Analysis and Optimization of Milling Process for Crankshaft Pin Based on Energy Consumption

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Abstract. A power acquisition & monitoring platform is set up based on RS485 bus, with all the power data of CKM200 milling machine tool during the crankshaft pin processing is collected and monitored in real time. The crankshaft inner milling process is analyzed from the perspective of energy consumption. Under the premise of not changing the process parameters, the crankshaft inner milling process optimization is carried out, the unnecessary movement is removed or optimized. As a result, the corresponding subsystem consumption is reduced, and the goal of reducing the total energy consumption of CKM200 crankshaft inner milling machine is achieved. It provides a reference for realizing green manufacturing.

Introduction

CNC machine tools are widely used in the machining process of the automotive industry, with enormous total amount of energy consumption. Therefore, research on energy characteristics and energy consumption in CNC machining is of great importance. In this paper, a power acquisition and monitoring platform is built, collecting the input power data of the two spindle motors and whole machine tools of the CKM200 crankshaft inner miller during its machining processing of the crankshaft pin, and the inner milling processing is analyzed from the perspective of energy consumption. These analysis and optimization may help to realize green manufacturing.

CKM200 Crankshaft Pin Milling Processing Analysis

The structure diagram of CKM200 crankshaft inner milling machine (hereinafter referred to as CKM200) is shown in Figure 1. In the experiment, the inner milling process of the four-cylinder engine ZD30 crankshaft blank pin was taken as the research object. During milling, the crankshaft is mounted on the machine tool with the journals at both ends. Two high-power spindle motors of CKM200 each drive an inner milling cutter as the main motion. With the support of the center frame, the large-diameter inner milling cutter simultaneously rotates and revolves to complete the enveloping cutting of the pin. The two cutter heads synchronously cut in and out twice to complete the 4-cylinder crankshaft pin inner milling. During the first cut, the cutter 1 processes #4 pin, the cutter 2 processes #2 pin; At the second cut, the cutter 1 processes #3 pin, the cutter 2 processes #1 pin [1,2]. The schematic diagram of the crankshaft of the four-cylinder engine ZD30 is shown in Fig. 2.
The original process and procedure for inner milling of cutter head 1 are shown in Figure 3.

| NC1 Program (Cutter Head 1 Inner milling program) | Processing Route | Time |
|--------------------------------------------------|------------------|------|
| N10 M03;                                         | ① Spindle (cutter) start | $t_{s1}$ |
| N15 M68;                                         | Workpiece clamping | $t_{s1}$ |
| N20 M101;                                        | Synchronization | $t_{s1}$ |
| N30 #164=216.22+#2104;                          | ② #4 Pin axial (Z-axis) positioning | $t_{c1}$ |
| N40 G90 G94 G01 Z#164 F 2000;                    | Center frame Closure | $t_{c1}$ |
| N50 M58;                                         | Synchronization | $t_{c1}$ |
| N60 M102;                                        | ③ #4 Pin Milling | $t_{c1}$ |
| N70 G102 R105 Q29 S51 A101.5 B6 E19.5 I1680 J225 K2000 C270 D4④ | Synchronization | $t_{c1}$ |
| N75 M103;                                        | Center frame Open | $t_{c1}$ |
| N80 M59;                                         | Synchronization | $t_{c1}$ |
| N90 M104;                                        | ④ #3 Pin axial (Z-axis) positioning | $t_{c2}$ |
| N100 #163=322.72+#2103;                         | Center frame Closure | $t_{c2}$ |
| N110 G90 G94 G01 Z#163 F 2000;                   | Synchronization | $t_{c2}$ |
| N120 M58;                                        | ⑤ #3 Pin Milling | $t_{c2}$ |
| N130 M105;                                       | Synchronization | $t_{c2}$ |
| N140 G102 R105 Q29 S51 A101.5 B6 E19.5 I1680 J225 K2000 C90 D3⑥ | Synchronization | $t_{c2}$ |
| N145 M106;                                       | Center frame Open | $t_{c2}$ |
| N150 M59;                                        | Workpiece Count | $t_{c2}$ |
| N152 M22;                                        | Process Completed | $t_{c2}$ |
| N155 M21;                                        | Synchronization | $t_{c2}$ |
| N160 M107;                                       | ⑥ Z axis back to reference point | $t_{c2}$ |
| N170 G91 G28 Z0;                                 | Synchronization | $t_{c2}$ |
| N180 M108;                                       | ⑦ Workpiece loosen and Spindle stopped | $t_{c2}$ |
| N190 M69;                                        | End of program | $t_{c2}$ |
| N200 M30;                                        | Stand-by Period | $t_{s2}$ |

Figure 1. Schematic diagram of CKM200 crankshaft inner milling machine.

Figure 2. Schematic diagram of the four-cylinder engine ZD30 crankshaft.

Figure 3. Original process and procedure for inner milling of cutter head 1.
CKM200 Inner Milling Processing Power Data Acquisition and Power Curve Analysis

The crankshaft CNC machine tool power acquisition & monitoring platform uses the three-phase electric parameter collector to obtain the digital signal, and RS485 bus communication method to transmit the data to the King view host computer and store it in the SQL Server database in real time.

The three-phase electric parameter collector adopts WB6830R2-P electronic energy collecting module. The electric current transformers are installed on the three-phase inlet lines of CNC machine tool and the two spindle motor inlet lines, and are connected to the input ends of the power collection modules. The output of the power collection module is connected with the data-server PC by means of RS485 ~ USB conversion module. The structure and hardware connection of the power acquisition and monitoring platform of the crankshaft CNC machine tool are shown in Figure 4.

The input power data of the machine tool and the two spindle motors during the inner milling process of the four-cylinder engine ZD30 crankshaft blank pin are collected, and arbitrarily intercepted data of one machining cycle. Using professional data graphics & analysis software OriginPro 8, data were analyzed to obtain CKM200 crankshaft processing power curve as Figure 5. According to the different characteristics, the power curve is divided into the spindle start-up period, the spindle idle period, the milling period and the standby period. The energy consumption calculated for one processing cycle is as shown in Equation 1.

\[ E = \int_{0}^{T} P \, dt = 1538030 \, J \]  

(1)

Figure 5. CKM200 crankshaft pin machining input power curve.
Optimization of Processing Technology Based on Energy Consumption

The original processing program has been applied to actual production for many years, and the processing parameters selection is reasonable, which can ensure the high quality and high efficiency of the production, so it remains unchanged.

Under the premise that processing parameters $a_p$, $f_i$, $a_x$, $D$, $n$, $N$ and $v_c$ are kept constant and workpiece material and cutting conditions remains unchanged, then the following can be obtained.

1. The duration of the spindle start-up period, the spindle idle period, the milling period and the standby period remain unchanged, i.e., the durations of the seven processing stages Phase ①, Phase ②, Phase ③, Phase ④, Phase ⑤, Phase ⑥, Phase ⑦, seven stages of processing are invariant.

2. When the spindle is unloaded and milling power is 0, main drive system input power $P_{M10}$, $P_{M20}$ is equal to main drive system no-load loss $p_{01}$, $p_{02}$, feed drive system input power $P_{F0}$ which equals the no-load power $p_{0F}$ of the feed drive system, and auxiliary system power $P_{AUX}$ are all constant losses [3].

3. During milling, main drive system input power $P_{M1}$ and $P_{M2}$ remains constant; feed drive system input power $P_F$ and auxiliary system power $P_{AUX}$ are unchanged as well.

4. Spindle start-up period (Phase ①) machine input power remains constant as Eq. 2.

$$P_{1st} = P_{M10} + P_{AUX}.$$  \hfill (2)

5. Spindle no-load period (Phase②, ④, ⑥) machine input power remains constant as Eq. 3.

$$P_{10} = P_{M10} + P_{M20} + P_{F0} + P_{AUX} = p_{01} + p_{02} + p_{0F} + P_{AUX}.$$  \hfill (3)

6. Milling time (Phase ③, Phase ⑤) machine input power is shown in Equation 4.

$$P_{1C} = P_{M1} + P_{M2} + P_F + P_{AUX} = [p_{01} + (1 + \alpha_1)P_{C1} + \alpha_2P_{C1}^2] + [p_{02} + (1 + \alpha_3)P_{C2} + \alpha_4P_{C2}^2] + P_F + P_{AUX}.$$  \hfill (4)

7. Standby time (Phase ⑦) machine input power $P_{IS}$ is equal to $P_{AUX}$.

8. Total energy consumption of CKM200 per unit processing cycle is the sum of all spindle start-up period energy consumption, spindle no-load period energy consumption, milling period energy consumption and standby period energy consumption. Similarly, the total energy consumption of the CKM200 for the unit processing cycle is also the sum of the energy consumption of the seven processing stages of Phase ①, Phase②, Phase ③, Phase ④, Phase ⑤, Phase ⑥, Phase ⑦.

Every movement or function realized during the process is necessarily accompanied by the energy transfer, conversion and consumption of the corresponding subsystem. The energy consumed by the corresponding subsystem does not change without changing the process parameters.

Based on the above, therefore, the following should be done.

1. Carefully analyze each stage of the CKM200 pin milling process, and distinguish the movement or function and non-essential movements that must be realized at this stage according to the processing requirements.

2. Whether it is necessary or not, the processing must be accompanied by the energy transfer, conversion and consumption of the corresponding subsystem. The safety of the production and the quality of the product are used as the criterion to evaluate the non-essential movements. If the movement is not necessary, it is optimized or removed in the processing program to reduce the consumption of the corresponding subsystem. Only by reducing the power loss in the machining stage can the goal of reducing the total energy consumption of CKM200 be achieved.

Table 1 is a breakdown table of the inner milling machining cycle of CKM200.
Table 1. CKM200 crankshaft inner milling machine tool pin milling process cycle breakdown table.

| stage  | Necessary movement (function) | Non-essential movement | Necessary energy consumption Subsystem | Non-essential energy consumption Subsystem | operation hours | Optimized power loss before | Optimized power loss |
|--------|------------------------------|------------------------|----------------------------------------|-------------------------------------------|----------------|-----------------------------|---------------------|
| ①     | Spindle start                | auxiliary system       | Main drive system                      |                                           |                | \( t_{st} \) \( P_{Mst} + P_{AUX} \) | \( P_{AUX} \)     |
| ②     | Workpiece clamping, Synchronization, #4/#2 pin axial positioning, Center frame closure, Synchronizatopm, #4/#2 pin X/Y axis interpolation cut | Spindle rotation | Feed drive system, auxiliary system | Main drive system |                | \( t_{01} - t_{st} \) \( P_{M10} + P_{M20} + P_{F0} + P_{AUX} \) | \( P_{F0} + P_{AUX} \) |
| ③     | #4/#2 Pin full circle milling | Main drive system, Feed drive system, auxiliary system |                                           |                | \( t_{c1} - t_{01} \) \( P_{M1} + P_{M2} + P_{F} + P_{AUX} \) | \( P_{M1} + P_{M2} + P_{F} + P_{AUX} \) |
| ④     | Synchronization, Center frame open, Synchronization, #3/#1 pin axial positioning, Center frame closure, Synchronizatopm, #3/#1 pin X/Y axis interpolation cut | Spindle rotation | Feed drive system, auxiliary system | Main drive system |                | \( t_{02} - t_{c1} \) \( P_{M10} + P_{M20} + P_{F0} + P_{AUX} \) | \( P_{M10} + P_{M20} + P_{F0} + P_{AUX} \) |
| ⑤     | #3/#1 Pin milling            | Main drive system, Feed drive system, auxiliary system |                                           |                | \( t_{c2} - t_{02} \) \( P_{M1} + P_{M2} + P_{F} + P_{AUX} \) | \( P_{M1} + P_{M2} + P_{F} + P_{AUX} \) |
| ⑥     | Synchronization, Center frame open, Workpiece count, Processing completed, Synchronization, Z- axis reference point, Synchronization | Spindle rotation | Feed drive system, auxiliary system | Main drive system |                | \( t_{03} - t_{c2} \) \( P_{M10} + P_{M20} + P_{F0} + P_{AUX} \) | \( P_{F0} + P_{AUX} \) |
| ⑦     | Loosen the workpiece, Spindle stop | auxiliary system       |                                           |                | \( t_{S} - t_{03} \) \( P_{AUX} \) | \( P_{AUX} \)     |

Phase ②, Phase ④ and ⑥ are the spindle idle time. During this period, the spindle motor speed is stable, the inner milling cutter tip has not been cut into the workpiece, and only the infeed, retraction or axial positioning is performed. Its main energy consumption is the no-load energy consumption of
the main drive system, the no-load energy consumption of the feed drive system and the auxiliary system energy consumption. The machine input power at this time can be indicated as Equation 5.

\[ P_{10} = P_{M10} + P_{M20} + P_{F0} + P_{AUX} = p_{01} + p_{02} + p_{0F} + P_{AUX}. \] (5)

In Phase ② the miller mainly completes the function of the axial positioning before the full-round milling of the #4/#2 pin; In Phase ④ the machine mainly performs the axial positioning function before the full-round milling of the #3/#1 pin; At Phase ⑥ the miller mainly performs the Z3 axis back to the reference point movement after the #3/#1 pin full circle milling finished. Therefore, the non-essential motion of phases ②, ④ and ⑥ is the spindle rotation, and the corresponding non-essential energy-consuming subsystem is the main drive system, and the unnecessary loss is \( P_{M10} + P_{M20} \).

Process is optimized in Phases ② and ⑥, delaying the spindle start-up time to the end of phase ②, which is after axial positioning of the pin #4/#2 and before #3/#1 pin X/Y axis empty cutting interpolation; the spindle stop time is advanced to the beginning of phase ⑥, after the center frame is opened. The no-load loss of the main drive system in phases ② and ⑥ is greatly weakened, and such that the goal of reducing CKM200 total energy consumption can be achieved. Considering that phase ④ is between two milling stages, it is not advisable to start and stop the spindle frequently in a short period of time, so phase ④ is not optimized and remains unchanged.

The process and procedure of the inner milling processing optimization of the cutter head 1 are shown in Table 2. Figure 6 shows the input power curve after the optimization of the CKM200 pin machining process.

Table 2. Process and program for optimization of internal milling of cutter head 1.

| NC1 program (cutter 1 inner milling processing program) | Processing route |
|--------------------------------------------------------|------------------|
| N10 M68;                                               | Workpiece clamping |
| N20 M101;                                              | Synchronization  |
| N30 #164=-216.22+#2104;                                |                  |
| N40 G90 G94 G01 Z#164 F2000;                           | ①#4 pin axial (Z axis) positioning |
| N50 M03;                                               | ②Spindle (cutter head) start |
| N60 M58;                                               | Center frame closure |
| N70 M102;                                              | Synchronization  |
| N80 G102 R105 Q29 S51 A101.5 B6 E19.5 I680 J225 K2000 C270 D4; | ③#4 pin milling |
| N90 M103;                                              | Synchronization  |
| N100 M59;                                              | Center frame open |
| N110 M104;                                             | Synchronization  |
| N120 #163=-322.72+#2103;                               |                  |
| N130 G90 G94 G01 Z#163 F2000;                          | ④#3 pin axial (Z axis) positioning |
| N140 M58;                                              | Center frame closure |
| N150 M105;                                             | Synchronization  |
| N160 G102 R105 Q29 S51 A101.5 B6 E19.5 I680 J225 K2000 C90 D3; | ⑤#3 pin milling |
| N170 M106;                                             | Synchronization  |
| N180 M59;                                              | Center frame open |
| N190 M05;                                              | Spindle stop      |
| N200 M22;                                              | Workpiece count   |
| N210 M21;                                              | Processing completed |
| N220 M107;                                             | Synchronization  |
| N230 G91 G28 Z0;                                       | ⑥Z- axis back to reference point |
| N240 M108;                                             | Synchronization  |
| N250 M69;                                              | ⑦Workpiece loosening |
| N260 M30;                                              | End of program    |

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At this time, the energy consumption of one processing cycle is as shown in Equation 6.

\[ E_0 = \int_0^T P \, dt = 1363990 \, J. \]  

The reduction rate of energy consumption in one processing cycle is as shown in Equation 7.

\[ \frac{E - E_0}{E} \times 100\% = \frac{1538030 - 1363990}{1538030} \times 100\% = 11.32\%. \]  

Summary

1. The crankshaft pin milling process is analyzed from the perspective of energy consumption.

2. Under the premise of not changing the process parameters, the crankshaft inner milling process optimization is carried out, the unnecessary movement is removed or optimized. As a result, the corresponding subsystem consumption is reduced, and the goal of reducing the total energy consumption of CKM200 crankshaft inner milling machine is achieved.

3. The power acquisition platform was built to optimize the inner milling process of the four-cylinder engine ZD30 crankshaft blank pin. The input power data of the machine tool and the two spindle motors were collected and compared by the professional drawing & data analysis software OriginPro 8.

4. The experiment data shows that the system energy consumption is significantly reduced after the process optimization, which is useful for exploring the ways of energy saving and consumption reduction of CNC machine tools and realizing green manufacturing.

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