workpiece temperature and volume removal rate as a function of workpiece temperature.

Results showed that no improvements to removal rate (Figure 4) could be made with the addition of temperature. To overcome this limitation a hybrid system was devised where the cutting tool was actively cooled simultaneously. Figure 5 shows a comparison of the volume of material removed as a function of various cutting schemes.

By keeping the tool cool and heating the workpiece hot, the best life and removal rate can be achieved. The hybrid process shows a 30% increase in removal rate versus LAM and a 35% increase in volume removal. Compared to a conventional process this yields a 50% improvement in material removal (cm^3).

Figure 5. Volume material removal as a function of process.

Summary

An experimental investigation was conducted to determine the effects of LAM on the machinability of titanium alloy Ti-6Al-4V. An optimum temperature of 250°C was established as the optimum material removal temperature (T_{mr}). Tool life was also improved by LAM for cutting speeds below 107m/min. Based on the results obtained through LAM, a hybrid machining process; simultaneously heating the workpiece and cooling of the tool by LN2 was proposed for machining at higher cutting speeds. 3-D machining simulations were also conducted using Third Wave Systems AdvantEdge© software respectively to predict the tool wear rate. The results obtained from the machining model compared well with the experimental data in terms of the measured cutting force and the tool wear rate prediction.

Lockheed Martin's interest lies in the ability to apply this technology to milling operations. Few papers have explored laser assisted milling because of the difficulty of applying the thermal source in conjunction with a machining operation in which the tool is rotating. The integration of the beam with the cutting tool is complicated. Generally, the beam can be arranged separately to tool or integrated with spindle.

The easiest way is to set the beam in front of tool in the feed direction. Since the limited spot size of external heat beam, it is not possible to cover the width of cut by a single beam in most cases. Therefore, the beam can only heat part of the width of cut, it could be the middle or tool entry point or both entry and exit points by two beams [11,12]. Since the dynamic impact on the cutting tool when the rotating tool intermittently engages with workpiece at the entry point causes a significant vibration and tool fracture, laser beam heating at the entry point is more significant in longer tool life and reduction of chatter.

Instead of heating the top surface with separated beam, two concepts were proposed to integrate the beam into machine tool [13,14]. This can be achieved by (1) beam being coupled in front part of the spindle by an interface radial to the tool axis; (2) the laser beam being delivered axially through the spindle and the end beam tool rotated with the spindle.

References

- [1] Yang, X., and Liu, C.R., 1999, "Machining titanium and its alloys," *Machining Science and Technology*, 3(1), pp. 107 – 139.
- [2] Ezugwu, E.O., and Wang, Z.M., 1997, "Titanium alloys and their machinability – a review," *Journal of Materials Processing and Technology*, 68, pp. 262 – 274.
- [3] Machado, A.R., and Wallbank, J., 1990, "Machining of titanium and its alloys – a review," *Proc. Inst. Mech. Engrs. Part B: Journal of Engineering Manufacture*, 204, pp. 53-60.

-
- [4] [Handbook of Materials Selection, 2002, Ed. M. Kutz, John Wiley and Sons Inc, 2002.
 - [5] Rozzi, J.C., Pfefferkorn, F.E., Incropera, F.P. and Shin, Y.C. Transient, Three-Dimensional Heat Transfer Model for the Laser Assisted Machining of Silicon Nitride: I-Comparison of Predictions with Measured Surface Temperature Histories, *International Journal of Heat and Mass Transfer* 43 (2000), 1409.
 - [6] Lacalle, L.N.L.d., Sánchez, J.A., Lamikiz, A. and Celaya, A. Plasma assisted milling heat-resistant superalloys, *Journal of Manufacturing Science and Engineering, Transactions of the ASME* 126 (2004), 274.
 - [7] König, W. and Zaboklicki, A.Z. in *International Conference on Machining of Advanced Materials* (NIST Special Publication, Gaithersburg, MD, 1993), pp. 455.
 - [8] Yang, B. and Lei, S. Laser-Assisted Milling of silicon nitride ceramic: a machinability study, *International Journal of Mechatronics and Manufacturing Systems* 1 (2008), 116.
 - [9] Thomas, T. and Vigneau, J.O. Laser-assisted milling process, US Patent 5906459 (1999)
 - [10] Lesourd, B. Maître, F.L. and Thomas, T. The chip formation in conventional and laser assisted machining - application to the milling process, *Manufacturing Systems* 24 (1995).
 - [11] Lacalle, L.N.L.d., Sánchez, J.A., Lamikiz, A. and Celaya, A. Plasma assisted milling heat-resistant superalloys, *Journal of Manufacturing Science and Engineering, Transactions of the ASME* 126 (2004), 274.
 - [12] Thomas, T. and Vigneau, J.O. Laser-assisted milling process, US Patent 5906459 (1999)
 - [13] Hügel, H., Wiedmaier, M. and Rudlaff, T. in *Laser Assisted Net Shape Engineering, Proceedings of the LANE'94*, edited by F. V. M. Geiger (Meisenbach Bamberg, 1994), pp. 439.
 - [14] Hügel, H., Wiedmaier, M. and Rudlaff, T. Laser processing integrated into machine tool - design, applications, economy, *Optical and Quantum Electronics* 27 (1995), 1149.

Light Metals Technology 2009

10.4028/www.scientific.net/MSF.618-619

High Speed Machining of Titanium Alloys

10.4028/www.scientific.net/MSF.618-619.159

DOI References

- [1] Yang, X., and Liu, C.R., 1999, "Machining titanium and its alloys," *Machining Science and Technology*, 3(1), pp. 107 – 139.
doi:10.1080/10940349908945686
- [2] Ezugwu, E.O., and Wang, Z.M., 1997, "Titanium alloys and their machinability – a review," *Journal of Materials Processing and Technology*, 68, pp. 262 – 274.
doi:10.1016/S0924-0136(96)00030-1
- [3] Machado, A.R., and Wallbank, J., 1990, "Machining of titanium and its alloys – a review," *Proc. Inst. Mech. Engrs. Part B: Journal of Engineering Manufacture*, 204, pp. 53-60.
doi:10.1243/PIME_PROC_1990_204_047_02
- [4] [Handbook of Materials Selection, 2002, Ed. M. Kutz, John Wiley and Sons Inc, 2002.
doi:10.1002/9780470172551.fmatter
- [5] Rozzi, J.C., Pfefferkorn, F.E., Incropera, F.P. and Shin, Y.C. Transient, Three-Dimensional Heat Transfer Model for the Laser Assisted Machining of Silicon Nitride: I- Comparison of Predictions with Measured Surface Temperature Histories, *International Journal of Heat and Mass Transfer* 43 (2000), 1409.
doi:10.1016/S0017-9310(99)00217-3
- [8] Yang, B. and Lei, S. Laser-Assisted Milling of silicon nitride ceramic: a machinability study, *International Journal of Mechatronics and Manufacturing Systems* 1 (2008), 116.
doi:10.1504/IJMMS.2008.018282