Correlations among Cutting Forces, Tool Condition and Work Surface

Integrity in Facing

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Summary

Correlations among cutting forces, tool condition and surface integrity of machined surfaces in facing have been investigated in this paper. A set of experiments were performed on a CNC lathe without coolant. SANDVIK tool inserts (type PF4015) were used to cut 45 carbon steel. It was found with the experiments that 1) Tool wear could be identified from the texture of a machined surface based on the gray level co-occurrence matrix. 2) Surface roughness and cutting forces could be used as indices of medium (VB>0.1mm) and large (VB>0.2mm) tool flank wear in facing 3) Residual stresses in radial direction of a machined surface tend to decrease as tool wear grows in facing.

Keywords: Tool wear, Tool condition monitoring, Surface integrity, Facing

1. Introduction

With the ever-increasing demand for cost saving and quality improvements, automating the metal cutting process is becoming more and more important in modern manufacturing. One of the crucial problems that must be solved in a fully automated machining environment is the development of reliable tool condition monitoring systems. In the last three decades, many efforts have been made to develop a reliable and cost-effective TCMS (tool condition monitoring system) for applications on the shop floor. Generally tool condition monitoring techniques can be put into two main categories (1)(2)(3): direct methods and indirect methods. The direct methods can be implemented using devices such as touch trigger probes, optical sensors, and proximity sensors to measure the geometry and/or the morphology of cutting edge. The indirect methods are based on the acquisition of process variables from which tool condition can be deducted according to certain known signal patterns. The former methods are reliable, but they cannot provide continuous in-process measurements because cutting edges are generally inaccessible during cutting; on the contrary, the latter methods can take measurements while cutting tools are actively engaged in cutting, which makes it possible to monitor the cutting tool condition monitoring on-line. Identification of tool condition relevant information in measured monitoring signals is essential for the success of indirect monitoring systems.

One of the parameters that are widely used for tool condition monitoring is cutting force, which has been reported to be one of the most sensitive methods among the suggested monitoring indices such as AE (acoustic emission), cutting power, and cutting temperature. There have been many research attempts at using cutting force patterns as an indication of tool wear for turning operations (4). Some experimental results showed that the cutting force components at axial and radial directions are influenced much more by tool wear than the tangential cutting force (the main cutting force) (5). However, there is also a report (6) contradicted the above findings and showed that the main cutting force gave the best indication of tool wear while the axial and radial force components were not suitable for in-process monitoring. Up to now, the extensive studies on tool condition monitoring using cutting force signals are generally for turning and milling operations (7)(8). Relatively less attention has been paid to the correlation of tool wear and cutting
force signals in facing operations.

On the other hand, according to the state-of-the-art review of miscellaneous tool condition monitoring research and development efforts\(^{(1)\rightarrow(6)}\), tool change decisions are generally based on tool conditions not on product quality which results in that potential damages to the surface integrity of machined surface due to tool wear still cannot be avoided. Direct monitoring of machined surfaces for both tool condition and product is of great importance for modern manufacturing systems. The main objective of this study is, by investigating the correlation between cutting forces and tool wear as well as their relationships with surface integrity of machined surfaces, to explore tool wear information both in cutting force signals and on machined surfaces in facing operations.

2. Experimental setup and procedures

The cutting experiments were carried out on a CNC lathe (Index G200) (Fig.1). Three cutting force components (tangential cutting force \(F_z\), radial cutting force \(F_x\), and axial cutting force \(F_y\)) were measured using a force dynamometer (Kistler type 9272), a charge amplifier (Kistler type 5019B141) and a PC based data acquisition software. Both machined surfaces and tool surfaces were examined and measured using a digital microscope (KEYENCE type VH-800). The residual stresses of machined surfaces were measured using an X-ray stress analyzer (X350A). The surface roughness was measured using a contact stylus roughness tester.

In order to get cutting tools (SANDVIK type PF4015) with different VB (flank wear width), machining operations were carried out on 1Cr18Ni9Ti stainless steel using the inserts. After that, the inserts with different flank wear width were used to face a workpiece made of 45 carbon steel which has a typical chemical composition given in Table 1 and no cutting fluid was used during machining. The cutting speed in facing was set at 200m/min. Depth of cut was 0.15mm. Feed rate was 0.15mm/rev. The three components of the cutting force were measured during facing operations using cutting tools with different flank wear. The machined surfaces of the workpiece were examined and their surface roughness and residual stresses were measured after each facing operation. The experimental data will be presented and analyzed in the next section.

![Experimental setup diagram](image)

**Figure 1. Experimental setup**

![Cutting force components in facing](image)

**Fig. 2 Cutting force components in facing**

| Table 1 Chemical composition of 45 carbon steel (in wt %) |
|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|-----------------|
| C               | Si              | Mn              | P               | S               | Ni              | Cr              | Cu              |
| 0.42-0.50       | 0.17-0.37       | 0.50-0.80       | <0.035          | <0.035          | <0.25           | <0.25           | <0.25           |

3. Experimental results and discussions

Variations of the three components of cutting forces with average flank wear width of cutting tools for
the cutting conditions (see section 2) are shown in Fig.3-Fig.5. The relationships between surface roughness and the tool flank wear are presented in Fig.6. The correlations between residual stress and tool flank wear are shown in Fig.7. The surface textures machined with a new cutter and a worn cutter are given in Fig.8.

It can be seen from Fig.3-Fig.5 that when tool flank wear width is less than 0.2mm, the three components of the cutting force signals do not change significantly. When tool flank wear width is in the range of 0.2-0.5mm, all of the cutting force signals increase as tool wear grows and the tangential component of the cutting force seems to increase with tool flank wear width proportionally. When the flank wear width of inserts reaches around 0.5mm, all three cutting force signals increase sharply. The tangential force increases by 86% as compared to the relatively sharp tools (flank wear width less than 0.2mm), the radial force increases by 146% and the axial cutting forces increases by 147%. Apparently, all cutting forces could be very good indices for large tool flank wear (VB>0.2mm) monitoring in facing operations.

Fig. 3. $F_x$ vs. average flank wear width
Fig. 4. $F_x$ vs. average flank wear width
Fig. 5. $F_y$ vs. average flank wear width
Fig. 6. $R_a$ vs. average flank wear width

Fig. 7. Residual stress vs. average flank wear width

a) Residual stress in peripheral direction
b) Residual stress in radial direction
It is shown in Fig.6 that cutting tools with small amount of flank wear (VB< 0.1mm) tend to have better surface finish on the machined surface than new cutting tools. However when tool wear develops further surface roughness increases significantly and severe tool wear results in surface roughness increased by 200~400%(Fig.6). The experimental results suggest that the surface roughness could be used as an effective index for medium tool wear (VB>0.1mm) monitoring.

As to the residual stresses of machined surfaces, the residual stresses in peripheral direction are always tensile and do not show any correlation with tool flank wear (Fig.7(a)). The residual stresses in radial direction are tensile and decrease as tool wear grows in early stage of tool wear (VB<0.2mm) and become compressive when tool wear is severe (VB>0.3mm) (Fig.7(b)). It seems that the residual stress in peripheral direction could be used as index for small (VB<0.2mm) as well as large (VB>0.2mm) tool flank wear monitoring.

![Surface textures and tool wear](image)

**Fig. 8 Surface textures and tool wear**

![ASM vs. VB](image)

**Fig.9 ASM vs. VB**

It is shown in Fig.8 that the surface machined with a new cutting tool has fine and even texture and the surface generated with a worn tool shows wide and rough texture. The gray level co-occurrence matrix(7) was used to analyze texture images of machined surface by the inserts with different VB. It is shown in Fig.9 that the ASM (angular second moment) of the gray level co-occurrence matrix generally increases as tool flank wear grows. And Sever tool flank wear (VB>0.3mm) ends up with significant increase of ASM. This unique characteristic of a machined surface with different tool wear conditions demonstrates great potential for indirect image recognition of tool condition from machined surfaces.
4. Conclusions

This study demonstrates some useful tool wear information both in cutting force signals and on machined surfaces in facing operations. Tangential, radial and axial cutting forces could all be very good indices for tool wear monitoring in facing operations provided that VB is larger than 0.2mm. Severe flank wear of a cutting tool deteriorates surface finish of a workpiece. However, surfaces machined with cutting tools with small amount of flank wear (VB around 0.1mm) tend to have better surface finish than that of new cutting tools. Tensile residual stresses in radial direction on a machined surface in facing seem to be the only promising index that could be used to identify tool flank wear under 0.2mm. ASM of the gray level co-occurrence matrix could also be a good index of tool wear on machined surface. The results of this study contribute to a better understanding of the influence of tool wear on surface roughness, residual stress and surface texture as well as cutting forces in facing operations and are beneficial to the research and development of monitoring systems for both tool condition and work surface integrity in automated machining.

5. References