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Procedia CIRP 46 (2016) 432 – 435

www.elsevier.com/locate/procedia

7th HPC 2016 – CIRP Conference on High Performance Cutting

Micro-machinability of A-286 steel with and without laser assist

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Abstract

Machinability of high nickel content steels (e.g. stainless) is known to be challenging. This paper presents an experimental study of the micro-machinability of A-286 (~43 HRC), a precipitation-hardened high nickel content steel. Micro milling experiments are carried out under dry, wet, and laser-assisted conditions, and the resulting surface morphology, burr, part feature depth, tool wear, and cutting forces are analyzed. It is found that laser-assist consistently yields the best results characterized by minimal chip adhesion to the workpiece surface, low cutting forces, good feature depth accuracy, low tool wear, and acceptable burrs.

Peer-review under responsibility of the International Scientific Committee of 7th HPC 2016 in the person of the Conference Chair
Prof. Matthias Putz

Keywords: Micro machining; Laser; Hybrid machining

1. Introduction

Laser technology has expanded greatly in many industrial fields in the last few decades. In this research, a laser is used to preheat and thermally soften a nickel-base alloy (A-286 steel) to assist a micro milling process. Nickel-base alloys have great mechanical strength, corrosion, and creep resistance at high temperatures. They are widely used in the aerospace industry. The nickel-base alloy used in this research (A-286 steel) has attractive mechanical properties (e.g. tensile strength of 1455 MPa and oxidation resistance up to 700 Cº) but is difficult to machine. For micro milling, additional difficulties arise from the well-known machining size effect and the fragility of the miniature tool. Material removal in micro milling is often characterized by significant ploughing and rubbing compared to conventional scale machining [1]. This produces high stresses and rapid tool wear. A-286 is also abrasive thereby making ploughing and rubbing more detrimental to the tool condition. These problems, along with the high strength of the alloy, require a new approach to micromachining this material. In this work, a laser is used to thermally soften and lower the mechanical strength of A-286 during cutting thereby enhancing its micro-machinability. In macro scale machining, laser assisted machining, or LAM, has been researched thoroughly [2-6], but very few have compared LAM to conventional wet assist methods. Bermingham et al. [5] found that MQL and flood cooling increased tool life far more than LAM. Dandekar et al. [6] used cryogenic wet cooling to assist LAM. However, at the micro scale, there is very little work that compares the use of wet cooling methods to laser assisted micro milling or LAMM (see Figure 1).

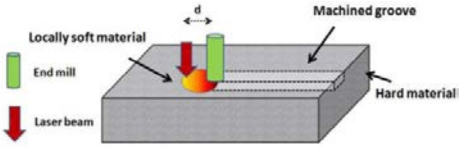

Figure 1: LAMM schematic [7].

Table 1 summarizes published work on LAMM. Mohid et al. [8, 9] showed that LAMM reduced forces and tool wear but increased chip adhesion for Ti6Al4V. Ding et al. [10] found that LAMM reduced the wear rate significantly and was most effective when preheating the top surface than the workpiece side. Shelton et al. [11, 12] found that LAMM reduced acoustic emission and improved the surface finish of

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doi:10.1016/j.procir.2016.04.049

316 stainless steel. Pfefferkorn et al. [13-15] found that LAMM lowered specific cutting energies, allowed for higher feeds, but could increase burr and surface roughness. Other studies of micro milling of tool steel also showed a significant reduction in the cutting force, higher material removal rates, and improvements in tool life [7, 16, 17].

Table 1: Summary of Literature on LAMM

Material	Variables	Measurements	Comparison
Ti6Al4V [9]	Feed, speed	Force, tool wear	Dry
Inconel 718 [8]	Feed, speed, depth of cut	Force, tool wear	Dry
Ti6Al4V, Inconel 718, AISI 422 [10]	Laser location, power	Force, wear, groove condition	Dry
Ti6Al4V, AISI 316, AISI 422 [11, 12]	Feed, speed, depth of cut, laser power	Acoustic emission, roughness	Dry
Al 6061, AISI 1018 [15]	Laser power	Force, roughness, burr	Dry
Al 6061, AISI 1018 [14]	Laser power	Specific energy	Dry
AISI 4340 [13]	Feed, speed	Force, burr	Dry
AISI A2 [17]	Tool coating	Tool wear	Dry
AISI A2 [16]	Feed, depth of cut	Force, tool wear, groove profile, roughness, burr	Dry

However, there is insufficient knowledge of micro milling of high nickel content steels. In particular, there are no reported studies of laser assisted micro milling of A-286 steel, which is widely used in aerospace and gas turbine applications. Current LAMM work presents laser assist as a hypothetical alternative to conventional wet techniques, but as seen in Table 1, there is no work that compares conventional wet assist methods to LAMM. This paper compares dry, wet, and LAMM for micro milling of A-286.

2. Experimental setup and procedure

2.1. System configuration

The hybrid LAMM machine used for the experiments is shown in Figure 2.

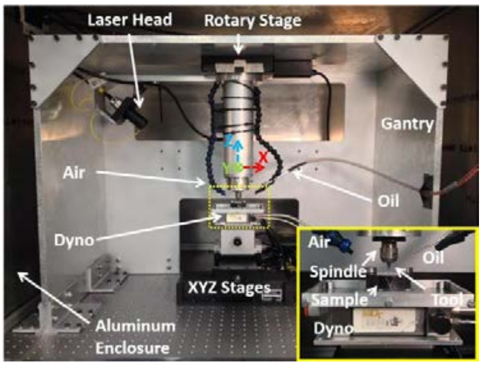

Figure 2: System configuration.

An aluminum enclosure contains laser radiation leaks to ensure user safety. The mill gantry holds the rotary stage, which allows the laser head to rotate 360° around the Z axis. An Ytterbium doped continuous wave near infra-red fiber laser (IPG Photonics – YLM 30) with a Gaussian beam of 1070 nm nominal wavelength is focused down to a diameter spot of 300 µm. A variable high-speed electric spindle is used to achieve a maximum spindle speed of 60,000 RPM. For XYZ motion, three stacked linear motion stages (Aerotech ATS-125 and AVS-105) are fixed on a passive anti-vibration table (Thorlabs®). A piezoelectric force dynamometer (Kistler Minidyne® 9256C2) is mounted on the stacked stages. A uniaxial accelerometer (Kistler Model 8636C50, ±50g range, 6 kHz frequency range) is attached to the dynamometer to detect tool-workpiece contact.

2.2. Experiment design

The A-286 nickel-base alloy (composed by weight of 56.8% Fe, 24.5% Ni, 14.1% Cr, 2.2% Ti, and small traces of other metals) was obtained as a cold reduced round bar, and precipitation age hardened to 42.8 ± 0.2 HRC. The tools used were square end, tungsten carbide, two flute, 500µm diameter, and TiAlN coated end mills (Mitsubishi MS2SSD0050). A new tool was used for every experiment. Each tool path consisted of six parallel 25.4 mm long grooves created on top a pre-machined workpiece surface for a total cutting length of 152.4 mm. The cutting parameters used in the experiments are listed in Table 2 and were chosen from a survey of other micro milling research [8, 18, 19]. The eight cutting conditions were applied to four assist mechanisms: dry, wet, and two LAMM cases, yielding 32 tests.

Table 2: Machining conditions

Condition	V_c [m/min]	f [mm/tooth]	a_p [mm]
1	19	0.01	0.02
2	19	0.01	0.04
3	19	0.03	0.02
4	19	0.03	0.04
5	41	0.01	0.02
6	41	0.01	0.04
7	41	0.03	0.02
8	41	0.03	0.04

Air flow at a pressure of 0.3 MPa was directed at the tool in the dry and LAMM experiments to blow away chips. Wet assist experiments consisted of flood cooling with oil (Hangsterfer's Hard Cut NG cutting oil) applied at 12 ml/min.

The laser parameters were chosen by analysing the theoretical temperature distribution produced in the material via a thermal model [17] and preliminary tests. Using the oxidizing temperature of the TiAlN coating as a limiting factor, the model was used to find the optimal laser parameters. The center of the laser spot (300 µm diameter) was located 450 µm from the tool center. Two laser powers, 12 W and 18 W, corresponding to peak intensities of 340 W/mm^2 and 510 W/mm^2, respectively, were used to investigate the effect of laser power on the process.

The grooves produced in the tests were imaged by optical microscope (Nikon Microphot-FXL) to analyze burr formation, chip adhesion, and surface morphology. A stylus