A sensory-based system for monitoring of cutting tip wear in the HS-F 1000

Abstract
We established a Tool Condition Monitoring (TCM) system based on measurement of vibration and torque of the milling spindle. The TCM system clearly detects the condition of worn out cutting tips and enables the tool change at the optimal point in time. The PrepMaster Analytics collects and evaluates all relevant data and initiates change of the milling head.

Key words
• Tool Condition Monitoring • Tool Wear • Vibration • Torque

Introduction
One crucial factor for efficient milling is the tool wear of cutting tips, which significantly affects cutting quality and downtimes of the machine. Tool Condition Monitoring (TCM) is playing an increasingly important role for fully automatic and efficient operation of a milling machine. In case of deviation from the normal status due to tool wear, the TCM system generates a notification to the operator or the system.

There are direct and indirect TCM approaches for wear monitoring of cutting tips. Direct methods include visual assessment with the naked eye, inspection with optical or raster electron microscopy and CCD cameras. While these methods allow a more or less precise evaluation of the worn surface, they require intermittent interruption of the process and reduce machine uptime.

Indirect TCM approaches use empirically obtained correlations between various sensor signals and extent of tool wear. Advantages of indirect methods are easier integration into existing machines and continuous measurement without process interruption. Disadvantage is the more imprecise assessment of the tool wear. Sensor signals typically used for wear monitoring include cutting forces, torque, vibration, acoustic emissions, engine current and output, temperature, and combination of different signals.

In this study, we gathered vibration data of the spindle block and torque of the spindle motor and correlated measured values with the cutting tip wear.
Methods

We used the HERZOG machine model HS-F 1000 (Figure 1) for milling of production samples of medium hardness from a local steel mill. The test series included nearly 2500 milling operations. We used a milling head with a four cutting items (Sandvik Coromant R200-068Q27-12L). Milling parameters were kept constant with spindle speed of 1000/min, milling depth of 8/10 mm, and milling head advance of 800 mm/min.

During each milling operation, we measured vibration velocity (v Peak) of the spindle block using a commercial vibration sensor (Figure 2). Simultaneously, we captured torque values of the spindle motor. After every fiftieth milling operation, we evaluated the tip wear with a 3-point rating system (1= No obvious or slight wear, 2= intermediate or advanced wear, no change necessary, 3= heavy wear, change necessary). At the same time, the radial and frontal view of all four cutting tips were documented by standard photographic procedure. The worn surface of each cutting tip was sized (square mm) using a graphic-editing program. In case of significantly changed vibration and torque values, we assessed the worn tip surface more frequently.

Figure 1: Model HS-F 1000 specially designed for preparation of steel and iron samples

Figure 2: Overlap of vibration measurements during a milling cycle of approx. 400 milling operations. At the end of life of cutting tips, vibration values significantly increases. This is due to increased tool wear.
Results

In each milling trial, we found an increase of vibration with increasing cutting tip wear (Figure 3).

The same was shown for torque values (data not shown).

Figure 3: Exemplary display of vibration values during one milling cycle. The vibration values increase continuously at the end of the milling cycle. The photographs show that the vibration increase is associated with increased wear of the cutting tip.

Based on the 3-point-rating system, we found a slight increase of vibration (Figure 4) and torque (Figure 5) for stage 2 (intermediate and advanced wear, no change necessary).

The increase in stage 3 (heavy wear, change necessary) was statistically significant for vibration (student’s t-test, P<0.0001) and torque (P<0.05).

Figure 4: Box plot diagram of vibration values at different stages of the tool wear

Figure 5: Box plot diagram of torque values at different stages of the tool wear.
Pairwise post-hoc analysis revealed a significant correlation between total worn surface of cutting tips and vibration ($r= 0.8558, P<0.0001$) and torque ($r= 0.7048, P<0.0001$).

Based on data density display of vibration and torque values, stage 3 condition of tool wear could be clearly allocated without significant overlap to stage 1 and 2 (Figure 7).

There was also a significant correlation between vibration and torque ($r= 0.7938, P<0.0001$) (Figure 6).

This finding was supported by cluster analysis (k-means clustering) revealing that stage 3 condition was uniquely identifiable by vibration and torque values.

Figure 6: Correlation diagrams for total wear surface of cutting tips, vibration and torque values. Post-hoc analysis show significant correlations between all three variables.

Figure 7: The combined evaluation of vibration and torque values of the milling spindle allow the clear and unambiguous identification of worn out cutting tips (stage 3).
Discussion

This study shows that wear of cutting tips can be monitored by vibration and spindle motor torque. Especially, the time for tool change can be determined easily and unambiguously.

Continuous tool monitoring produce clear benefits. First, TCM optimizes cutting tool management. The optimal time for tool change can differ significantly from cycle to cycle. In one cycle, lifetime of cutting tips is long allowing milling of several hundred samples.

In this case, premature change of cutting tips would waste money. In the next cycle, cutting tips break early due to, e.g., shrinkage cavities of samples. In this case, continuous milling with a worn out tool would have detrimental effects with tolerance deviation of surface removal and unfavorable impact on spectroscopic analysis results. Second, TCM releases the operational personnel from the mundane task of cutting tool inspection. Third, TCM opens up new perspectives for fully automated QC laboratories. Sensor signals are automatically collected, displayed and evaluated by special Scada system modules like the PrepMaster Analytics (Figure 8). The PM Analytics allows monitoring and management of an unlimited number of milling heads. If the PM Analytics detects tool wear it will automatically change the milling head and inform the operator. All data are stored and can be reviewed for optimizing milling parameters, tool type and analysis results.

Preliminary investigations have shown that reliable signal recording of spindle vibration depends on the design of the milling machine. The HS-F 1000 is a milling machine especially designed for preparation of steel and iron samples.

Due to shape and mineral composite casting, the frame of the HS-F 1000 has excellent damping features leading to greatly reduced machine vibration. This allows undisturbed vibration recording of the spindle reflecting tool wear. In machines showing worse vibration damping features, the signal noise is higher and may reduce the validity of the TCM system.

Figure 8: Screenshot of the PM Analytics showing the TCM functionality of the module.