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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.

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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).

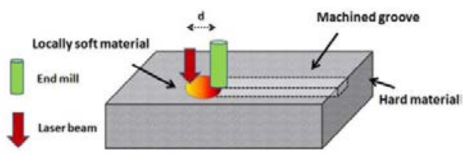

Figure 1: LAMM schematic [7].

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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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.

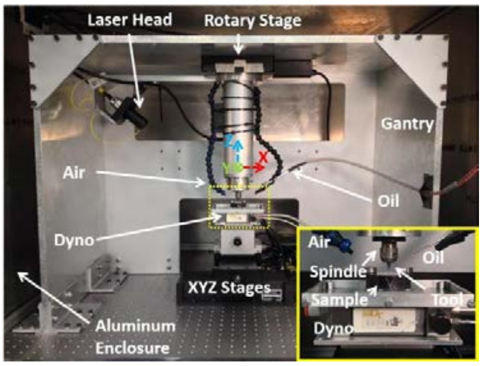

Figure 2: System configuration.

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 surface profilometer (Taylor Hubson Talysurf) was used to measure the groove cross sectional profile to evaluate the groove depth. Tool condition was evaluated by optical microscopy. Tool diameter was measured before and after the tests to quantify tool wear. Finally, the mean resultant peak forces for the first and last grooves were computed from the dynamometer data.

3. Results and discussions

3.1. Groove condition

The first groove in all the tests typically showed little to no burr or surface defects, because the tool was still new. However, by the sixth groove (~150 mm length of cut) the groove condition was affected by the cutting conditions and assist mechanism. Figure 3 shows the sixth groove for the dry cutting tests for machining conditions 1 through 8. Note that the dry tests at the higher depth of cut (0.04mm), i.e. conditions 2, 4, 6, and 8, have larger burrs and chip adhesion. For the dry tests at the lower depth of cut (0.02mm), i.e. conditions 1, 3, 5, and 7, far less burr and chip adhesion was observed.

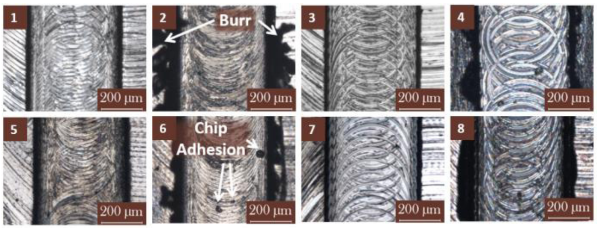

Figure 3: Surface morphology and burrs in dry cutting; cutting conditions 1-8 (6th groove).

Figure 4 compares grooves produced by machining condition 2 under dry, wet, 12 W and 18 W LAMM cases. As can be seen, there is significantly less burr in the wet test than in the dry test. In addition, there is little or no chip adhesion on the groove surface in the wet test, which looks much cleaner than the dry test. As seen in Figure 4, the LAMM tests yielded grooves of better quality than the dry and wet tests. Of the four assist methods investigated, the least amount of burr was produced in the 12 W LAMM test. The wet condition, however, had the least chip adhesion. More burrs were created in the 18 W test than the 12 W test. The 18 W test produced even higher temperatures causing the material to soften even more, which led to more burrs.

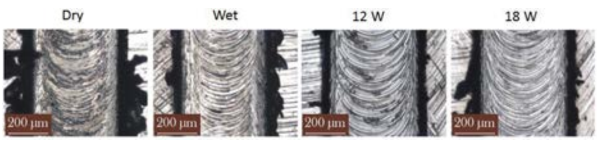

Figure 4: Comparison of grooves for dry, wet, 12 W, 18 W; machining condition 2.

Figure 5 shows how the groove depth is affected by the four assist mechanisms along the entire length of cut for machining condition 3. As seen, the 12 W LAMM test was the most accurate while the dry test was the least accurate. In the dry and wet tests, as the tool wore, less material was cut in the Z direction, thus reducing the axial depth of cut. In the LAMM tests, the depth of cut is higher than the target depth of cut due to thermal expansion of the workpiece, which can be easily compensated.

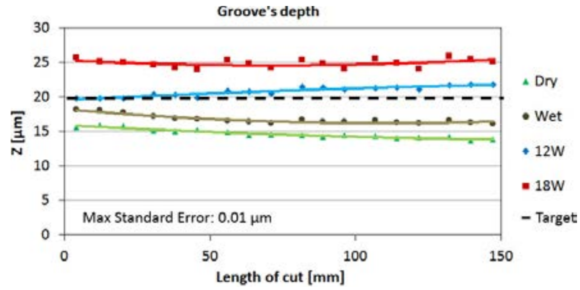

Figure 5: Comparison of groove depths for dry, wet, 12 W, 18 W cases; machining condition 3.

3.2. Tool condition and forces

The tool diameter was measured when the tool was new and after cutting six grooves. The difference in tool diameter due to wear for all 32 tests is shown in Figure 6. In the dry tests, cutting conditions 3 and 7 produced the least wear - only 30 and 35 µm, respectively, compared to more than 40 µm wear or chipping observed in all other tests. Cutting conditions 3 and 7 were the only two with a higher feed (0.03mm/tooth) and lower depth of cut (0.02mm). The higher feed reduced ploughing thereby reducing tool wear.

For the wet tests, marginal improvement in tool wear was seen compared to the dry tests under the same conditions.

The tool diameter wear for the 12 W LAMM test for all cutting conditions was better than in the dry and wet tests.

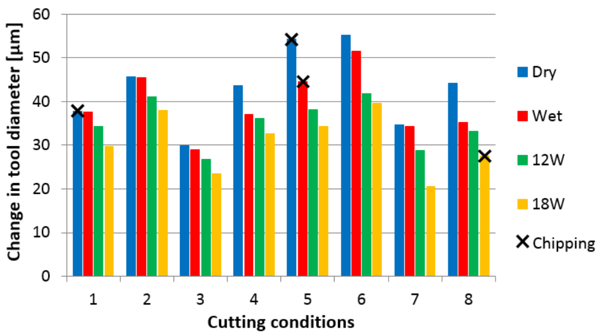

Figure 6: Tool diameter wear.

It can be seen in Figure 6 that most of the 18 W laser assist tests produce less wear than the 12 W case. At a higher laser power, the workpiece is softened more, which permits shearing of the material at a lower stress. The 18 W tests, however, did produce more adhesion of the work material to the tool. Nevertheless, in majority of the 18 W tests, the benefits of thermal softening appear to outweigh the harm caused by built-up-edge. Compared to dry cutting, the 18 W LAMM case produced, on average, 29% less tool wear. The maximum reduction in tool diameter wear (40%) in the 18 W case was observed for machining condition 7.

Figure 7 shows representative images of the tool flank for cutting condition 1 and the four assist mechanisms. Note that the tool chipped in the dry test, but there was no chipping in the wet test, which shows marginal reduction in flank wear. The 12 W and 18 W LAMM tests greatly reduced flank wear compared to the dry and wet tests for the same cutting conditions. As seen in Figure 7, the tool edge is relatively clean and sharp for the 12 W case but shows some flank wear. The 18 W case shows less wear than the 12 W case but shows more material adhesion. It is clear from these results that laser assist helps to reduce tool flank wear.

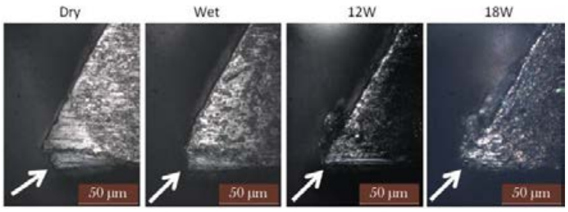

Figure 7: Flank wear for dry, wet, 12 W, 18 W cases; machining condition 1.

The mean resultant forces for the first and last grooves for all 32 tests are shown in Figure 8. The forces were always lower for the first slot when the tool was new but tended to increase by slot 6 due to wear.

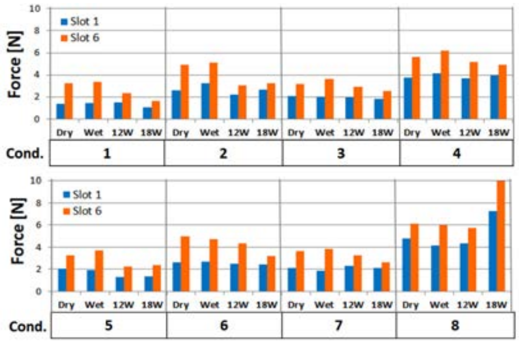

Figure 8: Mean resultant force for the first and sixth grooves.

For the higher depth of cut (0.04mm) cases, i.e. machining conditions 2, 4, 6, and 8, much higher forces were seen, irrespective of the assist mechanism. Interestingly, for all assist mechanisms, when the feed rate was tripled, i.e. machining conditions 3, 4, and 7, there only was a marginal increase in the forces compared to conditions 1, 2, and 5, respectively. At higher feed rates, the material is able to shear easily with less ploughing and rubbing. Most notable is that the 18 W LAMM tests, in comparison to the dry tests under the same cutting conditions, had forces that were, on average, 10% lower. The wet experiments typically showed higher forces than the dry tests but this is primarily due to the additional weight of the cutting oil that accumulates on the top face of the dynamometer.

4. Summary

LAMM proved to be greatly beneficial for micro milling of A-286, which is a high nickel content steel. It improved the groove condition and maintained a more precise depth of cut. It decreased tool diameter wear by 29% on average and yielded better tool life than the wet assist case. It also decreased forces on average by 10% when compared to the dry case. These trends were observed over a wide range of cutting conditions. These results are expected to help industry in applying the LAMM process to micro machine A-286.

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