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A new turning system assisted by chip-pulling

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ABSTRACT

This paper presents a new turning system where the guided cut chip during turning is pulled using an external pulling device to attain high-performance cutting. An electro-mechanical pulling device with sensor-less chip tension monitoring function is designed to steadily pull the guided chip and robustly assist the turning operation. The effect of chip tension on the process is modeled and experimentally verified. The developed chip pulling system is utilized to achieve direct real-time control of the cutting process and zero thrust force cutting is demonstrated. Developed system effectively reduces cutting energy for improved tool life and regulates cutting forces for high performance turning.

1. Introduction

Turning is an efficient cutting process where material removal rates up to 10^4–10^5[cm^3/min] can be achieved [1]. The process is typically controlled by a small set of parameters defining the cutting conditions such as the depth of cut, cutting feed and the speed. Those parameters are selected by the process planner where factors such as tool-workpiece pair, cutting forces, vibrations and tool life [2,3] force a compromise to be made between high material removal rate and machining accuracy/stability. In practice, optimal cutting conditions are determined utilizing process models, through experience and finally by trial and error. In an attempt to deliver greater productivity, cutting process may be tuned adaptively using monitoring information from external or, in-machine sensors [4,5]. However, these approaches are based on adjusting the existing cutting conditions and provide only a limited amount of improvement within the known process limits. The challenge is to exceed the limits to improve efficiency and accuracy of conventional turning by introducing new principles.

Recently, assistive techniques are employed to improve productivity and efficiency of turning process. For instance, laser assisted local heating is applied to improve efficiency of hard turning process [6,7]. Vibration assistance has been applied to various processes, such as drilling [8] turning [9] and grinding [10]. Vibration assistance can help improving process efficiency by facilitating coolant penetration, chip evacuation and even friction control [11]. For instance, elliptical vibration cutting (EVC) [10,12,13] process has been introduced as an enhancement to conventional turning for low speed ultra-precision machining. In EVC, the tool is vibrated elliptically in cutting and chip flow directions. As a result, it reduces the friction effect as the chip flows on the rake face, and thus reduces overall cutting effort (Fig. 1).

Inspired by this, it has been proposed that pulling the cut chip along the rake face during turning can reduce friction forces and thereby improve the cutting process [14]. The concept of chip-pulling cutting is presented in Fig. 2. As shown, if the chip flow could be guided in a controlled manner, an electromechanical device can be used to pull it to cancel the friction force on the rake face. So far, chip pulling has not been realized due to lack of suitable chip flow control methods [15]. Recently, authors proposed a chip guiding method to generate straight continuous chip [16,17]. The method utilizes a cutting insert with guide grooves carved on the rake face to suppress the chip curl and guide it towards a pulling system. This technique has the potential to realize the chip pulling turning process.

In this research, the automated chip-pulling turning process is presented, and the mechanics of this new cutting process is investigated. An electro-mechanical device is developed to continuously pull the cut chip and realize automated chip-pulling turning as shown in Fig. 3. The chip pulling force is introduced as an extra parameter to control the cutting process. Here, regulation of the chip pulling force, i.e. control of the applied chip tension, is critical. A sensor-less approach is favoured and a Kalman Filter [18,19] based disturbance observer technique is designed to estimate chip tension. The effect of chip tension on the process is modelled and experimentally verified. Finally, the chip tension is controlled to achieve high performance turning strategies such as "zero thrust force turning" to achieve precision turning of slender shafts.

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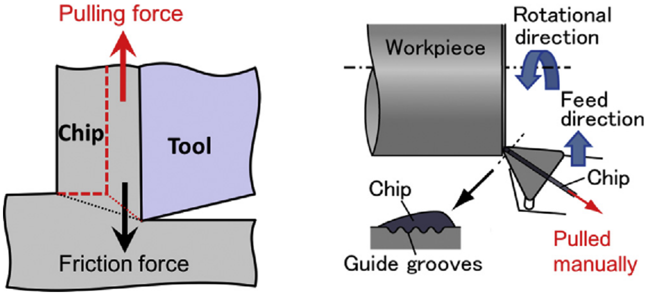

Fig. 1. Friction cancelling (a) and chip pulling turning (b) chip pulling turning concept.

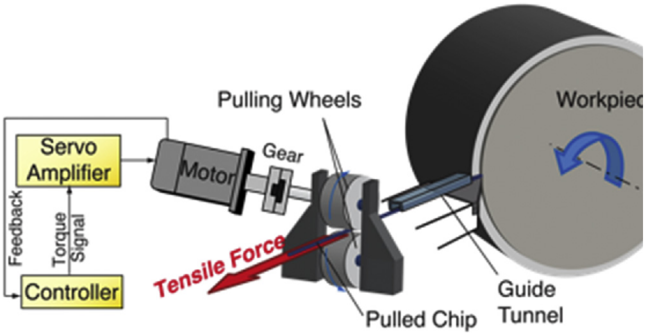

Fig. 2. Automated chip pulling turning process.

2. Development of an electromechanical pulling system for chip pulling turning

2.1. Mechanical design

The automated chip pulling cutting process is presented in Fig. 2. Firstly, a chip guiding system is designed to guide the chip towards the chip-pulling device and realize actual pulling. Fig. 3 shows the chip guiding system [16]. As shown, a tunnel-like structure is utilized to guide the cut chip from the cutting point. Once the cut chip is guided away, it is pulled by a “chip-pulling device” shown in Fig. 4. The pulling device is designed by a pair of rollers driven by servo motor system. Fig. 4(b) depicts the front view and Fig. 4(c) shows top view of the developed pulling device. The working principle of the device is as follows. The chip flows through the tunnel and once it enters in-between the rollers. The friction between the chip and the rollers pull the chip and help apply a tension force. As shown a servo-motor is used to drive the system. The motor torque and speed are controlled by a servo amplifier. The motor torque is transferred to the rollers via a gearbox with a total gear ratio of ½. The rollers are made of hardened steel and their width is 10[mm] with added flanges to restrict the chip escaping from pulling point (See Fig. 4b). In order to be able to smoothly pull the chip through the roller mechanism, the roller speed must be synchronized. This is done mechanically though the designed gearbox. Fig. 4c illustrates the gear-box design. Servo motor drives a master shaft, so-called the “hinge shaft”. Both lower and upper rollers are connected to the shaft with gears (See Fig. 4c). This shaft also serves as a hinge to adjust the gap between rollers. The spacing, i.e. gap, between upper and lower rollers is critical. During pulling, an initial gap between rollers (0.1–0.2[mm]) is set so that guided chip can be taken in easily. As the chip is caught and pulled in by rollers, original chip flow speed is altered. Pulling the chip at a higher speed than its original flow speed reduces the chip thickness. This is simply due to the fact that at a fixed cutting speed, feed and depth, the material removal rate is constant. Therefore, to accommodate continuous chip thickness variation, the gap between rollers must be regulated. This mechanism allows that the upper part of the pulling device, upper roller and associated gears, rotate around the hinge shaft and move the roller slightly up. While doing so, a coil type spring is employed to generate clamping force between the rollers. Clamping force and gap are adjustable where the design can produce up to 314[N] normal force. Considering the steel-to-steel friction coefficient, developed system can generate ~150[N] pulling force at speeds up to 200[m/min].

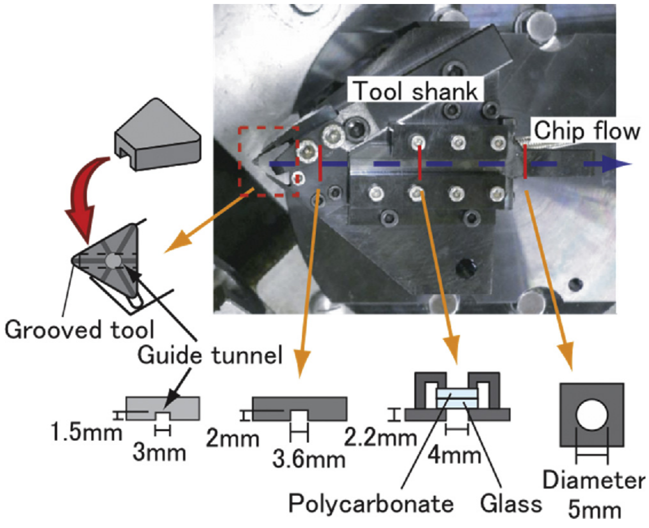

Fig. 3. Chip guiding system.

2.2. Control system

Another challenge is the control of the pulling speed and force. The roller rotation must to be regulated so that the guided chip is pulled gently without breaking it. A straightforward approach is to set the roller speed slightly higher than the original chip flow speed. This would apply a tension on the cut chip. A simple PI (Proportional Integral) speed controller [18] can be used in the servo controller to regulate the roller speed and thereby apply certain chip tension. In order to increase the applied tension, the chip pulling speed, i.e. roller speed, could be increased. Although the relationship is expected to be proportional, it is not necessary linear, and hence the applied pulling force (tension) needs to be monitored so that it does not cause yielding of pulled chip and break it.

The applied tension, in return, generates an equal reaction force on the pulling system. A force sensor or a force dynamometer can be utilized to measure the reaction force. In this work, a sensor-less cost-effective approach is pursued. The reaction force acts as a dynamic disturbance to the speed controller as it tries to resist the roller rotation. This disturbance force can be observed from motor torque and roller speed. A model based Kalman Filter [19] disturbance observer is designed to observe the generated chip tension from noisy roller position measurement and motor torque signal without using an external force sensor. In other words, servo-motor itself is utilized both as an actuator and also a force sensor Fig. 4.

Assuming that the gear mechanism does not have any dominant structural vibration modes, the entire chip pulling system can be modelled considering only the rigid body dynamics. The transfer function between motor torque to roller speed can be written as:

$$v(s) = \frac{1}{J_e s + B_e}[u(s) - F_d(s)],\ x(s) = \frac{1}{s}v(s) \tag{1}$$

where s is the Laplace (s) [18] operator. u[Volts] is torque command to servo drive, v[mm/sec] is the velocity at the pulling point and x[mm] is displacement, i.e. pulled chip length. The control signal equivalent inertia and viscous friction in the puling system are identified as $J_e = 3.13 \times 10^{-4}$[V/(mm/sec^2)] and $B_e = 5.39 \times 10^{-4}$[V/(mm/sec)] trough tests. F_d[V] represents the control signal equivalent lumped