Towards Active Chip Control

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Abstract

Current reliance on chip formers with fixed geometries suffers from limitations on the work materials and cutting conditions. This paper examines the feasibility of the hitherto unexplored concept of active chip control. An actuator with two degrees of freedom, utilizing an obstruction type chip former, and based on Nakayama's assertion that the position and orientation of the line of separation of the chip from the tool rake determines the chip form, has yielded encouraging results. Stable clusters of chip forms under varying cutting conditions have been obtained through appropriate geometric transformations of the control variables. Experimental work on a variety of sensors has identified chip form sensing through the use of electrostatic induction, optical fibers, and infra-red cameras to be amongst the most promising.

Keywords: Chip, Sensor, Control

1. Introduction

Currently, unmanned machining is not possible because of the need for periodic manual intervention to clear tangled chips from the working zone. Chips, in practice, take many forms depending on the process inputs: cutting operation, work material, tool geometry and cutting conditions. A detailed literature review concerning chip form control is available in the keynote paper presented by Jawahir and Luttervelt at the 1993 CIRP General Assembly [1].

The form of a chip, at the instance it leaves the cutting zone, depends on three basic chip form parameters: up-curl (of radius r_u), side-curl (of radius r_s), and chip flow angle (η_c). For instance, a combination of r_u and r_s usually leads to cylindrical-helical chips whereas the addition of η_c to this combination leads to conical-helical chips. However, there are no analytical models available which possess the ability to predict, with sufficient robustness, the magnitudes of these basic chip form parameters for given input conditions. The problem is further exacerbated by the fact that chips often substantially change their form or, even, break (which is generally desirable) when they encounter an obstacle *after* they have exited from the cutting zone.

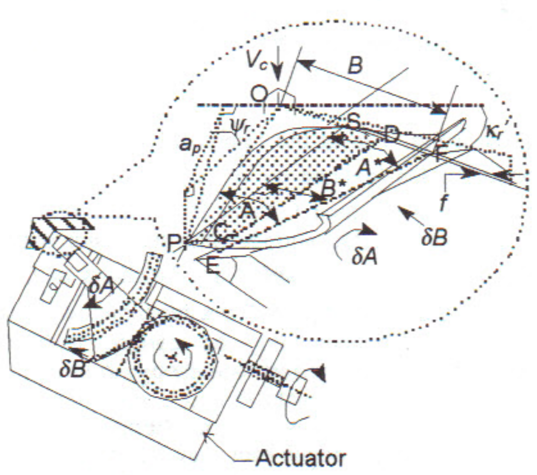

Fig. 1 An active chip control strategy

Chip forming and breaking technology has however continued to progress through the invention (inspired by tedious empirical studies owing to the absence of predictive models) of a variety of cutting inserts, each incorporating a specific set of chip forming features (bumps and troughs, usually, on the rake face) to suit specific process input conditions. This passive and off-line approach has resulted in a nightmarish (and, as some believe, purely market driven) proliferation of inadequately tested insert types.

An alternative to passive chip control is the use of *active* on-line chip control where the chip former geometry continuously adapts to changing process inputs such that the resulting chip forms are always of the desirable type. Little published material seems to be available concerning such active chip control techniques. The present paper examines the technical feasibility of a promising method of active chip control.

2. Chip Control Strategy

The chip control strategy developed in the present paper was inspired by an interesting observation made recently by Nakayama [2] with regard to chip forms obtained with single point tools. Nakayama noted that the basic chip form parameters (r_u, r_s, and η_c) are fundamentally determined by the location and orientation of the line of separation, CD, of the chip from the tool rake face (see inset in Fig. 1). Thus, if we could control line CD, we should be able to control the basic chip form parameters which, as already noted, control the initial chip form and path which, in turn, control the eventual breaking of the chips as they encounter some external obstacle.

In the present work, chip control is achieved by adjusting angle A and distance B between the major cutting edge and the leading edge EF of an obstruction-type chip forming wedge placed on the cutting insert's rake face (see inset in Fig. 1). The expectation is that a reduction in the magnitude of B (i.e. bringing EF closer to the cutting edge) will induce the line of chip separation, CD, to move closer to the cutting edge. Likewise, a change in angle A will bring forth a corresponding change in the orientation of CD.

The proposed control loop consists of a *two-axis actuator*, a *sensor system* and a *control unit*. A change in control signals to the actuator (which provides a rotary shift, δA, and a linear shift, δB, to the obstruction type chip forming wedge) will result in a corresponding change in the chip form. The major characteristics of the new chip form are sensed by the sensing system situated around the cutting zone. The control unit then evaluates the sensed signal, classifies the new chip form, compares the chip form with the desired chip form as specified by the user and, finally, issues the necessary correction signals, δA and δB, to the actuator.

Clearly, the design of such a control unit is not a trivial task since chips, in practice, take up a wide variety of forms as determined by the process input conditions. Further, the current chip form could be changing continuously in response to continuously changing feed rate and depth of cut as is usually found in profile machining on CNC machines. The control unit therefore needs to be capable of *learning* the wide variety of correlations that exist between specific combinations of control parameters (*A* and *B*) and the corresponding chip forms in the context of a wide variety of work materials, tool geometries, cutting speeds, feed rates, depths of cut, etc. Current understanding of these issues seems to be non-analytic and heuristic. However, Jawahir [3] has succeeded in applying fuzzy logic to the clustering of chip forms when the feed rate and depth of cut are changed. While significant future research is needed for the development of a control unit with such learning capabilities, it appears that Artificial Neural Nets (ANN) or Fuzzy-ANN may be found to be particularly attractive. The work of the present authors in this regard is still inconclusive. However, significant progress has been made with respect to the actuator and sensing systems. The following sections report on this progress.

3. Actuator Design

Fig. 1 shows one of the two-axis actuator designs used in this research. A standard, plane faced, and square carbide cutting insert is mounted on a small platform rigidly attached to a shank mounted on the tool post of a center lathe. The chip former, which is made of carbide (P20) is mounted at the end of a linear slideway (controlling shift δB) which, in turn, can rotate around the vertical axis passing approximately through the mid-point of the active portion of the major cutting edge (thus controlling shift δA). The design is such that the under-face of the chip former is always flush with the rake face of the insert. A suitably placed knob and a handle enable manual control of the rotary and linear shifts, δA and δB respectively, within preset limits. Alternatively these parameters may be controlled by two separate micro-stepper motors.

4. Turning Experiments

Turning tests using the two-axis actuator were conducted on AISI 1050 hot rolled bar stock of 100 mm nominal diameter. Square carbide cutting inserts were used (side rake, γ_f = -6°; back rake, γ_p = -6°; side cutting edge angle, ψ_r = 15° ; end cutting edge angle, κ_r' = 15°; and corner radius, r = 1 mm). The chip former wedge angle was equal to 60°.

Initially, exploratory experiments were performed by manually controlling parameters *A* and *B* <u>on-line</u> (i.e. <u>while</u> cutting was in progress). These tests confirmed that the operator could indeed learn to control the chip form provided that the cutting conditions were kept constant. In particular, continuous chips could be controlled to become broken. However, learning had to be repeated for each new set of cutting conditions.

Next, in order to develop an understanding of the interactions among the control parameters, cutting conditions and chip forms, a series of systematic tests were undertaken. Several hundreds of cutting tests were conducted using different combinations of *A* and *B*. Control parameter *B* was varied in the range 1 to 10 mm. Control parameter *A* was confined within the range -5° to 10° because preliminary tests showed that smooth cutting was not feasible outside this range. A fresh cutting insert was used for each test set {*A*, *B*}. For each set, tests were performed at different cutting conditions: cutting speed = 100 m/min.; feed rate, f = 0.1 to 0.3 mm/rev; and depth of cut, a_p = 0.5 to 5 mm.

Three chip samples were collected for each set of experimental conditions. For each sampled chip, the following parameters were measured using appropriate measuring equipment: chip thickness, chip width, helix angle, helix-pitch, cone angle, and the direction of the cone apex relative to the chip flow direction. Based on these data, each test chip was classified according to the chip classification and coding systems developed by Spaans [3] (a one letter alpha-code) and JSPE (a four letter alpha-numeric code).

5. Data Analysis and Discussion

The experimental data were then analyzed with regard to different chip form characteristics of practical interest: broken or continuos; conical, cylindrical, or washer type; has small, medium, or large curl radius; has small, medium, or large pitch; etc. The anticipation was that there would be significant clustering of each chip form in a specific region of *A* and *B*. However, no such clustering was noted. A more detailed analysis then revealed that this non-clustering of chip forms was due to the fact that different chip forms could appear at different combinations of depth of cut (a_p) and feed rate (f) although the magnitudes of *A* and *B* were maintained constant. This led to a search for a method capable of compensating for the effects of varying a_p and f.

Nakayama has noted that "experimentally the chip flow angle (η_c) is known to be determined by the depth of cut (a_p), feed (f) and the profile of the cutting edge (side and end cutting edge angles and corner radius) according to Colwell's rule ([4])" [2]. The inset in Fig. 1 shows the application of Colwell's rule to the present problem with the objective of defining an (idealized) equivalent single edge tool which takes into account the effects of the cutting conditions as well as the actual cutting edge profile.

Point S in Fig. 1 is at the intersection between the insert edge profiles (defined by ψ_r, κ_r', and r) set apart by the magnitude of feed f. Point P is the intersection between the unmachined surface and the major cutting edge. The coordinates of point S are functions of f, κ_r' and r. The coordinates of point P are functions of a_p, ψ_r, and r. These functions may be derived from the geometric analysis summarized recently by Armarego [5]. The straight line joining points P and S determines the equivalent single edge. Thus, the bar turning operation using the actual profile edged tool may be considered to be equivalent to turning a tubular workpiece with the equivalent single edge tool. This transformation implies that the orientation and distance of the leading edge of the clamp-on chip former need to be determined relative to the equivalent single edge.

Following the above argument, control parameters *A* and *B* were modified to A^* and B^* respectively (see Fig. 1). A^* is the angle between the equivalent single cutting edge, PS, and the chip former edge, EF. B^* is the distance between the midpoint, M, of line PS and the chip former edge, CD, measured in a direction normal to PS. Finally, the influence of B^* may be expressed in a non-dimensional form by dividing it with the un-cut chip thickness, $t^* = f \cos \psi_r^*$, where ψ_r^* is the side cutting edge angle of the equivalent single edge, PS.

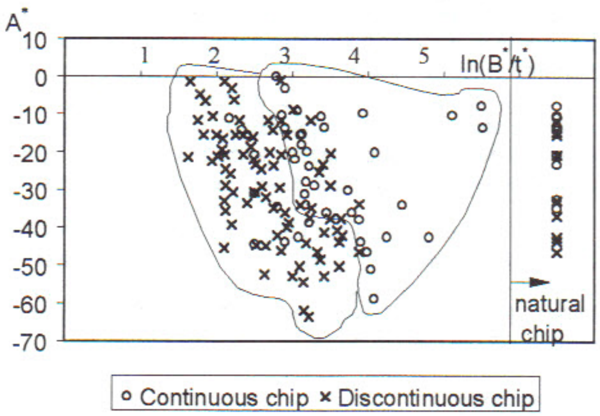

Fig. 2 An example of experimental results

Interestingly, a fair degree of clustering of chip forms was observed when the experimental data were re-analyzed using A^* and $\ln(B^*/t^*)$ as control parameters. Fig. 2 shows such clustering observed with regard to broken and continuous chips. Separate clusters of chip forms are evident albeit with some fuzziness regarding their boundaries. A similar degree of clustering was observed with regard to chip curl radius, chip helical pitch, and the chip form (up curling, side curling, and conical). This indicates that one can control the chip form fairly effectively through the use of (A^*) and $\ln(B^*/t_1^*)$ provided that the control algorithms incorporated in the control unit (i) include the required geometrical transformations between the actual profiled edge and the equivalent single edge, and (ii) adopt a logic that adequately recognizes the inevitable fuzzy nature of the chip form clusters.

6. Chip Form Sensing

In the absence of a robust model for predicting chip types, chip form has to be monitored on-line in order to obtain controller feedback. Three chip sensing schemes have been devised and tested successfully in dry cutting.

6.1 Monitoring for Entangled Chip

Early accumulation of the entangled chip in the proximity of the cutting zone is monitored on the turning lathe using eight photoelectric sensors with 1 mm thick fiber optic units. Emitter/receiver pairs are arranged in the opposition mode such that chips in between interrupt the light transmission. Sensors are divided into two groups of four (Fig. 3). One group scans the horizontal plane, and the other scans the vertical plane.

All emitting fibers are equipped with micro-lenses in order to increase the sensor range. This allows remote monitoring, which eases space demands around the cutting zone. In kinematic terms, sensors are fixed relative to the cutting tool.

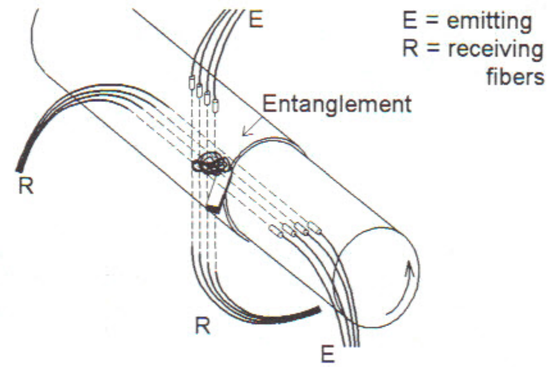

Fig. 3 Arrangement of optical fibers

Not every interruption of the light transmission between emitters and receivers may be interpreted as entanglement. Flying broken chips also interrupt this transmission. However, the time-frames and patterns have different characteristics because entanglements do not move as rapidly as flying broken chips. This allows differentiation between the two kinds of events. To signal chip entanglement, the developed computer program requires continuous beam interruptions over some period of time. This time period is specified as a function of the number of sensors detecting beam interruptions - the greater this number, the shorter the continuity requirement. These time constants are kept to the minimum values because the chip entanglement vibrates or drifts in space and, due to its low density during the stage of early chip accumulation, the light transmission through it is then intermittent. The largest time constant used was 0.8 seconds and pertained to the continuous interruption in transmission of one sensor only. This time threshold for signaling entanglement decreased rapidly (as e^{-n}) with the increase in the number of non-transmitting sensors (n).

Extensive tests were conducted to select the optimal distance between the emitting and receiving optical fibers. For the sensors used, 30 cm separation gave reliable performance without false detection of entanglements.

This photoelectric system was adjusted for high reliability of its conclusions. However, humans outperform it by signaling chip accumulation in the entanglements up to 30% sooner ; although with reduced confidence in such early conclusions when the ribbon-like chip may or may not continue to accumulate. Compared to manual monitoring, the greatest disadvantage of the photoelectric system is in its information processing. Instead of eight fixed thresholds (crisp sets) conservatively adjusted in the current program implementation, fuzzy ones would more suitably discriminate the imprecisely defined start of the building-up of entanglement. This is in line with the previously highlighted fuzzy nature of the chip form clusters.

In the case of broken chips, in principle, larger ones present themselves to the sensors over longer time periods as their time of "overflight" is longer. However, the variations were insufficient to provide size differentiation. The following scheme has been implemented to accomplish this task.

6.2 Monitoring for Chip Continuity and Size

In order to monitor chip continuity and size, a capacitor is formed between a metal plate and a portion of the corresponding surface of the workpiece (Fig. 4). This is achieved by maintaining a fixed potential of 15 V on the plate. Its electrostatic influence induces the opposite (negative) charge in a small area of the work-piece around the cutting zone. The shape and size of this area depend on the shape of the plate. Further from this zone of the workpiece, there is no charge as the machine is grounded.

The plate has a hole for the tool holder to pass through. The two move together as a rigid body. The tool holder is electrically insulated from the tool post. As the tool holder is obviously in contact with the workpiece during cutting, it must not be in contact with the plate as it would otherwise empty the capacitor formed. The plate is partially insulated to prevent loose chips from establishing a contact with the tool holder.

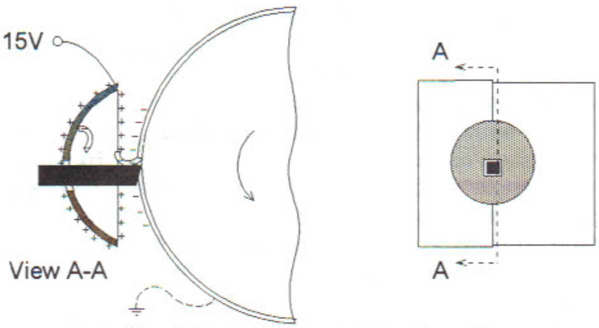

Fig. 4 Capacitive sensor schematics

With no chips produced, the unlike charges in the plate and around the cutting zone are static. There is no electric current across such capacitor.

A continuous chip which connects the workpiece and the plate empties the capacitor (shorted capacitor poles). This is easily detectable as it causes a practically total voltage drop on the plate accompanied with a maximum available current across the capacitor. The capacitor cannot charge back again for as long as the continuous chip is produced.

Each broken chip removed from the workpiece remains charged electrically until its eventual collision with the plate. The amount of electric charge carried out by each individual chip is approximately related to its size through its surface area. Hence, the problem of measuring the size of the individual chip is reduced to the problem of measuring the electric charge carried by the chip. Each individual chip colliding with the plate causes a small discharge which requires that an additional charge be brought to the plate for it to remain at the constant potential. This creates a peak in the electric current in the supply lead of the plate. The magnitude of this current corresponds to the chip size. It is not necessary that every chip collides with the plate since sampling of the chip population is sufficient.

This method cannot differentiate whether the chip "size" (surface area) is due to its thickness, width or length. It certainly cannot provide any information about the geometric shape of the chip such as helix pitch or the direction of the cone apex relative to the chip flow direction. Although these are irrelevant for the mere task of avoiding entanglement, a method of differentiating

6.3 Shape Differentiation

The third scheme uses an infrared CCD camera to acquire chip image. The Infrared vision domain was chosen in order to aid extraction of the hot-chip image from the background. A computer algorithm then tests the pixel connectivity in the acquired image and classifies chips as continuous or broken. The approximate size of the broken chip is evaluated as well. To accomplish this, the image is transformed by filtering and thresholding into a binary image which is also displayed on the computer monitor.

Tests have demonstrated the feasibility of using a vision system to classify chip type in single point turning.

The camera initially used was an ordinary CCD camera with an infrared-pass filter added for extraction of the hot-chip image from the background. Since these cameras have a limited range in the infra-red, only very hot chips were visible - heavier cuts were required in order to produce such chips. Both, light and heavy cuts were monitored successfully with the infrared camera since it is sensitive to much lower temperature chips.

The present implementation of this vision concept failed when cooling fluids were used. The first two sensing schemes (Sections 6.1 and 6.2) tolerate cooling fluids when applied such that only drops (or droplets) bounce off the cutting zone.

7. Conclusion

The technical feasibility of active chip form control through the use of an adjustable obstruction-type chip former has been demonstrated. The control requirements for compensation of the effects of varying depth of cut and feed rate have been identified and modeled. Three chip form sensing techniques have been devised and tested in dry cutting. One monitors for chip entanglements, the second discriminates the size of the chip including its continuity, and the third acquires information about the chip shape (which is not essential for the control task in question). Further research is required with regard to sensor fusion, sensor application in flood cooling and the strategy to be incorporated in the control unit.

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