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Cutting temperature responses to flank wear

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Abstract

This paper discusses one feature of a continuing research program with the ultimate objective of tracking continuously the deterioration of the machining process, which must be overcome in order to achieve unmanned machining stations. Recent work using the non-contact infrared (IR) thermographic technique to investigate the cutting temperatures during chip formation has shown a clear relationship between the measured chip-back temperatures and the tool–chip interface temperatures. This result and the very fast response of the technique provide the potential means for tracking the progress of tool wear. The measured temperature increases rapidly corresponding to a sudden breakdown of the sharp cutting edge; this is followed by a slight increase in the temperature with increasing uniform wear, and then by acceleration after a critical wear value has been reached. Other early results indicate a definite correlation between the measured temperature and tool flank wear, suggesting that control over the process is feasible if the chip-back temperatures are monitored during cutting.

Keywords: Cutting; Temperature; Tool life; Wear

1. Introduction

The major obstacle hampering the progress towards the development of unmanned machining centers, and hence unmanned manufacturing systems, has been the lack of effective machine tool monitoring systems, in particular, the lack of reliable tool wear sensing devices [1]. The wear of a cutting tool is the main parameter defining its lifespan. This parameter is accompanied by the consequences of machined part quality, such as the degradation of the surface finish, dimensional accuracy, etc.

Many investigators have observed that two basic wear mechanisms are dominant in different velocity ranges [2]. Abrasion wear is prominent in the low speed range. As the speed increases, adhesive wear becomes the dominant wear mechanism, while the effect of abrasion diminishes. Although the type of wear playing the most important role depends on the cutting conditions, the adhesive mechanism is predominant under the usual (or practical) conditions for carbide tools. The nature of adhesive wear can be considered to be a sort of rate process, which greatly depends on the temperature. The fact that the machining temperature has a critical influence on tool wear and tool life has been well recognized since the work of Taylor [3]. Such a concept was applied by Trigger and Chao [4], who found that the growth of crater wear at the tool–chip interface was directly governed by the temperature distribution along the interface. Furthermore, Sata [5] showed, experimentally, a close correspondence between crater wear and the cutting temperature. In practice, the amount of flank wear is used more often in determining the tool life. An important aim of this paper is to extend the research of rate processes to the problem of flank wear.

Attempts have been made to determine the temperature distribution in the chip by direct measurement. Thermocouples or optical pyrometers embedded in the cutting tools have been used to measure the temperatures at the tool–chip interface [6–8]. The hole in which the thermocouple is placed represents a disturbance and may appreciably change the temperature field being measured. In Boothroyd's experiments [9], the infrared (IR) radiation from the tool, work and chip was measured to establish the temperature field on the outside surfaces of these regions. Due to edge effects, the temperatures measured are lower than those actually occurring in the bulk of the material. The other main difficulty with radiation techniques is that they are generally limited to accessible surfaces. The previous experimental approaches are therefore not practical for determining the chip temperatures. In view of the above problems, an IR thermotracer instrument was used to measure directly the temperatures on the chip

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back (chip–air interface) in this work. Using this instrument, the relationship between the chip temperature and flank wear was investigated.

2. Experimental system

The experimental arrangement for measuring the chip temperatures during machining is illustrated in Fig. 1. A workpiece of annealed carbon steel (ANSI 1045) was straight machined on a lathe, while the temperature distribution of the chip-back area was simultaneously displayed on a color CRT as a frozen image through a high-sensitivity IR detector element of HgCdTe (liquid nitrogen cooling type). The thermotracer employed was an NEC San-ei model 6T62. The temperature measurement range was −50 to 2000 °C, with ±0.5% measurement accuracy and 0.1 °C resolution. In this measuring system, the detector unit first senses IR radiation and converts radiant energy into electrical signals. The electrical signal is then linearized to obtain the corresponding temperature values. The displayed image (thermograph) may also be stored on a floppy disk for further processing and analysis.

The three coordinate axis components of the cutting force were measured for each test. The force signals were amplified and recorded, and stored using a personal computer via a data acquisition system (Fig. 1). The forces were monitored to ensure that the measured temperatures corresponded to a steady state machining condition.

The machining tests were arranged so that orthogonal conditions could be assumed. Results were obtained with tungsten carbide tools of negligible nose radii. The tool wear tests were performed at a cutting speed of 100 m min^{-1} and with an undeformed chip thickness t of 0.015 mm. The depth of cut or the undeformed chip width b was maintained at 1.3 mm. In the preliminary tests to observe the measured temperature distributions, variations of the ratio b/t were allowed. The geometry of the machining process in relation to the orientation of the IR detector unit is shown in Fig. 2.

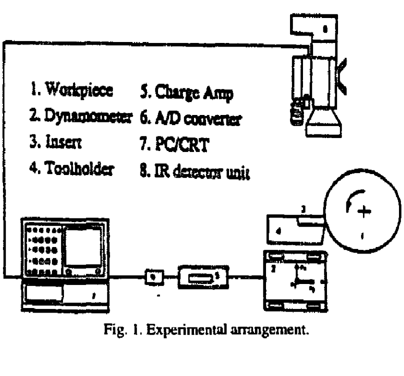

Fig. 1. Experimental arrangement.

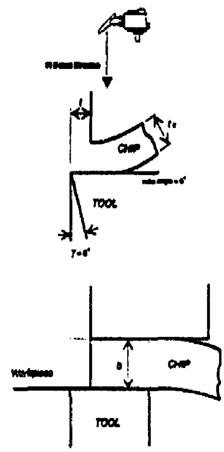

Fig. 2. Geometry of machining process.

3. Results and discussion

The present experimental investigation directly measured the chip temperature using an IR thermal tracer which was focused on the mid-section of the chip back. A wide area of the chip back could be covered by the detector unit. Both the maximum temperature and its corresponding location were then obtained. Typical contours of the chip-back temperatures are shown in Fig. 3. The coordinate system adopted in this paper is also presented in Fig. 3, in which the x axis coincides with the chip flow direction. It can be seen that, in the region near the cutting edge ($x \leq 1.5$ mm in this case), the edge effect is relatively small, while some distance away from the cutting edge ($x \geq 1.5$ mm), the edge effect in terms of the cutting temperature becomes prominent.

The temperature distributions along the mid-section of the chip back for the tested b/t ratios are shown in Fig. 4, in which the magnitude and location of the maximum temperature are both seen to increase as the b/t ratio decreases. It is interesting to note that virtually all the maximum chip-back temperatures occur beyond the contact length (h). In contrast, the location of the maximum tool–chip interface tem-

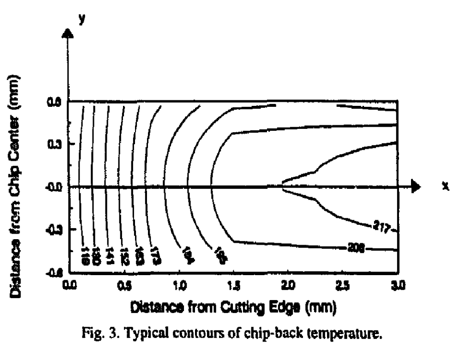

Fig. 3. Typical contours of chip-back temperature.

perature is found in the range 0.6–0.7h (obtained both experimentally by Arndt and Brown [10] and analytically by Tay et al. [11]). This can be explained by the heat transfer along the chip thickness (z direction) from the secondary deformation zone to the chip-back surface, which strongly indicates that the transfer of heat by conduction along the thickness direction is of great importance in chip temperature analysis.

The temperature distribution along the mid-section of the chip back can be separated into two regions (Fig. 4). Before the maximum temperature is reached, the temperature increases monotonically with the distance from the cutting edge. Similar trends have been given by Friedman and Lenz [12], except that the range of their observations was limited to within 1 mm of length, which resulted in a linear relationship of the temperature distribution along the chip flow axis. However, the chip-back temperature beyond the location of the maximum value decreases along the chip flow axis, which is caused by convection heat loss to the ambient atmosphere. In this region, a clear trend is observed: the respective chip-back temperatures are inversely proportional to the b/t ratio. This is attributed to the fact that more strain energy is associated with the deformation zones when the undeformed chip thickness t increases (consequently, b/t decreases with constant undeformed chip width b used in the present experimental observation).

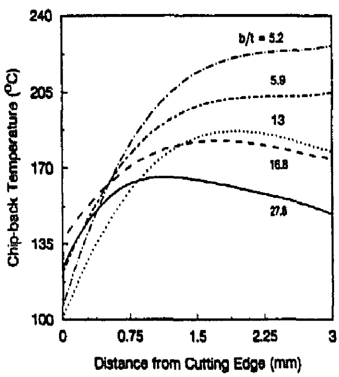

Fig. 4. Chip-back temperature distribution along chip flow axis.

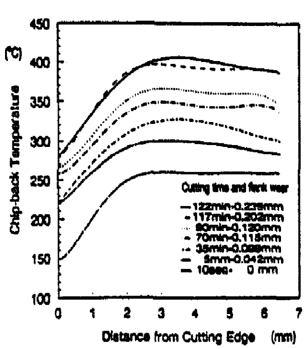

Fig. 5. Progress of flank wear with cutting temperature.

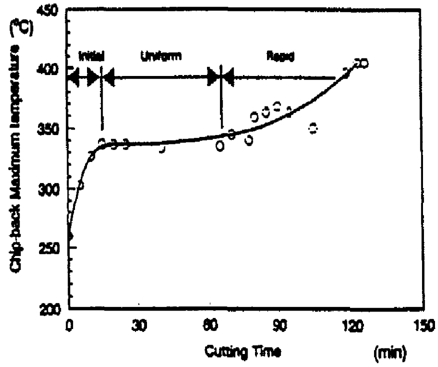

Fig. 6. Variation of maximum cutting temperature with time.

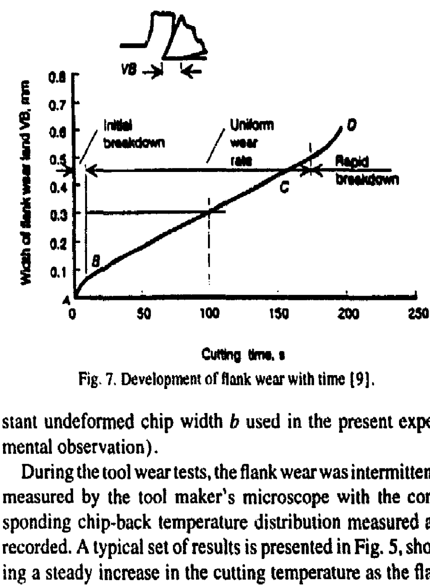

Fig. 7. Development of flank wear with time [9].

During the tool wear tests, the flank wear was intermittently measured by the tool maker's microscope with the corresponding chip-back temperature distribution measured and recorded. A typical set of results is presented in Fig. 5, showing a steady increase in the cutting temperature as the flank wear progresses. The maximum chip-back temperature is considered to be the key parameter representing the state of tool wear, and the relationship between this temperature and the cutting time is plotted in Fig. 6 for the results discussed above. The key features of the curve indicate a close resemblance to the results reported by Boothroyd [9], as shown in Fig. 7 where the progress of the flank wear land (VB in Fig. 7) is plotted against the cutting time. Three distinctive regions can be seen in each of the curves:

1. region AB (Fig. 7), where the sharp cutting edge is quickly broken down and a finite flank wear land is established;
2. region BC, where wear progresses at a uniform rate;
3. region CD, where wear occurs at a gradually increasing rate after a critical value (accelerated flank wear).

The experimental data, when re-organized as in Fig. 8, show a response curve of the cutting temperature to flank

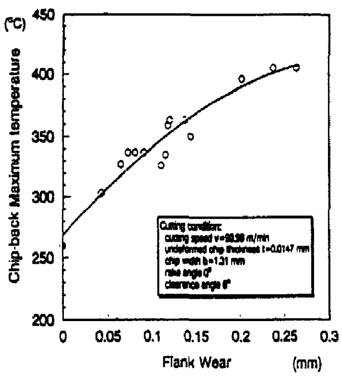

Fig. 8. Cutting temperature responses to flank wear.

wear. This clearly demonstrates that the wear phenomenon is strongly temperature dependent. If the critical temperature can be determined from manufacturing or laboratory tests, the tool can achieve a high production rate without accelerated wear. Alternatively, an attempt can be made to measure and control the cutting temperature with a view to obtaining the optimum machining conditions.

4. Conclusions

Tool wear has been shown to be strongly temperature dependent. Future study in the following areas is planned.

1. The properties of the critical temperature with the influence of the tool material and cutting conditions.
2. Control of the rate of wear and the wear level by removing the heat from machining.

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