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Effects of minimal quantity lubrication (MQL) on surface integrity in robotic milling of austenitic stainless steel

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Abstract

Robotic milling is considered to be a promising portable manufacturing technology for large scale part manufacturing industries such as nuclear, aerospace and power generation. However, considering the open environment of robotic milling, minimal quantity lubrication (MQL) stands to be one of the most suitable techniques for cooling and lubricating in robotic milling. In this paper, the effects of MQL conditions on surface integrity in robotic milling of austenitic stainless steel are discussed. The surface integrity is assessed in terms of surface residual stress (XRD) and surface roughness (optical metallography), where MQL conditions for improved tool life are also investigated.

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Keywords: MQL; Robotic Milling; MQL; Residual Stress; Surface Roughness

1. Introduction

Proper heat removal and lubrication is crucial for surface quality and tool wear in metal cutting. Mostly, flood cooling is used for machine tools having full enclosures around. However, there have been issues reported with the waste disposal, operators' health and negative effects on environment. Minimum quantity lubrication (MQL), which requires further investigation [1], is one of the proposed approaches to reduce the amount of metal working fluid. This suits robotic machining considering the lack of enclosure.

Shokrani et al. [2] reviewed cooling techniques such as dry, MQL, chilled air and cryogenics used in cutting of difficult-to-machine materials, but none of these were suggested as a suitable alternative to flood cooling. Further research on cooling techniques, cutter materials, cutting parameters and tool geometries were suggested. Spray pressure, nozzle to workpiece distance, nozzle angle to the feed rate direction and type of oils were the key performance parameters for MQL. The performance measures were tool wear progression, tool life, chip formation, surface roughness, surface residual stress, cutting forces, ecological issues, and aerosols.

In one of the early studies, Aoyama [3] showed that with proper supply of lubricant oil, MQL may perform better than flood cooling in terms of surface roughness, cutting torque, and tool life in drilling. Rahman et al. [4], compared performance of MQL to flood coolant in milling. No catastrophic failure of the tool was observed in MQL contrary to flood cooling. The tool wear was comparable to flood cooling. It was experimentally shown that the surface roughness and cutting forces generated by MQL were almost equivalent to flood cooling. Lacalle et al. [5] compared the performance of oil-water emulsion spray through computational fluid dynamics (CFD) simulations and experiments. It was shown that the orientation of the nozzles is of great importance to achieve increased tool life. It was also identified that the emulsion coolant is not efficient in high speed machining as it is not able to reach the flute-workpiece contact region. Whereas MQL flow penetrates in the cutting zone and it helps cooling, lubrication, and chip removal. Liao and Lin [6] studied the mechanism of MQL in high speed milling of hardened steel. One of the interesting conclusions was that MQL can provide extra oxygen, leading to the formation of a protective oxide layer between the chip and tool. As this layer includes Fe, Mn, Si, and Al elements, it acts

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as a diffusion barrier, leading to improved tool life. They identified an optimal cutting speed at which a stable protective layer can be formed. Tasdelen et al. [7] compared dry cutting with MQL, compressed air and emulsion coolant in terms of chip contact length and chip morphology in turning. They compared the effect of cooling techniques for different engagement durations by machining cylindrical samples with two and six grooves. MQL was found to be suitable for interrupted cutting. Park et al. [8] showed the effect of spray pressure and nozzle to workpiece distance on the droplet size and distribution through an empirical model. In a recent study, Ji et al. [9] proposed an analytical modelling approach for estimation of the residual stress in MQL cooling. The study coupled the cutting force and cutting temperature into a thermo-mechanical model. The kinematic hardening and strain compatibility are incorporated to predict the resulting residual stress. They showed that the average compressive residual stress decreases with the flow rate under MQL conditions.

Conformance of the parts to the surface residual stress and surface roughness standards is crucial to prevent stress corrosion cracks in nuclear manufacturing, where components stay in service for up to 60 years. Considering that MQL fitted robotic machining is a proposed alternative to large scale machine tools, this paper contributes to the understanding of the effects of MQL on surface integrity. In Section 2, the MQL fitted robotic machining setup is described, followed by the experimental procedure in Section 3. The paper is finalized with results and discussion in Section 4.

Nomenclature

b	step over
ω_t	tooth passing frequency
Ra	Arithmetic mean deviation of the roughness profile
θ	Residual stress measurement angle
P1, P2	Average max surface residual principal stress
S	Average max surface residual shear stress

2. Experimental setup and system configuration

A spindle is retrofitted with a Stewart type hexapod robot as the mobile machining platform, equipped with an MQL spraying system. In this section, technical details and capabilities of the machining unit developed for robotic milling with the MQL spraying system are given.

2.1. Robotic machining unit

The equipment configured for robotic milling consists of a Fanuc F200iB six degree of freedom parallel kinematic hexapod robot controlled by Fanuc R-30iA controller. The platform has 8kW spindle attached to the top plate as shown in Fig. 1. Based on the manufacturer's specification the hexapod platform is allowed to carry 100 kg payload, 60 kgfm of load moment at the face plate, which are enough for light or medium duty cutting operations. The motion speed limits of the platform are 18 m/min and 900 m/min in vertical (Y axis) and horizontal directions (X-Z plane), respectively.

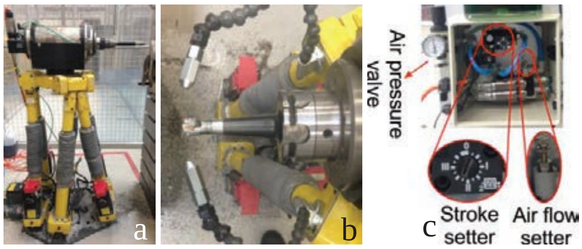

Fig. 1 MQL fitted robotic machining unit. (a) Spindle retrofitted mobile machining (b) MQL mist unit (c) MQL nozzles.

The tool tip is lubricated by misting the lubricant air mixture through two external nozzles (see Fig. 1b), where the lubricant is pumped by the system shown in Fig. 1c. The system consists of (i) air pressure valve, (ii) stroke setter, (iii) air flow adjuster. The system is able to supply air and oil through two channels, where the oil and air are mixed at the nozzle tip. The mist system can supply oil having up to 800cSt (40^{o}C) at a discharge rate from 0 to 40 mm^3 per stroke, where the number of strokes can be adjusted from 1 to 240 strokes/min. The air flow rate is adjusted by a screw having 11 threads. The air pressure can be adjusted between 4.5 and 7 bars. Overall, air pressure, oil-air ratio and the duty cycle affects the oil flow rate. Thus, it is important to identify adequate oil supply parameters in order to minimize the oil consumption to mitigate environmental effects.

The robot programming is performed in the following manner; the reference point of the workpiece is defined to the robot as a user frame, whereas the tool center point is taught as tool frame with respect to the global frame of the robot. The cutter pass control is performed by converting the tool path file to series of motion commands, where the tool path is generated using Siemens NX9 ©.

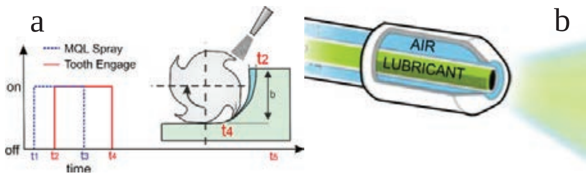

Fig. 2 MQL in milling. (a) Illustration of tool-chip interface and MQL spray operation. (b) Dual-channel MQL flow.

2.2. Design of experiments

The experiments are designed to investigate the effects of MQL parameters such as air pressure, lubricant flow rate and duty cycle on surface integrity. In the literature, it is mentioned that air pressure affects the lubricant particle size and hence the MQL performance [5]. The amount of lubrication and heat removal depends on the lubricant flow rate. The lubricant-air mixture is sprayed to the tool tip with duty cycle, i.e. number of strokes per second. As milling is an interrupted cutting process enough time is required to let the lubricant particles penetrate into the tool-chip interface. The engagement time of the tool-chip interface is mainly related to the step over, b, and the tooth passing frequency, ω_t, as illustrated in Fig. 2. The tool rotation period is from t_1 to t_5 and the tooth is engaged from t_2 to t_4. The MQL spray is on between the times t_1 and t_3. As oil-air mixture can't penetrate into the tool-chip interface from t_2 to t_4, setting the MQL timing appropriately is important. Based on this discussion, the experiments are given in Table 1, which are grouped as G1:[1,2,3,4], G2:[2,6,7], G3:[2, 5] to observe the effect of oil flow rate, the effect of air flow rate and air pressure, respectively. Experiment 8 is conducted as dry (D) cutting.

Table 1: Design of experiments.

Experiment		1	2	3	4	5	6	7	8
Duty Cycle (stroke/min)		240	60	30	15	60	60	60	D
Oil Flow Rate	(ml/h)	600	280	140	75	280	280	280	D
	(ml/stroke)	0.04	0.08	0.08	0.08	0.08	0.08	0.08	D
Air Pressure (bar)		6	6	6	6	7	6	6	D
Air Valve		9	9	9	9	9	5	2	D

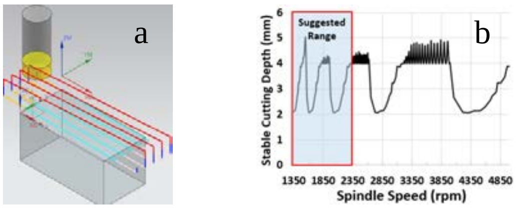

Fig. 3 Cutting tests (a) Cutting pattern (b) stability limit diagram.

3. Experimental procedure

3.1. Machining tests

AISI316L type of stainless steel was machined with a 25 mm diameter inserted cutter having three flutes. One insert was attached to the tool. Half immersion milling is used to mimic a practical machining case. Down milling is kept throughout the tests by applying raster cutting pattern as shown in Fig. 3a. Based on tool manufacturer suggestions and stability analysis (see Fig. 3b) the spindle speed and the cutting depth were selected as 1800 rpm (140m/min) and 1.5mm, respectively. In the stability diagrams it is seen that at lower spindle speeds the low frequency mode due to the robot is governing the stability and at higher spindle speeds the tool mode limits the stability. The feed per tooth was set as 0.1mm/rev. The sizes of the samples were 50 mm x 110 mm, where each machining test took 2.5 minutes. The nozzle to tool tip distance was set as 30 mm by visual observation of the mist distribution.

3.2. Surface roughness and residual stress measurements

Surface roughness measurements were performed using the 3D laser scanning confocal microscope Keyence VK-X200. In order to minimize the effect of accidental damage and local heterogeneity on confidence of the results ten random areas, covering a total area of approximately 4 mm^2, were selected to measure surface roughness. Residual stress measurements were carried out using laboratory X-ray diffraction by a ProtoXRD diffractometer. The Surface residual stress measurements were performed on the last cutting path of every sample with no overlapped cutting region involved to rule out the effect of zig cutting pattern as shown in Fig. 3b. The measurement points were selected in the middle region of the machined surface to avoid the two ends where the cutting tool was not fully engaged with the material. Three areas were measured in each sample to minimize the local microstructural inhomogeneity.

3.3. Evaluation of tool condition

The tool condition was monitored by observing the flank face through optical microscopy. Although 2.5 minutes of machining is not enough to evaluate tool life, it was aimed to observe the variation of the surface texture, i.e. the cutting heat affected zone (CHAZ) and the initial wear land. In only one case, the condition of the inserts was compared after 20 minutes of cutting with short and long duty cycle settings.

4. Results and discussion

4.1. Effect of MQL settings on surface roughness

The surface roughness, Ra, of the full sample set exhibited good surface finish conditions as plotted in Fig. 4a. Most samples showed Ra value around 0.7 µm with standard deviation (STD) less than 0.1 µm among the ten measurement areas for each sample. The STD among the samples was 0.04 µm. Thus, it can be said that the MQL settings do not have a significant effect on the surface roughness.

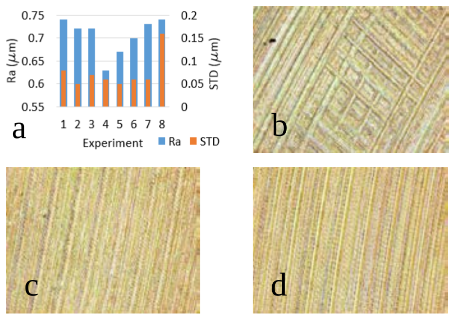

Fig. 4 Comparison of surface roughness (a) Ra and STD (b) Sample 1, (c) Sample 4, (d) Sample 8. (Each image covers area of 710×531 µm^2).

4.2. Effect of MQL settings on surface residual stress

The samples exhibited consistent residual stress values with variation lower than 60 MPa. The measured maximum average principal stress, P1, P2, and maximum average shear stress, S, are plotted in Fig. 5, where tensile residual stresses are observed. The high values of sample 1, 3 and 4 are presumably due to the shortest duty cycle and decreased oil flow rate, respectively. By comparing sample 2, 3 and 4, it is evident that the tensile residual stress increases with decreased oil flow rate. No significant effect of air flow rate variation on surface residual stress was observed by comparing sample 5, 6 and 7. The measured data of sample 8, which is dry milled, shows a second highest residual stress in the whole sample set. Therefore, it can be concluded that well controlled oil flow rate and duty cycle can effectively reduce the residual stress induced by the milling process.

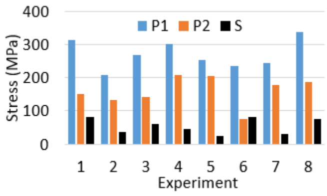

Fig. 5 Variation of surface residual stress among the experiments.

4.3. Effect of MQL settings on tool condition

Tool condition was monitored by measuring the CHAZ and initial wear land as shown in Fig. 6a. The results are plotted in Fig. 6b, where it is seen that the width of the initial wear land does not show a significant trend and was measured as 25 microns on the average. Whereas, the width of the CHAZ showed meaningful trend with the controlled variations. The highest width was observed as 324 µm for the dry cutting conditions and the minimum width was observed as 182 µm at the maximum oil flow rate (i.e. experiment 1). As the oil flow rate was decreased from 600 ml/h to 74 ml/h, CHAZ increased from 182 µm to 260 µm. However, the air flow rate (comparing 2, 6, and 7) did not affect the width of CHAZ. By increasing the air pressure from 6 bar to 7 bar, the width of CHAZ decreased from 217 µm to 190 µm.

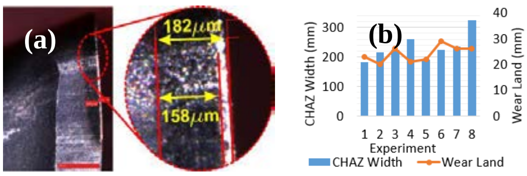

Fig. 6 Effects of MQL settings on tool condition. (a) Flank face after experiment 3. (b) Comparison of tool condition.

For a shallow depth of cut around 0.25mm, Experiment 1 and Experiment 3 were repeated until 20 minutes of cutting time is reached in order to see the long term effect of oil flow rate on tool wear propagation. The flank and rake face conditions are given in Fig. 7, where it can be observed that the tool was in a very good condition after Experiment 1. However, the tool was worn significantly after Experiment 3. Thus, as a first impression, it can be said that the duty cycle has a very important effect on tool wear progression.

5. Conclusions

In this paper, the effects of MQL conditions on the surface integrity and tool condition in robotic milling of AISI316L are investigated experimentally. The lubrication conditions such as duty cycle, i.e. oil flow rate, the air flow rate and air pressure can be adjusted. The cutting conditions were selected based on stability analysis and tool manufacturer. The experiments showed that the surface roughness is not affected by the MQL settings. However, the surface residual stresses can be decreased by well controlled MQL oil flow. The oil flow rate significantly affected the surface residual stress, whereas the air flow rate did not have a significant effect. The tool condition, i.e. flank wear and cutting heat affected zone, is significantly affected by lubrication settings. The most significant parameter was observed to be the duty cycle, which controls the oil flow rate. It was seen that increasing number of strokes per minute, i.e. increasing the oil flow rate, decreases the width of the cutting heat affected zone on the flank face. This can be associated with the heat barrier effect of thickened oil film, so that the heat transfer to the flank face decreases, where the amount of heat staying at the workpiece increases. The tool wear progression after 20 minutes of cutting with high and low number of strokes per minute showed a big difference. Under poor lubrication conditions the flank wear was significant.

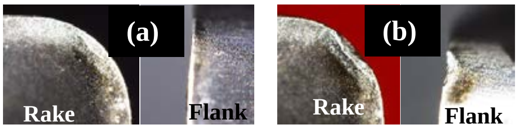

Fig. 7 Tool condition after 20 minutes. (a) Experiment 1, (b) Experiment 3.

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