

# **Diamond Fly Cutting Applied to Improve Form Accuracy by In-process Measurement and Control on an Ordinary Milling Machine**

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To improve the accuracy of the machined surface produced by an ordinary milling machine, a system called workpiece-referred form accuracy control (WORFAC) was developed and confirmed in diamond turning. However, non-rotational symmetric surface structures, such as V-grooves, pyramid structures, F-theta lenses, and other freeform surfaces cannot be machined by diamond turning. Previously, a system for improving micro-groove accuracy on an ordinary lateral milling machine was proposed by using controlled cutting with reference surface (CCRS), which is based on WORFAC. Simulations and experiments confirmed that CCRS improves the machined surface accuracy. The research showed that accuracy can be improved if the digital control sampling time is enough shorter than the error motion period associated with the feed rate. However, the surface roughness increased when the feed rate decreased because the feed rate and cutting speed are the same in shaping operations. Consequently, fly cutting with CCRS was proposed because it combines a high cutting speed and low feed rate.

In this study, we verified the effectiveness of fly cutting with CCRS on an ordinary milling machine and showed its potential for reducing the cost of manufacturing ultra-precision microstructures in an ordinary machining environment.

## **Components and configuration of control cutting system**

In order to improve the machined surface accuracy, a control cutting system was developed, including micro displacement servo (MDS), optical sensors for in-process measurement, diamond tool and fly cutter, mirror and mirror jig, displacement detector, PZT amplifier, HIPOSS amplifier and LK-H008W controller. Static rigidity of MDS were test, and it is considered that there is no influence of distortion due to cutting resistance. The LabVIEW control program used for control cutting system was developed. The system was tested and adjusted, including time spent to reach steady state, calibration, I-PD gain adjustment, transient characteristics.

## **Noise suppression of controlled cutting**

Because the noise, which appeared in the control cutting system, detected by LK-H008W affect the surface quality in control cutting process, different cutoff frequency was set by low-pass filter and then discussed the quality of machined surface in feed direction. The conclusions are as follows:

1. The high-frequency component that degrades the machined surface finish during shaping can be suppressed by fly cutting.
2. The accuracy of the machined surface can be improved on an ordinary milling machine by this control cutting system (to obtain  $S_z$  less than  $0.2 \mu\text{m}$ ).
3. Further noise suppression will increase the quality of the machined surface.

### **Feed rate experiment**

The machined surface was machined at different feed rate with and without controlled cutting and the machined quality was discussed.

From the result of machined surface profile, all the form accuracy of machined surface was improved with controlled cutting at different feed rate. However, periodical regular fluctuations appeared on machined surface became more and more obvious with the increasing of feed rate whether using controlled cutting or not. In this control cutting system, the regular fluctuations are mostly likely caused by fly cutter dynamic unbalance, spindle vibration, PZT vibration, mirror jig vibration. By reducing the effect of those vibrations, such as the dynamic unbalance of the fly cutter, it is possible to reduce the height of the periodical regular fluctuations at a fast feed rate. Therefore, if those vibrations are suppressed, the machined surface quality can be improved with control cutting at a faster feed rate when considering that the system response speed is fast enough. In that case, the control cutting efficiency can be higher.

But for the current situation, if not suppress the vibrations, by slowing down the feed rate to reduce the influence of periodical regular fluctuations and using control cutting at the same time to improve the form accuracy, a good quality machined surface can be obtained.

### **Disturbance removal experiment**

Base on the principle of CCRS, not only the table motion error but also the disturbance from outside should be able to be suppressed. To prove it, artificial disturbance was added between the fly cutter and the workpiece, and the difference of machined surface with controlled cutting and without controlled cutting was compared and discussed.

The step height of 2  $\mu\text{m}$  (affected by artificial disturbance) which appeared on the machined surface by uncontrolled cutting was suppressed within 0.6  $\mu\text{m}$  by control cutting. The step was not able to be completely compensated because the gains of HIPOSS and LK - H008W did not match completely. The cause of the dent shape on the machined surface after controlled cutting was that the PZT actuator could not respond to became short due to the control delay of this control system, so when the fly cutter approached the workpiece suddenly, the fly cutter shaved the workpiece deeply.

Therefore, by adjusting the gain and improving the system respond speed, the machined surface quality with controlled cutting will be better.

#### **Experiment for improving precision of circular machining**

The experiments of circular arc machining by uncontrolled machining and control machining were conducted, and the effectiveness of improving the circular arc machining accuracy of the general-purpose milling machine was confirmed.

After taking the arc shape from the machined surface with roughness meter, the values of machined surface  $S_p = 0.0727 \mu\text{m}$  and  $S_z = 0.4 \mu\text{m}$  after uncontrolled cutting, but the values became to that  $S_p = 0.0373 \mu\text{m}$  and  $S_z = 0.18 \mu\text{m}$  after controlled cutting. It showed that accuracy of arc machined surface was improved more than half.

In order to further improve the precision of circular arc machining with this control cutting system, it is necessary to adjust the gain to match between HIPOSS and LK-H008W.