Experimental research on high-speed dry milling performance of large-area nodular cast iron

P Yan¹,², Y B Wang¹, K J Chen¹, B X Ma¹, Y L Xiao¹ and X B Wang¹
¹Key Laboratory of Fundamental Science for Advanced Machining, School of Mechanical Engineering, Beijing Institute of Technology, Beijing 100081, PR China
E-mail: pyan@bit.edu.cn

Abstract. Nodular cast iron was with excellent casting performance, abrasion resistance, strength, and toughness, and successfully applied in large components with high requirements of complex load, strength, etc. While high-efficiency precision machining of large-size plane nodular cast iron was difficult in actual production. In this study, the influence of cutting parameters on cutting performance in the precision milling of large size nodular cast iron was systematically investigated. The spindle peak-power ratio increased linearly as the increase of cutting speed and cutting depth, while it was the lowest at a feed rate of 0.10 mm on account of the minimum cutting depth effect. The surface roughness Rₐ was decreased linearly as the increase of cutting speed, while the change trend of Rₐ was not significant as feed rate and cutting depth. As the cutting speed increased, the flaky chips shortened and the helical chip crimped intensity; as the increase of feed rate or longitudinal cutting depth, the length of the foil or ribbon chips increased and the crimp of the helical chip increased. The results could be the guide of the actual machining process of nodular cast iron engine box and cover to improve the machining efficiency and surface quality.

1. Introduction
Nodular cast iron (or ductile iron) was a kind of high-strength cast iron material which developed in the mid-20th century [1]. Through spherical and inoculation treatment, the lamellar graphite in ordinary cast iron was transformed into spherical, and the stress concentration caused by lamellar graphite was also reduced. So, the impact toughness and shear strength of nodular cast iron could be enhanced effectively [2], compared with ordinary cast iron. Benefited from its good casting performance, abrasion resistance [3] and excellent strength and toughness [4], ductile iron had been successfully applied in the components with high requirements of complex load, strength, toughness and abrasion resistance, such as engine box, crankshaft, camshaft, etc.

In the large-size plane milling process (the size could be over 1000 mm) of diesel engine box and cover, high surface quality, machining efficiency and tool life were all required [5]. While, as the high hardness & strength, high cutting temperature and low thermal conductivity during the machining process of nodular cast iron [6], the machined efficiency was low, with serious wear of cutting tool [7-10] and unstable machined surface quality [11, 12]. The high-efficiency precision dry machining of large-size plane nodular cast iron was one of the major problems in actual production [13-16].

In order to improve the efficiency and quality of the precision milling of large-size engine box and cover parts which were nodular cast iron, the influence of cutting parameters on surface roughness and chip morphology were systematically investigated in this study. The results of this study could be the guide of the actual machining process of nodular cast iron engine box and cover to improve the
machining efficiency and surface quality.

2. Experimental procedures

The ductile iron material selected in this research was QT400-15, which was a ferrite ductile iron with tensile strength ≥400 MPa, elongation ≥15%, and yield strength ≥250 MPa. The main the chemical composition of QT400-15 were shown in table 1. The strength and toughness were both high, and it was universally used as diesel engine box. The specimen size applied in this study was about 800×600×180 mm.

Table 1. The main chemical composition of QT400-15.

| Element (wt%) | C  | Si  | Mn  | S  | P  | Ni |
|---------------|----|-----|-----|----|----|----|
| Content (wt%) | 3.6~3.9 | 2.5~2.9 | ≤0.5 | ≤0.08 | 0.03 | 0.04~0.06 |

The end milling experiments were taken on a vertical five-axis machining center DMU 80 mono BLOCK with a full length in width cutting without cutting fluid. The cutter head selected was S-60-160Q40-09HX (Sandvik) with diameter 160 mm and 8 inserts, and the cutting length was 600 mm. The inserts were HNEF 09 05 04-KL (Sandvik Coromant), with rake angle γ 0.5°, clearance angle α 7.5°, edge radius γ 0.4 mm. In order to ensure the uniformity of cutting depth of each insert during the machining process, the inserts were adjusted several times on a tool auto-checking instrument (Zoller) and the axial height difference of each insert was ≤8 μm. The main cutting parameters were shown in table 2. Based on the pre-test, the basic cutting parameters selected were: v=360 m/min, a_p=0.10 mm, f_z=0.10 mm. The machined surface roughness Ra was measured by Landtek SRT-6200 at nine positions symmetrically distributed on the machined surface and the average was taken.

Table 2. The cutting parameters adopted in the research.

| No. | Cutting speed v (m/min) | Feed rate per tooth f_z (mm) | Cutting depth a_p (mm) |
|-----|-------------------------|-------------------------------|------------------------|
| 1   | 180                     | 0.10                          | 0.10                   |
| 2   | 240                     | 0.10                          | 0.10                   |
| 3   | 300                     | 0.10                          | 0.10                   |
| 4   | 360                     | 0.10                          | 0.10                   |
| 5   | 420                     | 0.10                          | 0.10                   |
| 6   | 500                     | 0.10                          | 0.10                   |
| 7   | 360                     | 0.05                          | 0.10                   |
| 8   | 360                     | 0.15                          | 0.10                   |
| 9   | 360                     | 0.20                          | 0.10                   |
| 10  | 360                     | 0.10                          | 0.05                   |
| 11  | 360                     | 0.10                          | 0.15                   |
| 12  | 360                     | 0.10                          | 0.20                   |

3. Results and discussion

3.1. Spindle peak-power ratio

During the full-length milling process of this large-size cutter head, as the number of cutting edges and the length of cutting contact zone was very large at the same time, the cutting forces and spindle power were enormous. As the size of the sample and cutter head applied in the experiments were both oversize, the conventional multi-component dynamometer like Kistler 9257B or Kistler 9123C was not applicable in this research. So during the milling process, the spindle peak-power ratio was obtained and recorded directly from the numerical control system of DMU 80, which could reflect the cutting force and torque during the cutting process. Due to the well lubricating properties of graphite, the cutting force during the cutting process was relatively stable.
The recurring spindle peak-power ratio was selected as the peak-power ratio during the milling process, and the change trend indexed with the milling parameters was indicated in figure 1. The spindle peak-power ratio mainly increased linearly as the increase of cutting speed and cutting depth. The spindle peak-power ratio at a feed rate of 0.10 mm was the lowest. That was mainly because that for the face milling, the feed rate determined the actual depth of cut. When the feed rate per tooth was too small (0.05 mm), the real cutting depth may be lower than the minimum cutting depth, the plowing effect and plastic flow of the material caused the higher cutting force and cutting torque. When the feed rate per tooth was larger than 0.1 mm, the increase of real cutting depth resulted in the increase of cutting torque.

Figure 1. The variation of spindle peak-power ratio indexed with milling parameters.

3.2. Surface roughness $R_a$

The machined surface roughness $R_a$ at different cutting parameters were shown in figure 2. It indicated that machined surface roughness $R_a$ was decreased linearly as the increase of cutting speed, while the change trend of $R_a$ was not significant as the change of feed rate and cutting depth, which confirmed the general principle of metal cutting. Consequently, for the end milling process of ductile iron material, the increase in cutting speed was helpful for the lower surface roughness.
3.3. Chip formation

According to the time-varying characteristics of the real cutting depth during end milling process, the chip forms were very complex. Commonly there were often multi chip forms existed simultaneously under the same cutting parameter. In this research, the main chip forms were selected and investigated under each cutting process.

Figure 3 shows the typical chip forms at different cutting speed. It indicated that when the cutting speed was 240 m/min and below, the chip form was mainly foiled, with some debris. When the cutting speed was over 300 m/min, the helical chip formed, and the crimp levels of the helical chip increased as the cutting speed increased, with the length of foil chip decreased. If the cutting speed was higher than 420 m/min, the chip forms were severe crimp with regular short foils. Optical micrographs of the chip indicated that as the increase of cutting speed, the color of the chip changed from silver to gold, then dark. That was mainly because that as the cutting speed increased, the deformation rates of chip increased. Meanwhile, high cutting temperature at high speed resulted in the oxidation or burns, which represented as the color changed from silver to golden or even dark. Generally, as the cutting speed increased from 180 to 500 m/min, the flaky chips shortened and the helical chip crimped intensity.
Figure 3. Optical micrographs of the chip varied as cutting speed ($a_p=0.10$ mm, $f_z=0.10$ mm).

Figure 4 illustrates the typical chip forms at different feed rate. It shows that when the feed rate $f_z$ was lower than 0.05 mm, the chip form was mainly debris. When the feed rate $f_z$ was over 0.10 mm, the chip form was mainly foil and helical. As the increase of feed rate, the length of the foil or ribbon chips increased, and the crimp of the helical chip increased. During the end milling process, the real cutting depth was determined by the feed rate. The radial depth of cut increased when the feed rate increased, the stability of ribbon chips and the normal force on the rake face increased; then the friction force on the tool-chip interface increased, which could increase the crimp of the helical chip.

Figure 5 indicated the typical chip forms at different longitudinal cutting depth. It showed that when the longitudinal cutting depth was low, the chip form was mainly ribbon. When the longitudinal cutting depth was over 0.10 mm, the chip form was mainly foil and helical. As the increase of longitudinal cutting depth, the length of the foil or ribbon chips decreased, and the crimp of the helical chip increased. In the end milling process, the cutting width increased as the longitudinal cutting depth increased, and the friction force on the tool-chip interface increased, which could increase the crimp of the helical chip.
As there was some amount of spherical graphite in the nodular cast iron, a lot of dust may be produced during its machining process especially in dry cutting, which would contaminate the cutting fluid, the machine tool lubrication system or the working condition. The formation of debris or shot foil chips would aggravate the pollution. So the control of chip form was very important. According to the observation and analysis of chip forms mentioned above, it was concluded that the ribbon or helical chips were preferred during the milling of nodular cast iron.

Figure 4. Optical micrographs of the chip varied as feed rate ($v=360$ m/min, $a_p=0.10$ mm).
4. Conclusions
Focused on highly efficient precision milling of large size nodular cast iron, the influence of cutting parameters on cutting forces, surface roughness and chip morphology were systematically experimental investigated under dry milling. The main conclusions are as follows:

- The spindle peak-power ratio increased linearly as the increase of cutting speed and cutting depth, while it was the lowest (about 24%) at a feed rate of 0.10 mm on account of the minimum cutting depth effect.
- The surface roughness $Ra$ was decreased linearly from 1.34 to 0.524 $\mu$m as the increase of cutting speed, while the change trend of $Ra$ was not significant as the change of feed rate and

Figure 5. Optical micrographs of chips varied as longitudinal cutting depth ($v=360$ m/min, $f_z=0.10$ mm).
cutting depth. The increase in cutting speed was helpful for the lower surface roughness.

- As the cutting speed increased, the flaky chips shortened and the helical chip crimped intensity; as the increase of feed rate or longitudinal cutting depth, the length of the foil or ribbon chips increased and the crimp of the helical chip increased.

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