HIGH PERFORMANCE TURNING ASSISTED BY CHIP-PULLING

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INTRODUCTION

Friction is one of the key factors limiting the achievable productivity and efficiency in most machining processes. Typically, adverse effects of friction in machining has been addressed through better tool material design and use of coolants [1,2]. This paper presents an innovative technique to significantly increase the efficiency of turning processes by alleviating friction forces using an assistive device. As opposed to breaking the cut chip using chip breakers, in the proposed technique, the chip is not broken but pulled using a system to realize a new turning process so-called the “chip-pulling turning”. By pulling the cut chip externally, the friction force acting along tool’s rake face could be reduced and even cancelled. This, in return, increases the shear angle and leads to efficient material removal with significantly lower process forces and energy. An electro-mechanical chip-pulling device is designed that can pull the guided chip continuously during the turning operation. Design of the chip-pulling system, proposed pulling device and its automatic control are presented. The effect of chip-pulling is validated experimentally through various cutting experiments. Furthermore, orthogonal cutting force models are used to model the effect of chip-pulling on the process.

CANCELLING FRICTION BY CHIP-PULLING

Figure 1 depicts the basic mechanism to cancel friction forces in orthogonal cutting and chip guidance. As shown in Fig.1a, chip pulling force (tension) is applied on the cut chip as it flows on the rake face of the tool. This tension directly cancels the friction force. As a result, shear angle could be increased, and the chip thickness ratio is improved. Fig.1b presents the manual chip-pulling pulling concept and Fig. 1c shows the changes in cutting forces when the cut chip is pulled manually by hand [3,4]. As shown, during turning of low carbon steel(SPCC), cut chip can be pulled robustly and cutting forces can be lowered greatly. Also notice that, when the chip is pulled the chip thickness reduces validating the change in the chip compression ratio, which confirms the shear angle increase.

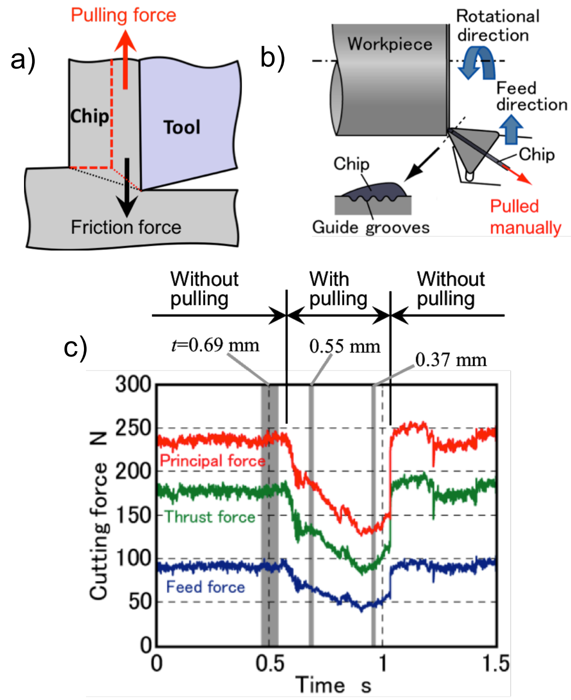

FIGURE 1: Friction cancelling (a) and Chip pulling turning (b) chip pulling turning concept c) Manual chip-pulling results

AUTOMATED CHIP-PULLING SYSTEM

Based on the preliminary results obtained through manual chip pulling. An automated chip pulling turning system is developed. Fig. 2 shows the concept system. As shown, the cut

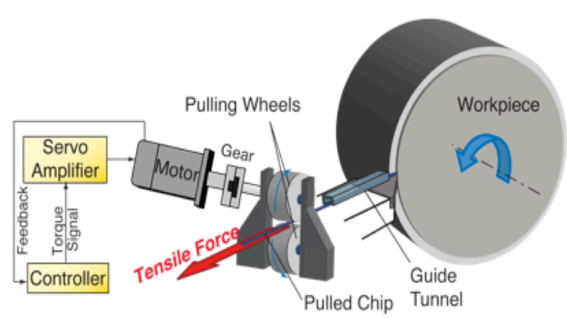

FIGURE 2: Automated chip-pulling turning

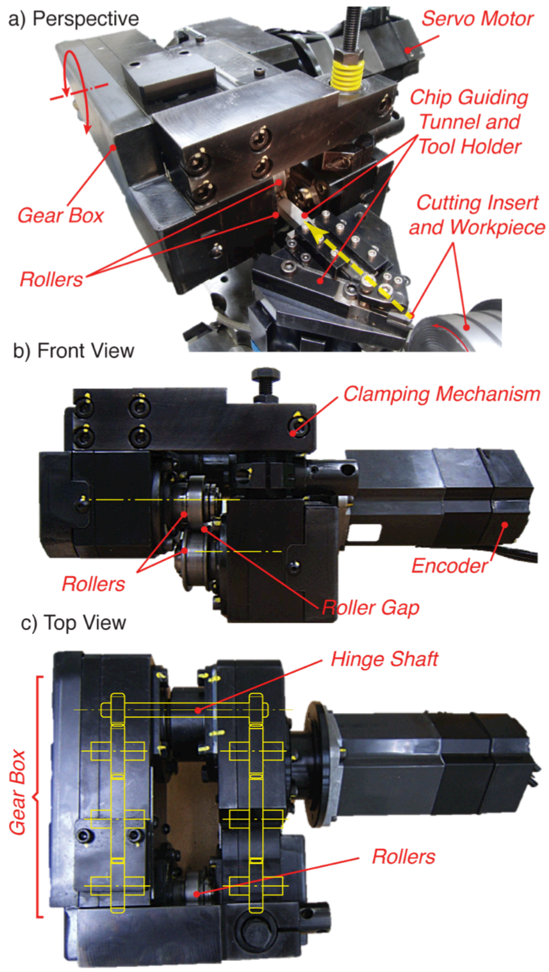

FIGURE 3: Prototyped chip pulling device

chip is guided through a tunnel to a pulling device. The pulling device is designed with a pair of rollers driven by a servo motor. Fig.3 shows the prototyped electromechanical pulling device. The servo motor drives a pair of rollers through a gear box. The pulling speed and force can be controlled by the servo control system [5,6,7]. Tension inserted on the chip is regulated by simply controlling the chip pulling speed, i.e. chip flow velocity. By pulling the chip faster than its original chip flow speed; greater tension is inserted. Overall chip-pulling speed is limited by the maximum tension that the chip can carry.

TURNING ASSISTED BY CHIP-PULLING

The effect of chip pulling in turning process is demonstrated briefly in the previous section. As compared to conventional turning, in chip-pulling turning, process forces can be minimized by applying tension on the cut chip by cancelling the friction forces as experimentally demonstrated in Fig.1. This section models effect of chip pulling on the process based on the orthogonal cutting theory [8,9,10] based on the single thin shear plane model.

Assuming a thin shear plane, a cutting force diagram is drawn for chip pulling cutting in Fig. 4. Firstly, when the chip is pulled, pulling force directly cancels friction force on the rake face by the amount of F_{pull}, which rotates the resultant force direction. Since shear deformation occurs by the resultant force, the shear direction also rotates creating a larger shear angle, ϕ'. The new shear plane has a smaller shear area due to increased chip thickness ratio. Normal and friction forces are reduced to F_n' and *f'* as depicted in Fig. 4. In contrast, friction angle does not change significantly and is assumed to be constant as a property of the material-tool pair [9]. Since chip pulling force cancels friction force, the deducted friction force f'-F_{pull} defines a new friction angle β' and a resultant force vector, *R'*. It should be noted that β' is defined as the 'effective friction angle' associated with the chip pulling cutting process, and it can be manipulated by the pulling force.

Thus, the idea of 'effective friction angle', β', allows incorporation of the pulling force to the well-known orthogonal cutting model and facilitate analysis of the process. Firstly, maximum shear stress or minimum energy principle [8],

$$\phi' = 45^0 + \alpha - \beta' \text{ or } \phi' = 45^0 + \alpha/2 - \beta'/2 \quad (1)$$

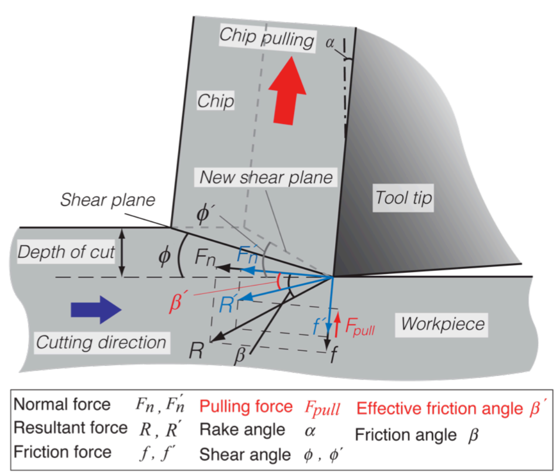

FIGURE 4: Thin shear plane model incorporating chip pulling force effect

can be used to predict the modified shear angle. The resultant force of the new process is calculated from shear strength τ_s and cutting area A as:

$$R' = \frac{\tau_s A}{\sin(\phi')\cos(\phi' - \alpha + \beta')} \tag{2}$$

The relationship between normal and friction forces are obtained from the force diagram (see Fig.4) and Eq. (2):

$$\left.\begin{aligned} F_n' &= R'\cos(\beta') \\ f' &= R'\cos(\beta')\tan(\beta) \end{aligned}\right\} \tag{3}$$

Using above relationships, pulling force to achieve the desired effective friction angle is calculated as:

$$F_{pull} = \frac{\tau_s A}{\sin(\phi')\cos(\phi' - \alpha + \beta')} \times \left[\cos(\beta')\tan(\beta) - \sin(\beta')\right] \tag{4}$$

Eq. (4) defines the required chip tension to control the effective friction angle and thus the

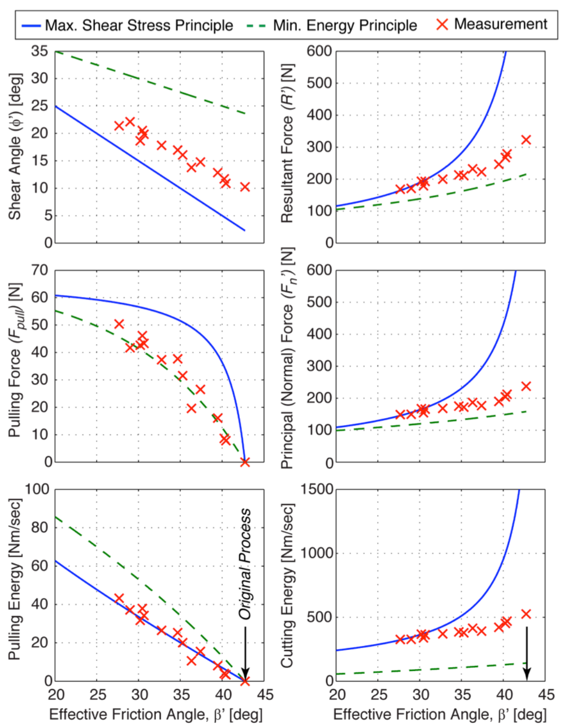

FIGURE 5: Analytical and experimental results. (Workpiece: low-carbon steel (JIS: S10C), Tool: sintered tungsten carbide insert, nose radius of 0.8[mm] and rake angle 0[deg], Feed: 0.12[mm/rev], 215[rpm], Cutting speed: 133 [m/min], Depth of cut: 0.4[mm])

cutting process. The model is evaluated at various pulling conditions where simulated cutting forces, cutting energy and the required pulling effort are compared to actual measurements. Note that, accuracy of max. shear stress and min. energy principle models depend heavily on cutting conditions. Given the zero-rake angle condition and simplicity of the Merchant's model [10] as shown in Fig. 4, both max. shear stress and min. energy principles actually capture the chip-pulling process mechanics well. Both models validate that introducing controlled tension on the chip; process forces could be reduced almost by half without changing any of the actual cutting parameters. It introduces an opportunity to cut in higher material removal rate and efficiency with lower forces. In particular, for certain processes thrust force can be cancelled completely by the pulling force for precision or chatter-free cutting of flexible work-pieces, which is demonstrated in the following section. As the pulling force is increased, friction energy consumed by cutting is reduced. The advantage obtained in reduction of cutting energy is more than 5 times than that of inputted by pulling. This in return reduces overall energy, heat generation and helps to improve tool life.

PRECISION TURNING WITH CHIP PULLING

In conventional turning processes the thrust force component acts in the radial direction and therefore causes deflection errors or chatter vibrations on slender/thin compliant workpieces. If adjusted correctly, the chip pulling force can be used to reduce friction force on rake face to achieve zero thrust force cutting as well. Note that if the pulling force is greater than then friction force, workpiece can even be pulled towards the tool generating negative friction force component. This characteristic is actually similar to the mechanics elliptical vibration cutting process [11].

Here, a preliminary application is considered, and results are demonstrated in Fig. 6. In this experiment compliant soft copper workpiece is machined with a PCD tool. As shown, friction force on the tool is cancelled by the pulling force, which is controlled by the developed chip tension control system. This, in return, allows cancellation of the thrust force component and enables precision finish of slender shafts without deflection and circumventing vibration problems [12,13].

CONCLUSIONS

This paper presented a new turning process that is enhanced by pulling the cut chip. An electromechanical pulling system is designed for automatically pulling the chip. It is shown that develop chip pulling system can pull the chip at different speeds and apply controlled tension to cancel friction forces and thereby improve the process efficiency. The system demonstrated that the friction force could be fully cancelled to achieve precision turning of slender work-pieces. Lastly, the thin shear plane model is utilized to model the mechanics of the chip pulling cutting process. The model captures the fundamental effect of chip pulling reasonably well and provides guidance for planning the process.

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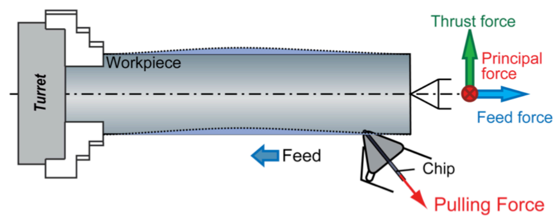
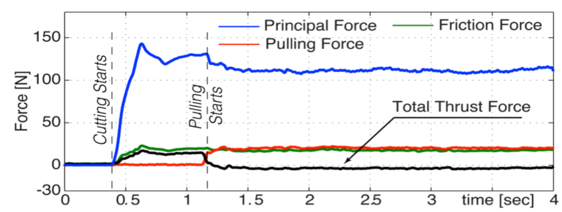


a) Force relations



b) Measured cutting forces

FIGURE 6: Zero thrust force control. (Workpiece: tough pitch copper, Tool: PCD insert with a guide groove, nose radius of 0.8[mm] and rake angle of 0[deg], Feed: 0.12[mm/rev], Rotational speed: 315[rpm], Depth of cut: 0.6[mm], Cutting speed: 65[m/min])