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Design of hybrid steel/composite circular plate cutting tool structures

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Abstract

Substituting composite structures for conventional metallic structures has many advantages because composite materials have both high specific stiffness and damping characteristics compared to conventional metallic materials. In this study, circular plate cutting tools which are used for rough machining of bearing sites in crankshafts or camshafts were designed with the fiber reinforced composite material to reduce tool mass and to improve the dynamic stiffness of circular plate cutting tools. The hybrid steel/composite circular plate cutting tool was analyzed by finite element method with respect to material types such as composite and foam, stacking angles of the composite, adhesive bonding thickness, and dimensions of the cutting tool. Also, the constrained damping characteristics of the tools were experimentally investigated with respect to the adhesive bonding thickness and material type such as composite and PVC foam. From the finite element analysis and experimental results, optimal design parameters for the hybrid steel/composite circular plate cutting tool were suggested.

Keywords: Hybrid steel/composite circular plate cutting tool; Fiber reinforced composite; Mass reduction; Damping characteristics; Dynamic stiffness

1. Introduction

Rough machining of bearing mounting sites in crankshafts or camshafts are generally performed by circular plate cutting tools such as turn–turn broaching tools and external milling tools. These machine tools require both high static stiffness and high damping capability for the high dynamic stiffness of cutting tools which is required for machining stability. During machining workpieces either by rotating circular plate cutting tools or by rotating workpieces with fixed circular plate cutting tools, self-excited vibrations which are frequently called as chatters occur when a surface defect produced during one revolution of the workpiece can generate a new defect one revolution later [1]. The chatter, which is the vibration of cutting tool relative to the workpiece, not only makes the surface accuracy of products worse, but also increases tool wear and deteriorates the machine tool. The chatter occurs at or near the natural frequencies of a vibrating part, and is caused by the instability in the cutting process itself. Since the number of natural frequencies of a machine tool is infinite due to its continuous structural nature, chatter occurs near one of these frequencies, usually near the several lower frequencies. Therefore, the dynamic stiffness which is proportional to the damping capability and static stiffness of the machine tool is important factor for machining stability without chattering [2].

Nowadays, CNC machining centers with an automatic tool changer have been widely used, which requires the reduction of cutting tool mass due to the limitation of driving force of automatic tool changers or the difficulty of handling tools by operators. Since the diameter and thickness of conventional turn–turn broaching tools and external milling tools are about 700 mm and 60 mm, respectively, the mass of these tools if they are made of steel is usually larger than 100 kg, which is too heavy for manual operation during replacing of tool tips or fixing operation. Furthermore, the spindle for the circular plate cutting tool such as the external milling cutter is mounted on the

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machine tool as cantilevered shape, which increases load on the machine tool spindle as shown in Fig. 1. Therefore, the reduction of cutting tool mass has much benefit.

The two functional design requirements of the conventional steel circular plate cutting tool are to reduce the mass of the tool and improve dynamic stiffness of the cutting tool. In this work, in order to reduce the mass of circular plate cutting tool without sacrificing its stiffness and to increase damping capability, fiber reinforced polymer composite materials were chosen because fiber reinforced polymer composite materials have high specific stiffness and high damping capability. Fiber reinforced polymer composites have high damping because they are composed of high damping polymer resin and high stiffness fiber, compared to conventional metal materials such as aluminum and steel [3]. Several researchers have developed machine tools using fiber reinforced composites for improving dynamic characteristics of tools. Lee et al. developed composite boring bars used for machining and enlarging holes [4], in which they investigated the dynamic characteristics of composite boring bars with respect to adhesive thickness, core material, and steel cover thickness. Lee et al. developed also the slides of high speed CNC milling machines with sandwich structures composed with carbon epoxy composite face and honeycomb core material for reduction of mass and damping improvement [5].

Many researchers have used the damping treatment of structures to improve the dynamic stiffness of structures. Rao formulated a theory for the prediction of damping and natural frequencies of laminated composite beams with multiple viscoelastic damping layers [6]. Vuure et al. modeled the damping of multilayered sandwich beam by calculating the distribution of strain energies [7]. Although many researchers have investigated applications of fiber reinforced composite materials to various parts of rotating structures such as composite automotive driveshaft, high speed spindles, rollers, etc. [8–10], the attempts to apply composite materials to the circular plate cutting tools are rare.

Therefore, in this study, rotating circular plate cutting tools which are used for rough machining of bearing sites in crankshafts or camshafts were designed using a hybrid type structure composed of steel, composite, and foam core materials to reduce the mass and to improve the dynamic stiffness of the cutting tool. The performances of the hybrid circular plate cutting tool were estimated with finite element analysis with respect to material types such as composite and PVC foam, adhesive bonding thickness, steel cover thickness and dimensions of the hybrid steel/composite circular plate cutting tool. Also, the damping characteristics of the box type cutting tool specimen were investigated with respect to adhesive bonding thickness and material type. From the finite element analysis and experimental results, optimal design parameters for the hybrid circular plate cutting tool were suggested for high performances of the cutting tools.

2. Design of the hybrid steel/composite circular plate cutting tool

Fig. 2 shows a conventional circular plate metallic cutting tool that consists of main shaft joining part, body, and cartridges at which many tool tips are mounted. The main shaft joining part joins the body to the machine tool spindle. The body and cartridges are joined by bolts, and tool tips are mounted on the cartridges. Since the total deflection of cutting tool by cutting force is important for the cutting accuracy, the deflection of the conventional circular plate cutting tool during machining operation by the applied force was estimated by finite element analysis. The cutting force component F_θ in the circumferential direction of the cutting tool is expressed in terms of specific cutting force K_s, depth of cut a, and feed rate f_r as follows [1]:

$$F_\theta = K_s a f_r \tag{1}$$

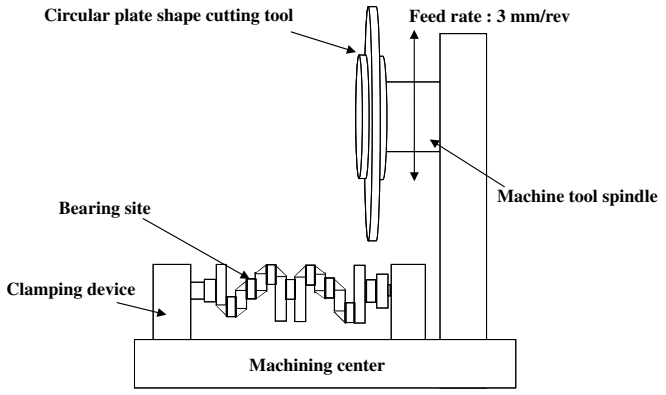

Fig. 1. Configuration of the machining process for the bearing sites of a crankshaft by the circular plate cutting tool.

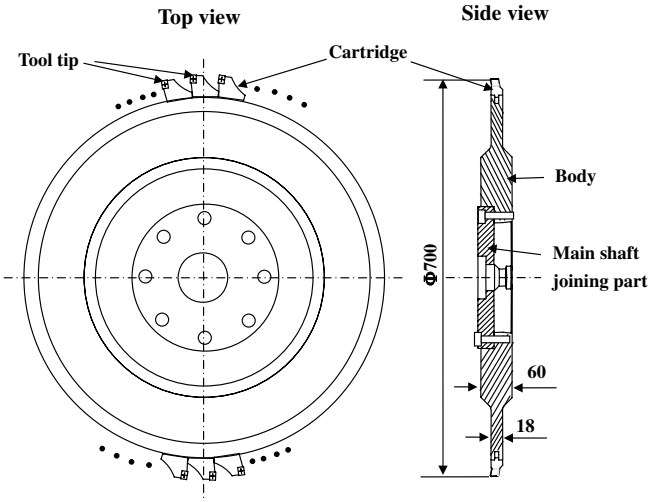

Fig. 2. Schematic drawing of a conventional steel circular plate cutting tool.