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Research on the Chip Formation Mechanism during the high-speed milling of hardened steel

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ABSTRACT

An easy-to-produce sawtooth chip is the main feature of the high-speed milling process for hardened steel. This chip may lead to a high-frequency periodic fluctuation of the cutting force and accelerate the tool's wear rate. This study investigated the process of chip formation and the change in chip morphology during the high-speed milling of hardened steel (51, 62 HRC). The formation condition of continuous and sawtooth chips and various characteristics of the sawtooth chip, such as cutting speed, feed rate, axial depth of cut, and others, were also studied. The results showed that the chip of materials with different hardnesses could be controlled as a continuous chip through the optimisation of a combination of cutting speed, feed per tooth, and cutting depth. If the feed per tooth and axial depth of the cut were too large within the range of proper cutting speeds generated by a continuous chip, the chip morphology turned into a sawtooth. Increasing the cutting speed during the cutting process not only strengthened the material's hardness but also increased the local temperature of the shear band rapidly and aggravated the material's heat softness. When these parameters became balanced, the shear deformation became highly localised in the shear band and resulted in adiabatic shear. A quantitative evaluation of the sawtooth-shaped chip's deformation degree was performed using the cross-sectional area and angle of the sawtooth chip. By establishing a geometric model of the sawtooth chip formation during the high-speed milling of hardened steel, that was used to predict the shear strain and strain rate during chip formation, the range of shear angles generating a sawtooth chip was calculated to be 40–60°.

1. Introduction

High-speed milling has the advantages of high machining precision, low surface roughness, drastically shortening machining time and being capable of machining hardened steel directly, all of which have brought about a revolution in the manufacturing of moulds, cars, aviation, and more [1–5]. Due to the high hardness and poor machining capability of the hardened steels used for dies and moulds, the cutting force and power increase when high-speed milling these materials, the cutting temperature rises, tools wear quickly and the formation of a sawtooth chip gives rise to the periodic cycle transformation of the cutting force and high-frequency vibrations, which affect tool life spans and lead to premature tool failure [6].

High-speed milling has a complex, dynamic cutting process. A common understanding of the sawtooth chip's formation mechanism has not yet been agreed upon, but can be summarised as two main theoretical systems: sudden thermoplastic shear theory and adiabatic shear theory. Komanduri et al. [7] have proposed the sudden instability mechanism of sawtooth chips and its two-stage model based on the material's thermoplastic instability. After leading experiments on the high-speed turning of hardened bearing steel using a CBN coated tool, Davis [8,9] has proposed a sawtooth chip formation mechanism during right-angle free cutting to explain Komanduri's adiabatic shear theory. Shaw and Vyas [10,11] have investigated the sawtooth chip formation mechanism under deep axial depths and put forward a cycling brittle fracture theory model, verified by a cutting experiment performed during the high-speed milling of hardened steel (AISI 8620, equivalent to 20CrNiMoA, 61 HRC) with PCBN tools. They have considered the reason for sawtooth chip formation during this process to be the fracture generated on the free surface of the work piece, which continues to expand along the shear face to become a cycle of full brittle fracture. The microcrack area shows shear instability only after the full brittle fracture area is generated. The effect of the shear instability on the flow stress and material thermostability has been proposed by Poulachon [12,13] based on a similar shear instability criterion theory presented by Recht et al. for sawtooth chip formation during the high-

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Nomenclature

a_e	radial depth of cut (mm)
a_p	axial cut depth (mm)
b_{ch}	chip width (mm)
b_D	cut width (mm)
f_z	feed per tooth (mm/Z)
D	tool diameter (mm)
F	total cutting force (N)
F_{max}	maximum cutting force (N)
F_x	cutting force in the feed direction (N)
F_y	cutting force in the normal direction (N)
F_z	cutting force in the axial direction (N)
h_{ch}	equivalent chip thickness (mm)
h_D	cut thickness (mm)
h_1	chip thickness at local shear deformation (mm)
H	maximum thickness of sawtooth chip (mm)
L	tool overhang length (mm)
n	spindle rotate speed (r/min)
P_c	distance of sawtooth chip segmentation (mm)
v	cutting speed (m/min)
V_{ch}	sawtooth chip speed (m/min)
Z	number of tool teeth
β	helix angle (deg)
γ_o	rake angle (deg)
γ	shear strain
$\dot{\gamma}$	shear strain rate
δ	sawtooth chip shear band width (μm)
ξ	chip thickness deformation coefficient
ξ'	chip width deformation coefficient
Φ	shear angle (deg)
Φ_1	sawtooth chip angle (deg)
Δ	sawtooth chip area (mm^2)
K	sawtooth chip correction coefficient

speed milling of hardened steel. Hu [14] has investigated the chip formation mechanism created when high-speed milling hardened steel (AISI H13, equivalent to 4Cr5MoWSiV, 55 HRC) with a TiAlN-coated ball-end mill and found that the surface quality is determined by an appropriate cutting parameter created through the observation of the chip by SEM. During the high-speed milling of BS817M40 with a carbide tool, Barry et al. [15] have found that the periodic release of strain energy is the main source of acoustic emissions during the process of sawtooth formation. Research on the milling of AISI H13 hardened steel using a Φ 12.7 mm PCBN ball-end mill executed by Elbestawi [16] has showed that the chip colour is yellow when the hardness of the work piece is 45 HRC and turns to deep blue when the hardness is 55 HRC. No sawtooth chip is generated at a spindle speed of 10,000 rpm because the fracture on the free surface of the work piece ends due to the softening of the metal. A sawtooth chip is generated when the spindle speed is 6000 rpm, and the fine part of the chip is melted into a globular mass under high temperatures. Elberstawi [17] has used the fracture mechanics theory to study the sawtooth chip of hardened steel and proposed that the chip's free face is similar to a brittle material. Crack initiation and propagation toward the cutting edge occur under certain a cutting condition and eventually become a sawtooth chip. Liu Zhanqiang et al. [18] have investigated various characteristics of the chips resulting from cutting speed varying from 30 m/min to 7000 m/min during the process of cutting AerMet100. Becze [19] has studied the change in the chip when cutting AISI D2 by constructing a miscut mechanical model. Dolinsek et al. [20] have studied the segmentation frequency, figuration and size of the chips and the size of the deformation area and non-deformation area, the optical micrographs, SEM observation and microhardness measurements have been used to explain the different chip formations, but they have not explained in detail the effects of process parameters on the transition from continuous chips to sawtooth chips from micro-observation, microhardness, chips shape, chips thickness, etc. in high-speed milling, and deformation mechanism of sawtooth chip formation has not been interpreted further. During the cutting of AISI H13L with a PVD TiAlCrN/NbN-coated tool, Ning et al. [21] have found that the formation mechanism of a sawtooth chip results from a combination of fracture theory and thermal isolation shear theory, and the process of chip formation experiences strain hardening, thermal softening and finally a chilling phenomenon. Yuan Ning [22] has investigated the high-speed milling of AISI H13 hardened steel with a ball-end mill and found that a proper chip can be achieved by changing the tool figurations and cutting conditions. This study has also found that the classic thermal isolation shear phenomenon is absent from the process of high-speed milling with a ball-end mill.

Although several achievements and conclusions have been made in the field of high-speed milling of hardened steel, they were not thorough enough in the areas of chip formation, chip morphology, and the formation conditions and micro-characters of sawtooth chips during the milling process. Because the chip formation mechanism is so complicated, previous studies of the chip deformation have used tools containing different materials to cut steels of varying hardnesses, simulated the process of high-speed milling of hardened steel with finite element technology, and studied the cutting forces, chips, cutting temperatures, etc. by using modified Johnson–Cook constitutive equations. However, in terms of the morphology, properties and formation models of these chips, it has been necessary to do further research on the formation mechanism of sawtooth chips to increase the efficiency and improve the quality, reduce the tool wear, and monitor the process during the cutting of hardened steel.

With these aspects of chip formation in mind, this investigation studied the chip formation process and change in chip morphology, analysed the conditions for the generation of sawtooth chips and their micro-characters, built a sawtooth chip formation geometry model under high-speed milling conditions, and calculated the deformation degree of the cutting thickness and width.

2. Material and methods

The experiment was performed on a DMU 60T High Speed Machining Centre (spindle motor power of 15 kW, with a maximum spindle speed of 24,000 rpm, travel distances of the operating platform in the X, Y and Z directions of 780 mm, 560 mm and 560 mm, respectively, and maximum feed rate of 26 m/min). Down milling and dry cutting was performed. Fig. 1 is a schematic of the high-speed milling experiments.

The research objects in this experiment were SKD11 cold-worked mould steel with a high carbon content ($\geq 1\%$) and S136 plastic mould steel with a low carbon content ($\leq 0.3\%$). The chemistry constituents and hardness of the mould steel are listed in Table 1.

The solid carbide flat-bottom sharp corner mill cutting tools with a TiSiN coating used in the experiments were TH Nano Coating Series products of HITACHI. Their coating hardness is 3600 HV and oxidation temperature approximately 1100 °C, they