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Detection of tool breakage during hard turning through acoustic emission at low removal rates

M. Neslušan [a,*], B. Mičieta [a], A. Mičietová [a], M. Čilliková [a], I. Mrkvica [b]

[a] University of Žilina, Faculty of Mechanical Engineering, Univerzitná 1, 010 26 Žilina, Slovakia
[b] VŠB-Technical University of Ostrava, 17. listopadu 15, 70833 Ostrava, Czech Republic

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ABSTRACT

The paper deals with a new method for the detection and prediction of the catastrophic tool failure (CTF) of ceramic inserts through an acoustic emission (AE) technique and associated chip formation analysis during the hard turning of bearing steel 100Cr6. The capability of different AE sensors with respect to the different processes in the cutting zone during hard turning is discussed as an initial study. Then a new concept of process monitoring is suggested based on the application of two sensors and rationing of chosen parameters such as AE_{rms}, $AE_{strength}$ and $AE_{absolute\ energy}$. The specific character of the formed chip is associated with raw AE signals. Conventional data processing of AE signals does not enable the different phases of tool wear to be clearly recognised or the prediction of CTF, while the new suggested concept does. This concept is based on the rationing of AE features recorded in different frequency ranges in connection with the different processes in the cutting zone during chip separation.

1. Introduction

The high industrial relevance of hard turning operations corresponds with the development in machine tools (especially CBN and ceramic tools for hard turning operations) as well as the design of new lathes of high stiffness and accuracy. Thus hard cutting can seriously be regarded as an alternative to grinding operations under certain circumstances. In general, a high flexibility, high removal rate and the ability to manufacture complex workpiece geometry in one-set can be viewed as the main advantages of hard cutting in comparison to grinding [1]. Furthermore, the substitution of the grinding process with cutting processes enables coolants to be avoided, and therefore the significant cost and ecology benefits should also be considered [1,2].

Many studies related to the hard machining were reported recently. Aslantas et al. [3] analysed tool life and wear mechanism of mixed ceramics tools in turning hardened steel. Kumar et al. [4] investigated wear behaviour of coated tools in laser assisted micro milling of hardened steel. Bartarya and Choudhury [5] discussed about state of the art in hard turning.

However certain disadvantages of hard turning can be also discussed: surface roughness dependence on cutting conditions (mainly feed), the formation of white layers induced in the early stages of tool wear and the high risk of unexpected catastrophic tool failure (CTF) at the end of the normal phase of tool wear (mainly associated with the application of ceramic tools [6]). Despite improved progressive ceramic inserts (TiC whisker reinforced) and higher resistance against strong impact and stress, CTF still should be considered a significant aspect of hard turning operations. CTF can cause damage to the machined surface, tool holder and machine, and also alters the workpiece

* Corresponding author. Tel.: +421 415132785.
E-mail address: miroslav.neslusan@fstroj.utc.sk (M. Neslušan).

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dimensions. Consequently, hard turning operations need the incorporation of properly proposed monitoring systems for the detection or much better prediction of CTF.

Lee et al. [7] reported on a variety of sensors, each having a certain degree of applicability, for the monitoring of the cutting process. Monitoring techniques based on the implementation of dynamometers, accelerometers laser interferometers, etc. were proposed and properly integrated into the control system of machines. However, the proposed monitoring system for hard turning operations should meet specific requirements corresponding to the specific mechanism of chip formation. It should be noted that the proposal for a reliable monitoring system should be based on the detailed knowledge of the cutting mechanism. Hence a realistic and detailed understanding of the mechanism of chip separation is essential.

Due to the poor plasticity, high hardness and strength of hardened steel, segmented chips are produced during hard turning [8,9]. While the mechanism of strain hardening predominates during the turning of conventional soft steels, a decrease in flow stress due to thermal softening occurs in hard turning [8–10]. Fig. 1 illustrates the formation of segmented chips during the turning of hardened steel 100Cr6. An interesting study on chip formation was reported by Shaw and Vyas [8]. They found that thermal instability in the shear zone takes a significant role. However, they report that segment separation during hard cutting cannot be fully explained in terms of an onset of adiabatic shear, and that crack initiation theory should be considered. Poulachon and Moisan [11] presented outstanding quick-stop photomicrographs and soundly investigated the chip segmentation process during hard turning and its stages as follows:

1. Chip formation starts with crack initialisation near the free surface. Crack propagates towards the tool tip of the cutting edge (zone Ib, see Fig. 2).
2. Crack propagation transforms into a plastically deformed region (but micro cracks still occur in this zone, (zone Ia, see Fig. 2). A band of concentrated shear propagates towards the tool face in a straight line, followed by bands that begin to curve towards the tool face.
3. The formed segment gradually moves outward due to sliding along the fully cracked surfaces, together with the extension of bands of concentrated shear in the micro cracked region.

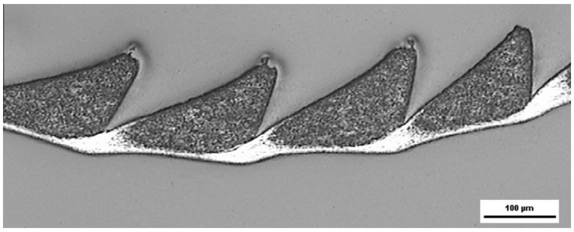

Fig. 1. Segmented chip, 100Cr6 (hardened 62 HRC), $v_c = 100\ \text{m min}^{-1}$, $f = 0.271$ mm.

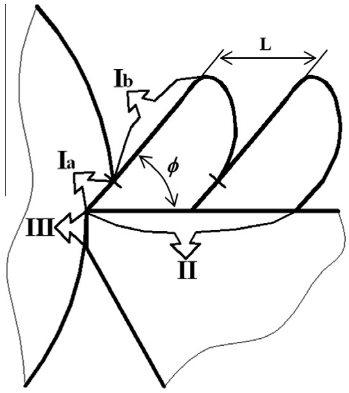

Fig. 2. Sketch of cutting zone during hard cutting, L – segment length, ϕ – shear angle, (Ia) micro cracked and plastically deformed shear zone, (Ib) cracked region, (II) tool – chip contact, (III) tool – workpiece contact.

4. Micro cracked region becomes thinner as the chip moves up the face of the tool.

Fig. 1 also indicates that intensive transformation in the form of narrow white bands occurs at segment boundaries, while the structure inside the segment remains nearly untouched. A significant feature of chip formation during hard turning is its relaxation character. Nakayama et al. [10] stated that due to the poor plasticity and high strength of hardened steel, the cutting energy accumulated ahead of the cutting edge is suddenly released when the shear strain near the free surface attains the ultimate value over which the structure cannot exceed. Then a segment is gradually formed as stated above (see stages 1–4), with the subsequent accumulation of cutting energy as the workpiece moves up the tool face.

This phenomenon is directly related to fluctuations in cutting force. The relaxation character of the cutting process and the characteristic segmentation frequency during hard turning depend on cutting conditions (especially cutting speed and feed). Shaw and Vyas [8] determined that for a cutting speed $100\ \text{m min}^{-1}$, feed 0.28 mm and hardness of case carburised steel (62 HRC) the segmentation frequency is about 18 kHz.

Dynamic analyses of deformation processes that fluctuate at a frequency over 25 kHz with the application of conventional accelerometers or dynamometers are difficult to conduct and usually require special techniques. On the other hand, past research and existing monitoring systems based on acoustic emission (AE) have been developed. Acoustic emission techniques enable the investigation of processes that fluctuate at a frequency over several MHz.

Acoustic emission is the stress waves produced when a material undergoes stress (internal change) as a result of an external force. It is well known that AE is a phenomenon occurring in for instance mechanical loading, generating sources of elastic waves. This occurrence is the result of a small surface displacement of a material produced due to stress waves generated when the energy in the material, or on its surface, is released rapidly. AE is usually applied for process monitoring [12]; for which it is one of the most