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A novel work holding method for hard turning using the shoe-centerless concept

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ABSTRACT

The widespread use of hard turning processes in industry has been facilitated by efficient work holding methods. In this paper, a novel application of the shoe-centerless work holding method is proposed for hard turning. Since changes in cutting forces during hard turning affect force balance, rotational instability can occur with shoe-centerless work holding. This paper describes the effect of changes in cutting forces due to tool wear on work rotational stability during shoe-centerless hard turning. It also presents guidelines to determine the optimum shoe setup angles for various hard turning process conditions to ensure work rotational stability and geometrical rounding stability.

1. Introduction

Hard turning has emerged as a flexible process for the finish machining of hardened workpieces. The benefits of hard turning – including faster setup times, and the capability to generate the desired form, profile accuracy and required surface integrity – have expanded the field of hard turning applications [1–3]. However, the dimensional, form and profile tolerances for the surfaces finished by hard turning depend on proper selection of the work holding system during hard turning. While the majority of research in hard turning has been focused on the cutting mechanics and the resultant properties of the hard turned surface [1,2], very limited work has been done to develop new work holding methods to improve the productivity and efficiency of the hard turning process.

The common work holding methods for hard turning workpieces include center-type work holding and magnetic chucks. Center-type work holding requires addition of centers; thus, its practical application is limited to solid workpieces—particularly shafts. Magnetic chucks on the other hand, offer flexible work holding with minimum elastic deformation, but their application is limited by the available clamping force, which is dependent on the workpiece's surface contact area.

While both these methods have an advantage in their capacity to finish multiple workpiece surfaces in the same setup, the associated material handling time – especially the workpiece centering time for magnet chucks – is very long. In the high-volume production of precision components, it is crucial to reduce material handling time. Hence, the development of efficient work holding methods is a critical factor in the use of hard turning processes for high-volume production.

Shoe-centerless work holding was developed by Cincinnati Milacron in the 1960s for grinding cylindrical workpieces [4]. Fig. 1 shows a typical shoe-centerless setup used for finishing ring-shaped workpieces. The datum face of the workpiece is in contact with the rotating magnet driver, and the workpiece is supported on its outside diameter by shoes at defined angles along the circumference. When a workpiece is freely placed, the offset distance between the center of rotation of the workpiece and the magnet driver forces the workpiece against the shoes. This self-centering system does not require precise positioning of the work piece and allows very short loading and unloading times. As a result, shoe-centerless work holding is commonly used in high-volume grinding processes in the bearing and automotive industries. This type of work holding method is similar in concept to the centerless grinding process.

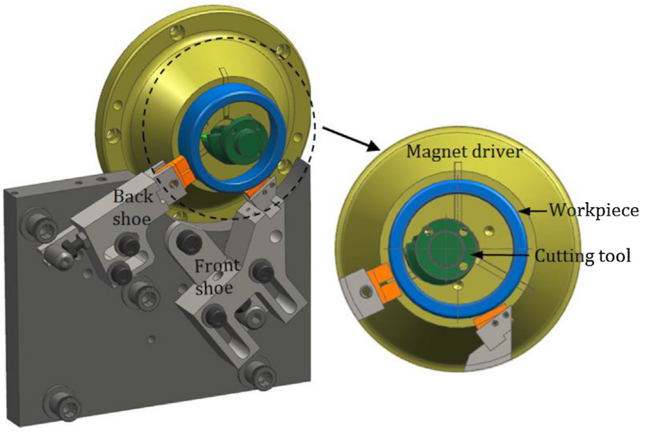

Fig. 1. Shoe-centerless setup.

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The factors affecting work rotational stability during centerless grinding have been studied in detail [5–8]. However, the application of the shoe-centerless work holding concept for single point cutting processes is new, and also challenging due to the significant changes in cutting forces that occur during useful tool life [1,2,9]. In this paper, the authors propose an application of the shoe-centerless work holding method for hard turning the internal diameter of ring-shaped workpieces, and provide guidelines for determining the optimum shoe setup angles for ensuring work rotational stability.

2. Mechanics of the shoe-centerless method

Fig. 2 shows a free body diagram of a workpiece supported on the external diameter in a shoe-centerless setup. The workpiece, with an internal radius of r_1 and external radius of r_2, is supported by two shoes along the circumference at angles θ_1 and θ_2 respectively. The center of rotation of the workpiece and the magnet driver are offset by distances δx and δy, resulting in a drive force F_d, that forces the workpiece against the shoes. The magnitude of the offset distance is usually very small, just enough to allow the workpiece to freely move into the shoes.

During hard turning, normal and tangential forces F_n and F_t act on the workpiece at the cutting point at an angle α. The force ratio γ is defined as the ratio of normal to tangential force. F_f and F_b are the normal forces acting on the workpiece at the interface with the front and back shoes, respectively, and μ is the coefficient of friction between the workpiece and the shoes.

Wear-resistant material such as carbide is often used for the shoes. The surfaces in contact with the workpiece are flat or ground at the same radius as the workpiece diameter. In addition, coolant is commonly used to prevent any burnishing marks from the rubbing of the shoes against the workpiece surface. These factors result in a smaller coefficient of friction between the shoes and the workpiece.

During idling conditions when there is no cutting, a rotating magnet driver facilitates workpiece rotation while in contact with the shoes.

Under equilibrium conditions, the sum of horizontal and vertical forces is equal to zero:

$$-F_d\cos\beta - F_n\cos\alpha + F_t\sin\alpha + F_b\cos\theta_1 + \mu F_b\sin\theta_1 + F_f\cos\theta_2 + \mu F_f\sin\theta_2 = 0 \tag{1}$$

$$-F_d\sin\beta - F_n\sin\alpha - F_t\cos\alpha + F_b\sin\theta_1 - \mu F_b\cos\theta_1 + F_f\sin\theta_2 - \mu F_f\cos\theta_2 - W = 0 \tag{2}$$

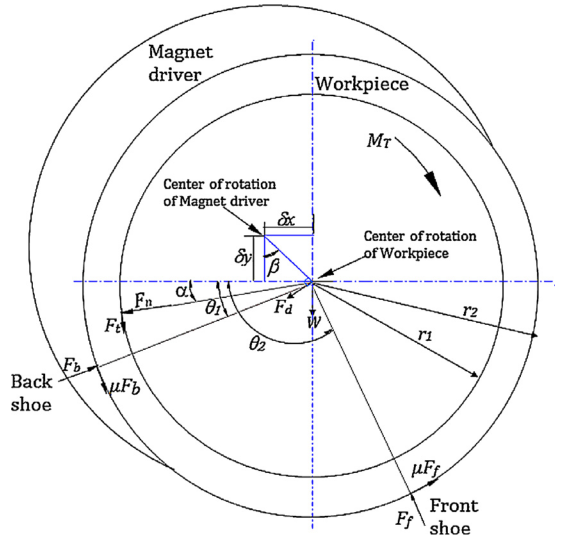

Fig. 2. Free body diagram of the workpiece.

Also under equilibrium conditions, the sum of torques is equal to zero:

$$M_T - r_1F_t - r_2\mu(F_b + F_f) = 0 \tag{3}$$

During hard turning, unstable rotation due to force imbalance may result in the workpiece losing contact with the shoes. In addition, the torque imbalance may result in the stoppage of the workpiece rotation. So, to maintain work rotational stability, the force and torque balance as defined by Eqs. (1) through (3) must be satisfied under all cutting conditions. For this purpose, it is necessary to define the range of optimum values of shoe angles θ_1 and θ_2.

Solving Eqs. (1) and (2), the normal forces F_b and F_f acting on the back and front shoes can respectively be obtained as:

$$F_f = a_1\,F_d + b_1\,F_n \tag{4}$$

$$F_b = a_2\,F_d + b_2F_n \tag{5}$$

where

$$a1 = \left[\frac{\sin(\theta_1-\beta) - \mu\cos(\theta_1-\beta)}{(1+\mu^2)(\sin\theta_1-\theta_2)}\right] \tag{6}$$

$$b_1 = \left[\frac{\sin(\theta_1-\alpha) + \frac{\mu}{\gamma}\sin(\theta_1+\alpha) - \left(\mu+\frac{1}{\gamma}\right)\cos(\theta_1-\alpha)}{(1+\mu^2)\sin(\theta_1-\theta_2)}\right] \tag{7}$$

$$a_2 = \left[\frac{\sin(\theta_2-\beta) - \mu\cos(\theta_2-\beta)}{(1+\mu^2)(\sin\theta_2-\theta_1)}\right] \tag{8}$$

$$b_2 = \left[\frac{\left(1-\frac{\mu}{\gamma}\right)\sin(\theta_2-\alpha) - \left(\mu+\frac{1}{\gamma}\right)\cos(\theta_2-\alpha)}{(1+\mu^2)\sin(\theta_2-\theta_1)}\right] \tag{9}$$

Substituting Eqs. (4) and (5) in Eq. (3), the driving torque can be obtained as:

$$M_T = c_1F_d + c_2F_n \tag{10}$$

where

$$c_1 = r_2\mu(a_1 + a_2) \tag{11}$$

$$c_2 = r_2\mu(b_1 + b_2) + r_1/\gamma \tag{12}$$

During idling rotation as well as during cutting, the workpiece must be supported by the shoes; therefore, the front and back shoe forces must maintain a certain magnitude. Also, the driving torque must be sufficient to provide workpiece rotation. These conditions are satisfied when:

$$F_b > 0; F_f > 0 \tag{13}$$

$$M_T > c_1F_d + c_2F_n \tag{14}$$

During idle rotation of the workpiece, the range of shoe angles that satisfy Eq. (13) is

$$\theta_1 < \beta + \tan^{-1}\mu \tag{15}$$

$$\text{with} \quad \begin{array}{l} \theta_2 > \beta + \tan^{-1}\mu \\ (\theta_2 - \theta_1) > 0 \end{array} \tag{16}$$

As discussed previously, the offset distances between the magnet driver and the workpiece are very small (less than 0.5 mm), resulting in a smaller driving force F_d. During hard turning, the cutting forces are much larger compared to the driving force F_d and the work weight W. Hence, their influence on Eq. (13) can be neglected. The range of shoe angles to satisfy Eq. (13) during hard turning can be considered as given by:

$$\theta_1 < \tan^{-1}\left[\frac{\left(\frac{\mu}{\gamma}-1\right)\sin\alpha - \left(\mu+\frac{1}{\gamma}\right)\cos\alpha}{\left(\mu+\frac{1}{\gamma}\right)\sin\alpha - \left(1+\frac{\mu}{\gamma}\right)\cos\alpha}\right] \tag{17}$$

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