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Study on tool wear mechanisms in milling laser sintered material †

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Abstract

This paper investigates tool wear mechanisms of a ball end mill in cutting laser sintered material. Cutting edge temperature is measured by using a three-color pyrometer with an optical fiber. Bulk carbon steel JIS S55C is selected as the standard steel. Experimental results show that tool life in cutting sintered material is shorter than that in cutting JIS S55C. Observations by SEM show that adhesion of the work material and micro chipping are the main wear mechanisms in cutting sintered material. The corresponding cutting edge temperature shows a continuous increase as wear evolves with cutting time.

Keywords: Ball end mill; Cutting edge temperature; Tool wear; Laser metal sintering

1. Introduction

A milling-combined laser sintering system (MLSS), which is a rapid tooling machine that combines laser assisted metal sintering and high speed end mill, has made a complicated injection mold that allows the creation of a deep rib. With MLSS, the dimensional accuracy is improved and a cooling channel can be easily created: for instance, spiral holes along the mold profile, which is difficult in the conventional machining process [1]. Therefore, it is important to study cutting characteristics of sintered materials, if we want to take advantage of MLSS as a new invention in making complicated injection molds in a shorter time. Yassin et al. [2] investigated the machinability of a sintered material. The results showed that the machinability of the sintered material is lower compared with JIS S55C. In this paper, tool life and tool wear mechanisms are investigated. It is crucial to investigate tool life when cutting sintered materials because tool wear could greatly influence the dimensional accuracy and surface finish. Besides that, the flank wear and the corresponding cutting edge temperature were measured.

2. Milling-combined Laser Sintering System (MLSS)

In MLSS, the apparatus for laser sintering consists of a continuous wave Yb:Fiber laser ($\lambda = 1.07$ μm) with a maximum output power of 200 W, laser spot diameter of 94 μm and maximum laser scanning speed of 1000 mm/s. The apparatus for high speed milling consists of a spindle with maximum rotational speed of 50000 rpm and maximum feed speed 1000 mm/min.

Two alternating processes occur in MLSS: forming a layer profile by laser sintering and surface finishing by high speed milling. Fig. 1 illustrates the concept of the MLSS. The process of MLSS can be summarized as follows. A 3-D model is designed using CAD and is divided into sliced layers whose thickness is 50 μm. Then, this model is transferred to the MLSS. Prior to the laser sintering process, a sandblasted steel base plate is placed on the building platform. Next, a predetermined layer thickness of 50 μm of loose metallic powder is spread on the base plate using a recoating blade. Successively, the laser beam is irradiated to the surface of a layer of loose metallic powder, and this will produce a layer-wise profile according to the CAD data of the sliced layer, see Fig. 1(a). After forming a few layers of sintered material, the milling process is executed at the periphery surface as shown in Fig. 1(b). The sintering and milling at the periphery surface are repeated, whereas the top surface is not cut after all layers are sintered. The laser sintering and cutting processes are performed in a nitrogen atmosphere at room temperature to prevent oxidization.

3. Sintered material

Table 1 gives the properties of the metallic powder used to sinter a sintered part. The metallic powder mixture consists of

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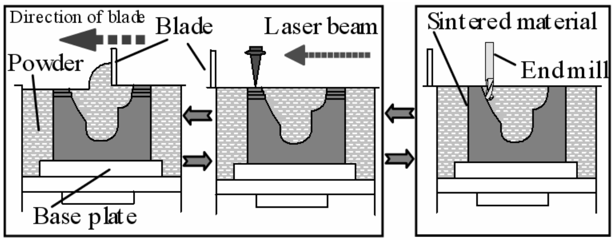
Table 1. Properties of metallic powder.

Material		SCM	Ni	Cu
Particle diameter	μm	30	30	30
Powder density	kg/m^3	4690	4040	4690
Specific heat	J/g.K	0.45	0.49	0.38
Thermal conductivity	W/m.K	0.13	0.17	0.17

Table 2. Experimental conditions.

Tool material	Coated cemented carbide
Diameter	2.0 mm
Cutting speed	V :250 m/min
Feed per tooth	f : 0.025 mm/tooth
Axial depth of cut	Ad: 0.1 mm
Radial depth of cut	Rd: 0.4 mm
Cutting method (Down cut without cutting fluid)	Peripheral milling



(a) (b)

Fig. 1. Concept of milling-combined laser sintering system(MLSS) (a) forming layers and (b) high speed milling.

70 wt.% SCM, 20 wt.% Ni and 10 wt.% Cu. The work material was made by the MLSS without executing the milling process and is denoted as $E_{\rho 9}$ in this paper.

To investigate the influence of powder consolidation mechanisms, two conditions are defined: outer surface, $E_{\rho 9}$ (y=0) and inner surface, $E_{\rho 9}$ (y=1). The outer surface is a surface in which the unmolten and partially molten powder remained on the surface while inner surface is a surface in which the metallic powder melted completely. The hardness and density of the $E_{\rho 9}$ material are 275 HV(0.3), and 7680 kg/m^3, respectively [2].

4. Experimental procedures

The experiments were carried out using an air spindle unit machine. Table 2 gives the cutting parameters for tool wear measurement. Maximum flank wear width was measured by a micrometer-equipped microscope. This was plotted against cutting time and cutting was stopped when the flank wear reached a value of 200 μm. Worn out tools were further examined with a scanning electron microscope (SEM).

Cutting edge temperature was measured by using a three-color pyrometer with an optical fiber, and it has a flat response to about 500 kHz. This pyrometer has enough response speed to measure cutting edge temperature of the tool, which is rotating at high revolution speed [3]. The experimental arrangement is indicated in Fig. 2(a) and the detail of temperature measurement condition is shown in Fig. 2(b). The distance between optical fiber and cutting edge was set at t=0.2 mm. The infrared rays radiated from the cutting edge are caught by a chalcogenide optical fiber and lead to a three-color detector. These signals are converted into electric signals and stored in the digital memory. The three-color detector consists of InAs, InSb and MCT detectors which are mounted in a sandwich configuration. By taking the ratio of output voltage from InAs/InSb and InSb/MCT, the temperature can be obtained. The angle α indicates the angle in a horizontal plane and β indicates the angle in a vertical plane as shown in Fig. 2. The point where the cutting edge has just finished cutting is indicated by α = 0. The vertical angle β and horizontal angle α of the optical fiber were set at β =0 and α=180^o respectively.

5. Experimental results and discussion

5.1 Tool life

Fig. 3 shows the comparison of tool life among $E\rho_9$ (y=0), $E\rho_9$ (y=1) and JIS S55C. It was observed that non uniform wear, micro chipping and adhesion were found to dominate in cutting $E_{\rho 9}$ material; see Fig. 4. In cutting JIS S55C, uniform flank wear, which was observed at the initial stage, tends to be suppressed as cutting progresses. The shortest tool life was obtained in cutting $E\rho_9$ (y=0) and the longest one was obtained in cutting JIS S55C. This is probably due to the difference of cutting temperature for each work material. Many research studies found that cutting temperature has the greatest influence on tool wear [4]. Yassin et al. [2] found that cutting edge temperature in milling sintered material is higher compared with JIS S55C. This is due to the smaller thermal conductivity of $E\rho_9$ (10 W/mK)[1] as compared to JIS S55C (53 W/mK) [5]. The cutting edge temperature in cutting $E\rho_9$ (y=0) is higher than that with $E\rho_9$(y=1) due to the existence of partially molten powder on the outer surface of the sintered material [2].

5.2 Progress of the maximum flank wear width and cutting edge temperature

During the cutting process, the flank wear and the corresponding cutting edge temperature were measured. Fig. 5 shows the progress of the maximum flank wear width and cutting edge temperature during the tool life in cutting $E_{\rho 9}$ (y=0). At the initial cutting stage, the Vb_{max} increased at a slower rate and showed a similar trend to the corresponding temperature curve as shown in Fig. 5. Adhesion of the $E\rho_9$ work material was found onto the flank face throughout the cutting length, demonstrating a strong bond at the work material-tool interface. The formations of the adhered $E\rho_9$ material onto the flank face were probably due to the high temperature at the cutting zone. A similar conclusion is reported in [6]. Due to the dynamics of the milling process, the layers of adhered work material were cyclically removed and replaced. The strong bonding strength between tool materials and the adhered layers causes the hard particles of the tool material to

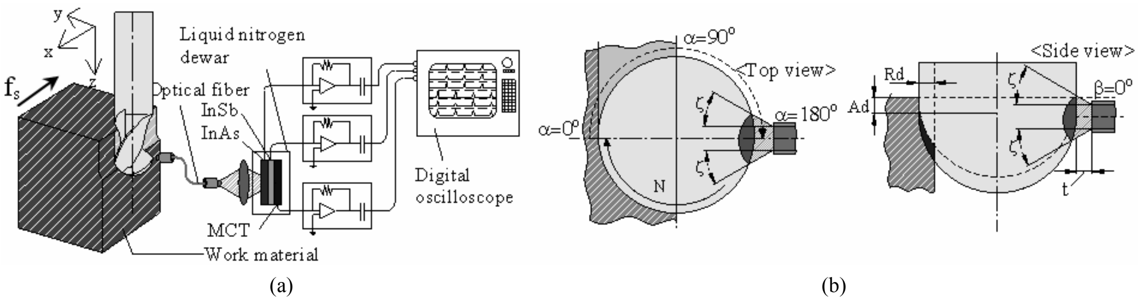


Fig. 2. (a) Schematic illustration of the experimental arrangement and (b) arrangement of optical fiber.

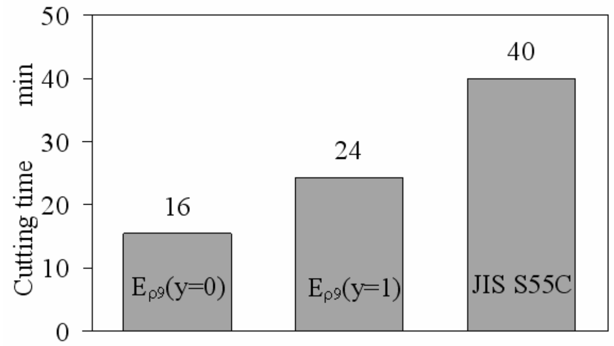


Fig. 3. Tool life for different work materials.

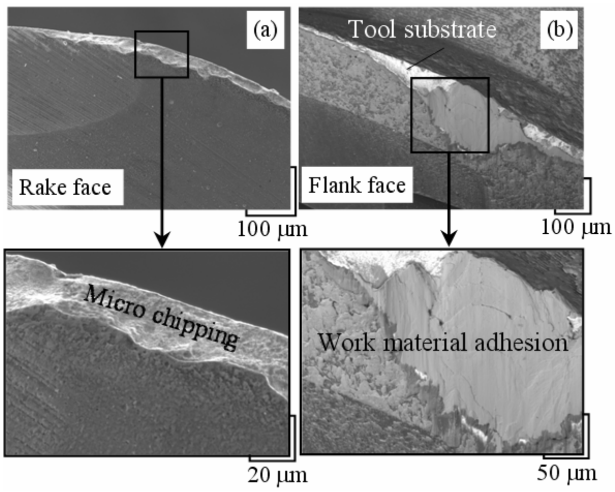


Fig. 4. SEM of the rake face and flank face of the tool in cutting $E_{\rho 9}(y=1)$ at cutting time (a) 13min and (b) 24min.

be carried away from the tool; hence a severe abrasive action and micro chipping occur. In addition, the formation of partially molten powder on the outer surface of the sintered material intensifies the wear. Partially molten powder is superior to fully molten powder in showing greater hardness [2]. When a cutting edge cuts the partially molten powder, the temperature increases drastically which results in higher thermal stresses. This accelerates the micro chipping and Vb_{max} increased drastically as shown in Fig. 5. This tendency is compatible with the corresponding temperature curve as depicted in Fig. 5.

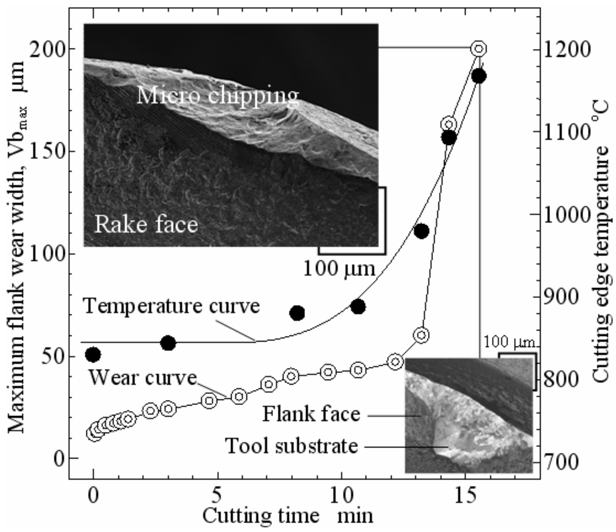


Fig. 5. Progress of the maximum flank wear width, Vb_{max} and cutting edge temperature with cutting time.

6. Conclusions

Experiments are carried out to investigate the tool wear mechanism and cutting edge temperature progression in cutting laser sintered material at a high cutting speed. The results show that non-uniform wear, chipping and adhesion are the dominant wear mechanisms of the tool in cutting laser sintered material. As for JIS S55C, uniform flank wear is observed at the initial stage and this uniform flank wear tends to disappear as cutting progresses. Tool life in cutting sintered material is lower than that in cutting JIS S55C. The formation of the adhered work material onto the flank face in cutting $E\rho_9$ material results in chipping of the cutting edges and also accelerates the flank wear. The formation of partially molten powder on the outer surface increases the temperature and this accelerates the wear rate. The wear of cutting tools has a substantial effect on cutting edge temperature. It shows that as wear evolves with cutting time, the corresponding cutting edge temperature shows a continuous increase because of larger contact surfaces between the work material and the cutting tool.

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