US NSF-CHINA NSF WORKSHOP ON SUSTAINABLE MANUFACTURING

Energy Efficiency of Machining Systems

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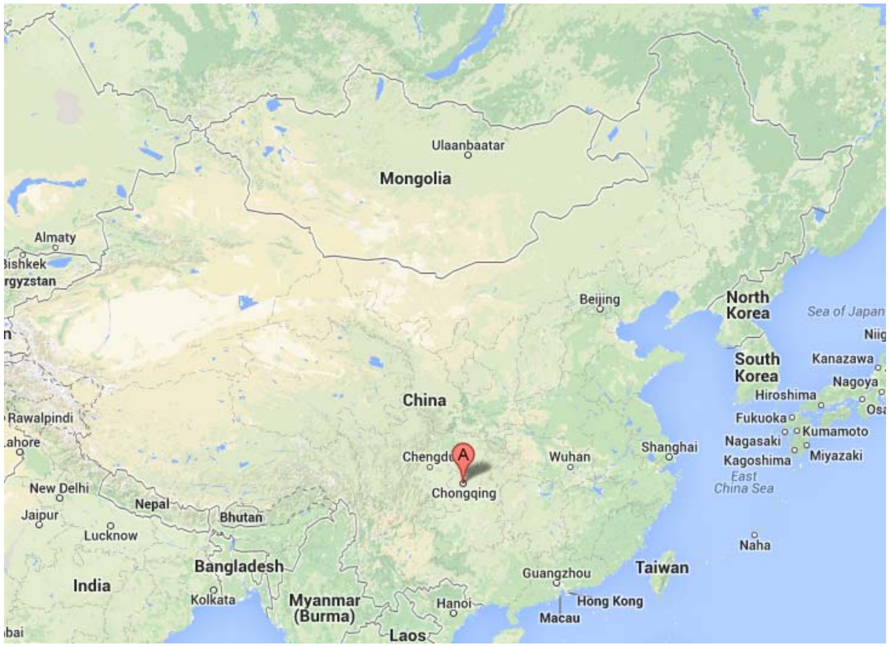
1. Introduction to IME, CQU
2. Energy Usage in Machining Systems
3. Energy Efficiency Improving Strategies
4. Energy Consumption Prediction Models
5. Conclusions and Suggestions

1 About IME of Chongqing University

Chongqing (Chungking) is located in south west of China, one of four major cities directly controlled by the central government.

Chongqing university (CQU) founded in 1929, and now is one of top ten Chinese universities in mechanical engineering subject area.



1 About IME of Chongqing University

Institute of Manufacturing Engineering(IME) was formed in 1993 initiated by the Prof. LIU Fei, the former president of Chongqing university. IME started the research on energy efficiency of machining system since 1992, sponsored by NSFC. The name of the project is ***Study on energy consumption characteristics in a machining system(project No. 59175237 ,1992-1994)***

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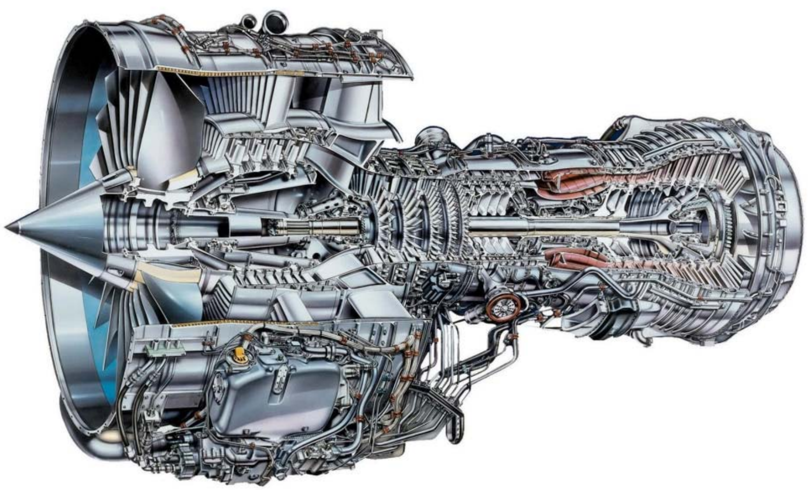
2 Energy usage in machining systems

Machining systems is one of the most widely applied discrete manufacturing systems for metal cutting from material blanks to finished products and parts in automobile, aeronautical industry, constructive machinery industry, military industry etc. A typical machining systems consists of machine tools, cutting tools, material handling devices, management & control systems, and the power systems, etc.

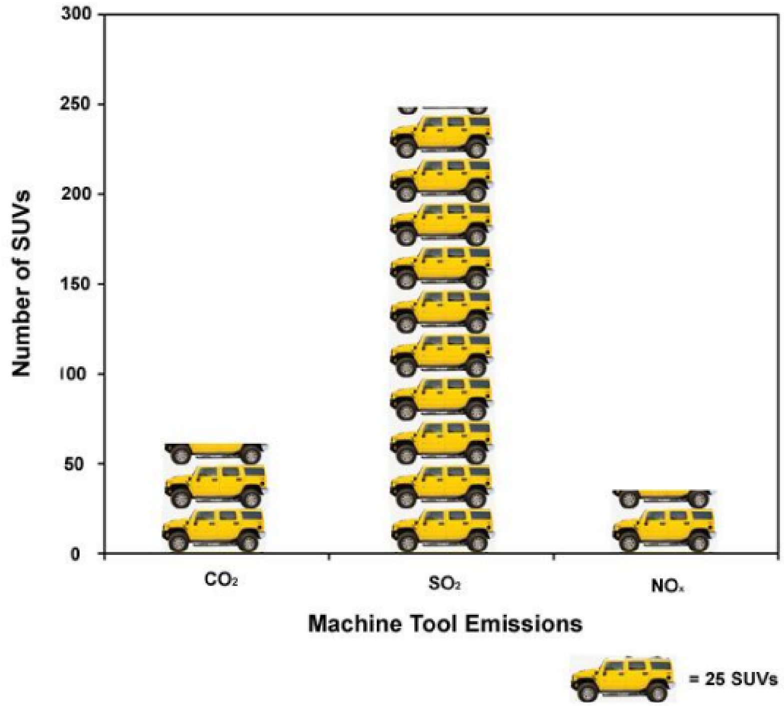


2 Energy usage in machining systems

Machine tool is the core equipment in machining systems and also is the main energy consuming source. Prof. Gutowski from MIT gave a comparision between SUVs and Machine tools on their energy and emissions.

Annual emissions resulting from the operation of a typical production machine tool

(22 kW spindle, cutting 57% of the time, 2 shifts, auxiliary equipment, electricity from US grid)



As measured in annual SUV equivalents

(12,000 miles annually, 20.7mpg)

By Prof. Timothy G. Gutowski, 2006, MIT

Energy usage of machining systems in China

China holds No.1 machine tool population of more than 7 million to support the largest mechanical manufacturing systems in the world.

How much are their total rated power?

In China, the machining systems involves more than 7 million machine tools

Assuming the average power of each machine tool is 10 kilowatts, the total power is about 70 million kilowatts, more than 3 times than the total capacity of the power station.

VS

The total capacity of Three Gorges hydro power station is about 22 million kilowatts.

Energy usage of machining systems

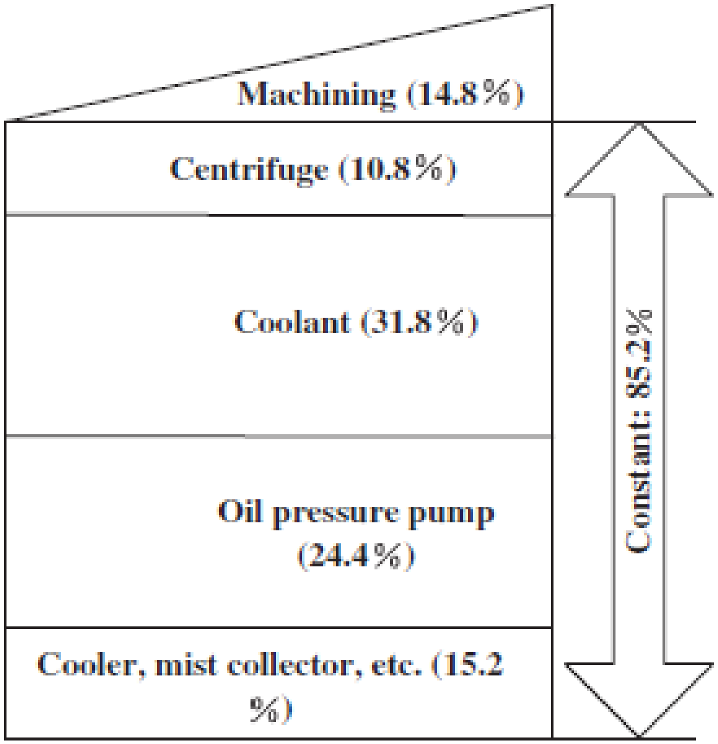
Are they running in high efficiency?

The energy efficiency usually defined as:

$$Eff = E_c / E_t = \int P_c(t)dt / \int P_t(t)dt$$

$$Eff_{-average} \leq 30\%$$

By our experiments in IME

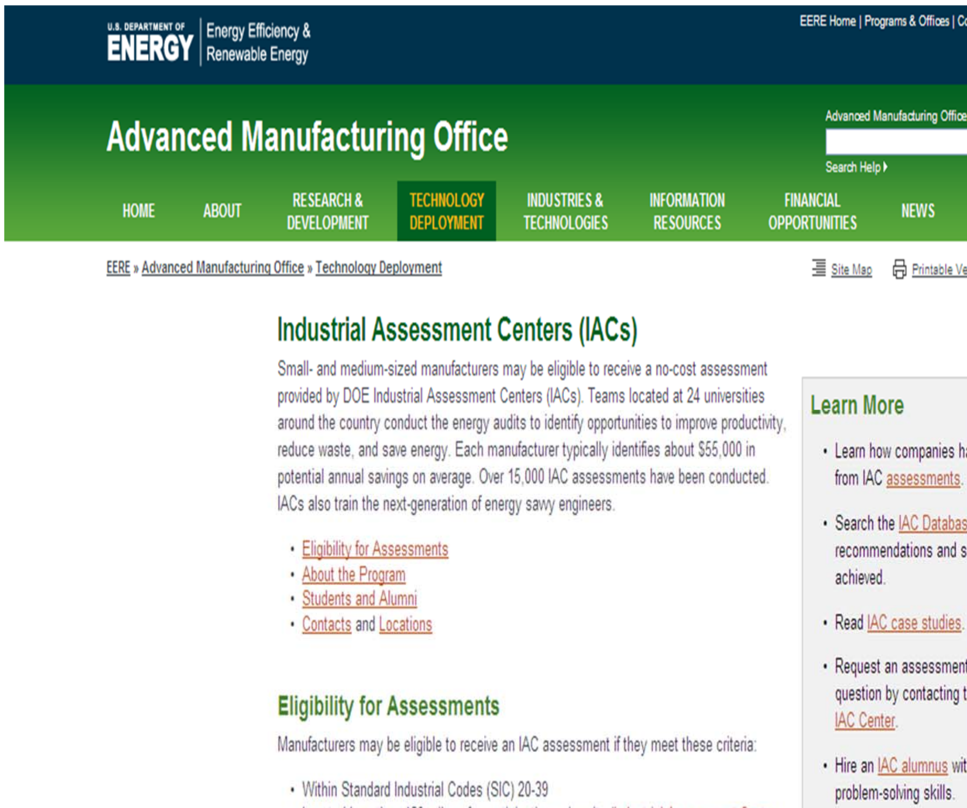


Machining energy use breakdown of a machining center (Dahmus and Gutowski, 2004).

Therefore, there exists great potential for energy saving in machining.

The research on the energy consumption and energy efficiency in machining is growing rapidly in recent years, which mainly refer to following aspects.

- Energy efficiency assessment
- Energy efficiency promotion



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3 Energy Efficiency Improving Strategies

➢**Optimization of NC Code of machining processes to reduce unnecessary energy waste and smooth peak power impact**

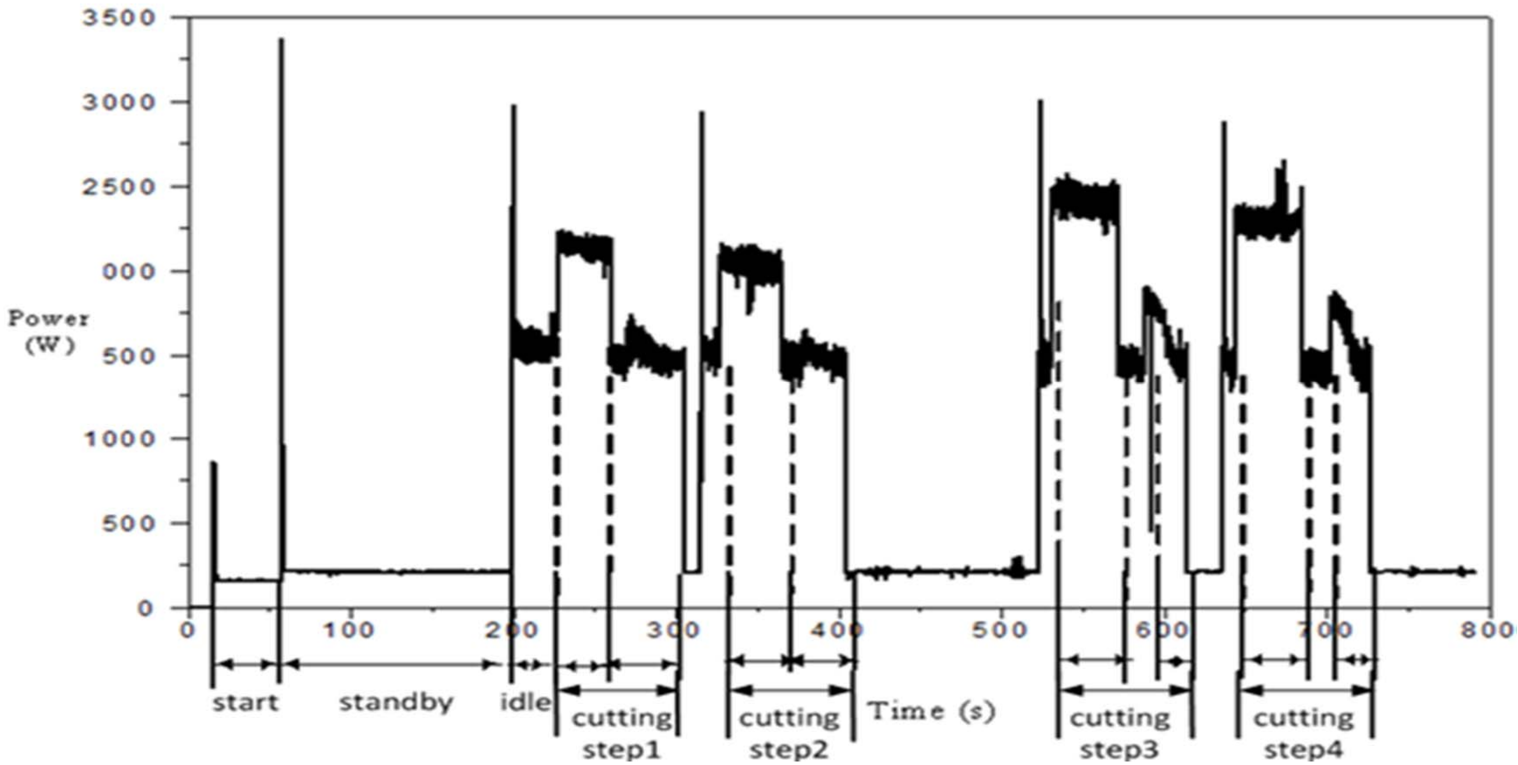
Energy consumers of machine tools

NC codes

```
N10  M03  S200;
N20  G00  X215.0  Z128.0;
N30  G01  X110.0  F80;
N40  G00  X110.0  Z133.0;
N50  G71  U1.0  R1.0;
N60  G71  P70  Q120  U0.5  W0.2  F80;
N70  G01  X180.0  F20;
N80  Z128.0;
N90  X178.0  Z127.0;
```

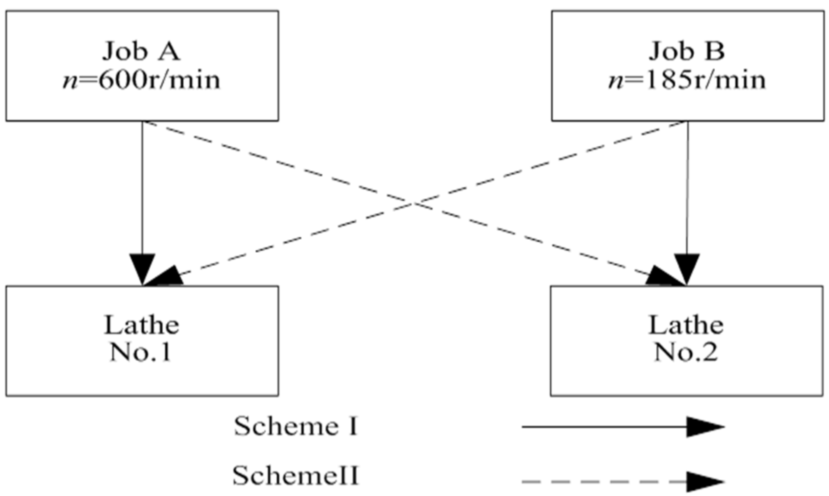
Code	Energy consumer	Behaviors	FANUC Code
M	Spindle motor	Spindle motor on	M03, M04
		Spindle motor off	M00,M01,M02, M05,M30
	Feed motor	Feed motor on	M00, M01, M02, M30
	Cool pump motor	Cool pump on	M07, M08
		Cool pump off	M00,M01, M02, M09, M30
S	Spindle motor	Set rotate speed	
G	Feed motor	Fast feed	G00
		Work feed	G01,G02,G03
F	Feed motor	Set feed rate	

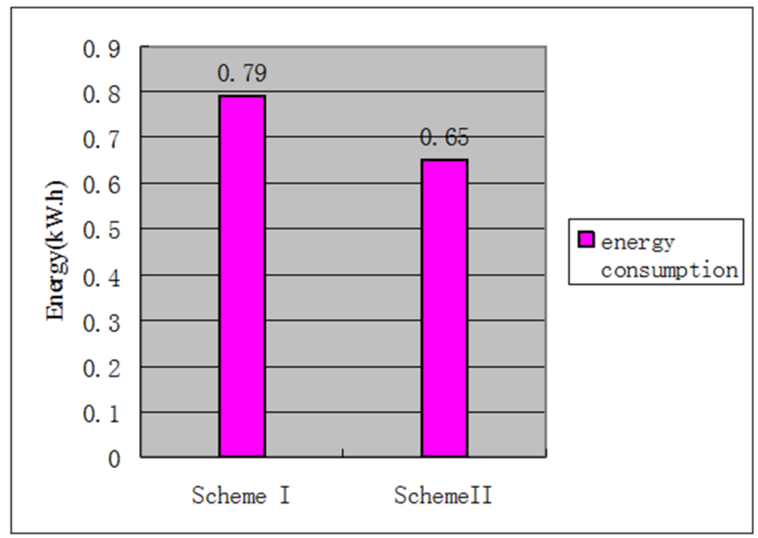
3 Energy Efficiency Improving Strategies



3 Energy Efficiency Improving Strategies

➢Scheduling for energy saving in Job shop with multi machine tools and multi processing task.

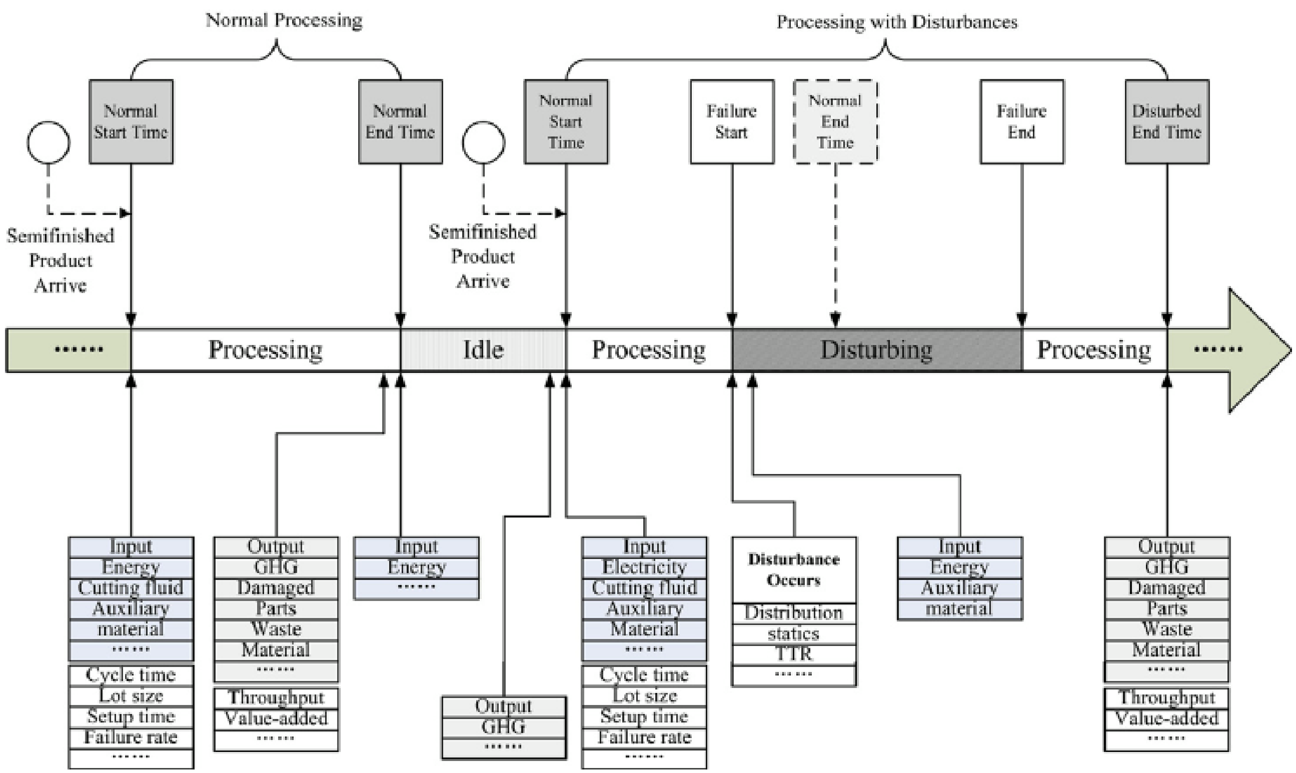




There is an about 17.7% saving-energy of Scheme II for the two jobs scheduling. It is observed that there is potentially a significant amount of energy savings by job scheduling in manufacturing system.

3 Energy efficiency improving strategies

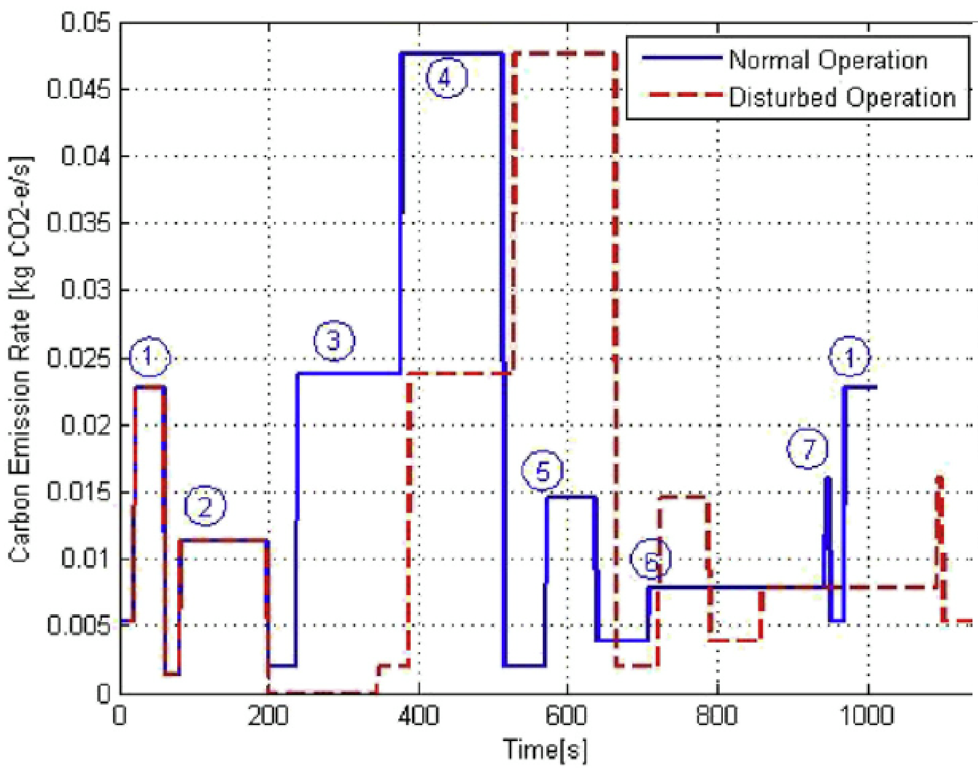
➢**Improving equipment utilization and reliability could significantly improve efficiency by reducing the waste of equipment's productivity**



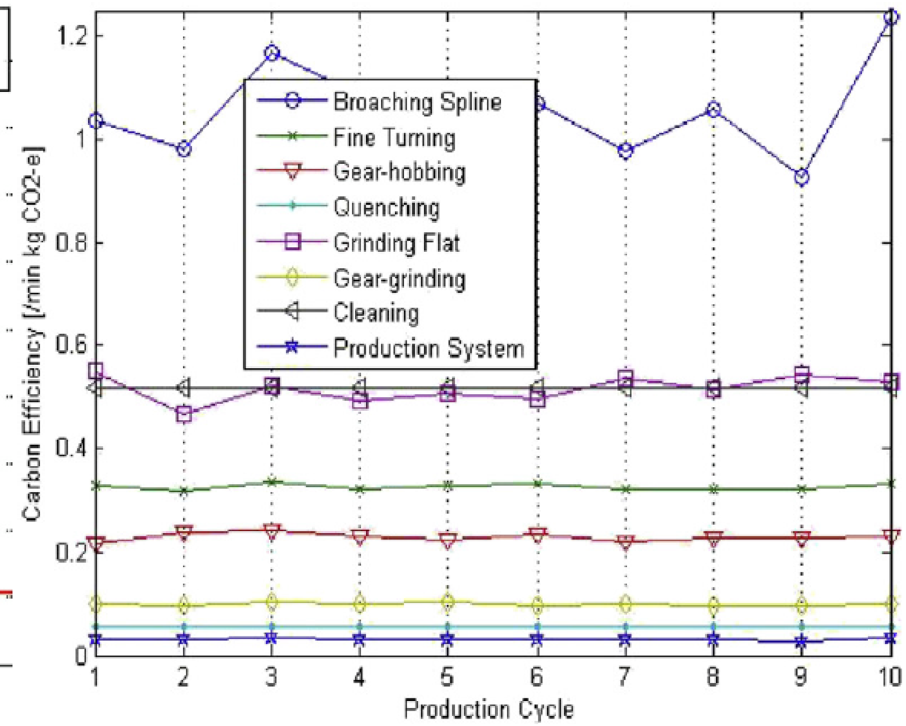
Temporal evolution of a gear production process considering disturbances.

3 Energy efficiency improving strategies

➢Improving Equipment Utilization reliability



Comparison of carbon emission rate profile of Gear Processing due to disturbance.



Comparison of carbon efficiency profile

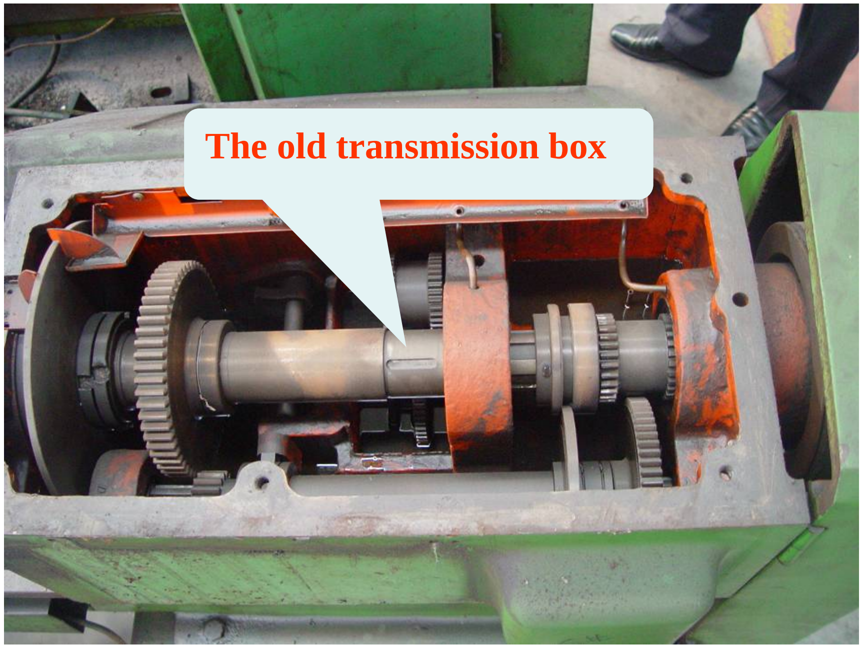
3 Energy efficiency improving strategies

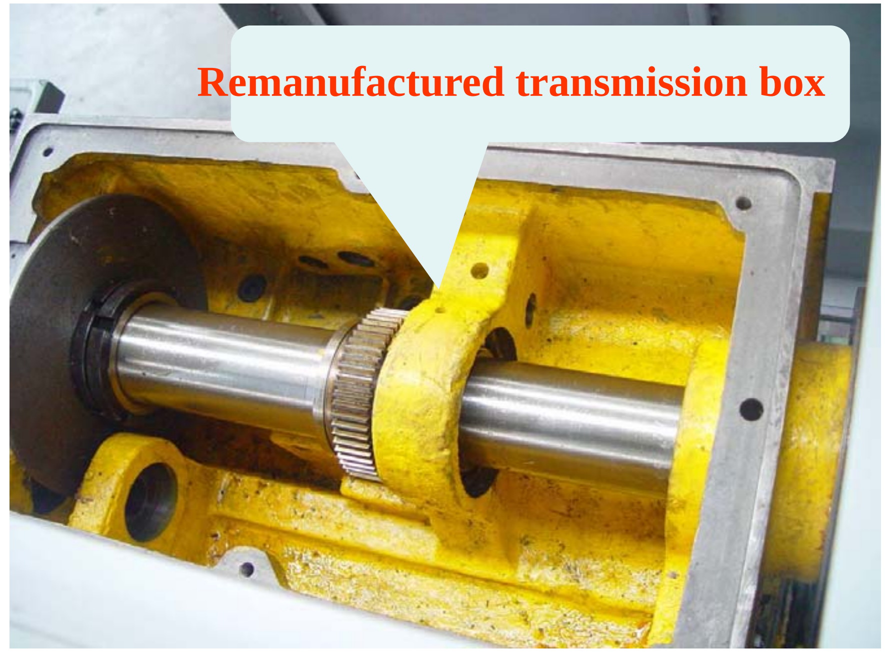
➢Upgrading and re-manufacturing of Equipments

Integrated re-manufacturing of machine tools is a new mode for machine tool manufacturing based on resource recycling of the used machine tools.

One example for this case is to remanufacture transmission system of lathe C616 which is produced by Chongqing Machine Tool Corporation.

Old Lathe C616



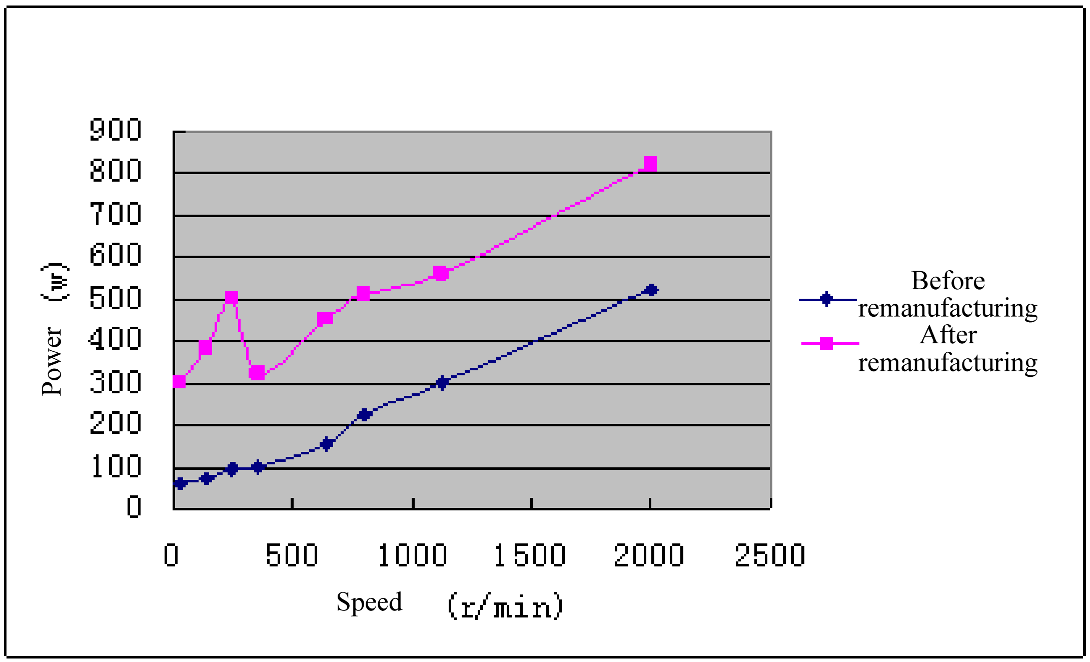


The old lathes

Remanufactured machine tool

3 Energy efficiency improving strategies

Generally, 20% energy-saving can be achieved when the machine tool is idling.



Remanufactured machine tool with higher energy efficiency

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A reliable prediction of process energy consumption will enable industry to develop potential energy saving strategies during product design and process planning, such as:

(1)Evaluating energy efficiency in machining systems;

(2)Setting workpiece energy consumption quota;

(3)Optimizing the cutting parameters and optimizing the process planning for reducing energy consumption.

There have been some related studies about the prediction the energy consumption in machining

But for practical application, the following problems need to be solved.

The practical machining process of a workpiece consists of a lot of the start-up periods , idle periods and cutting periods , so how to predict for the whole machining process?

The present methods by modeling and simulating are based on the historical production information and data base of energy consumption, but how to predict the energy consumption of a new workpiece?

The additional load loss in machining is very complicated and can not be neglected, which sometimes is more than 20% of the cutting energy, so how to predict the value of the additional load loss ?

The method proposed in this presentation is going to solve all the above problems.

In machining, it is very difficult to predict the energy consumption of main driving system (MDS) which consists of the motor and the mechanical transmission system. But it is relatively easy for others such as coolant, centrifuge, lighting, etc., because their powers are usually constant.

In addition, the energy consumption of MDS is the principal part of all energy consumption of a machine tool. For some common lathes, it is more than 90%.

Therefore, this presentation mainly focuses on the energy consumption prediction of MDS.

Take the machining process of the workpiece shown in Fig. 1 as an example.

The machining process includes the cylindrical surface turning at first, then the head face turning and finally cutting off the workpiece .

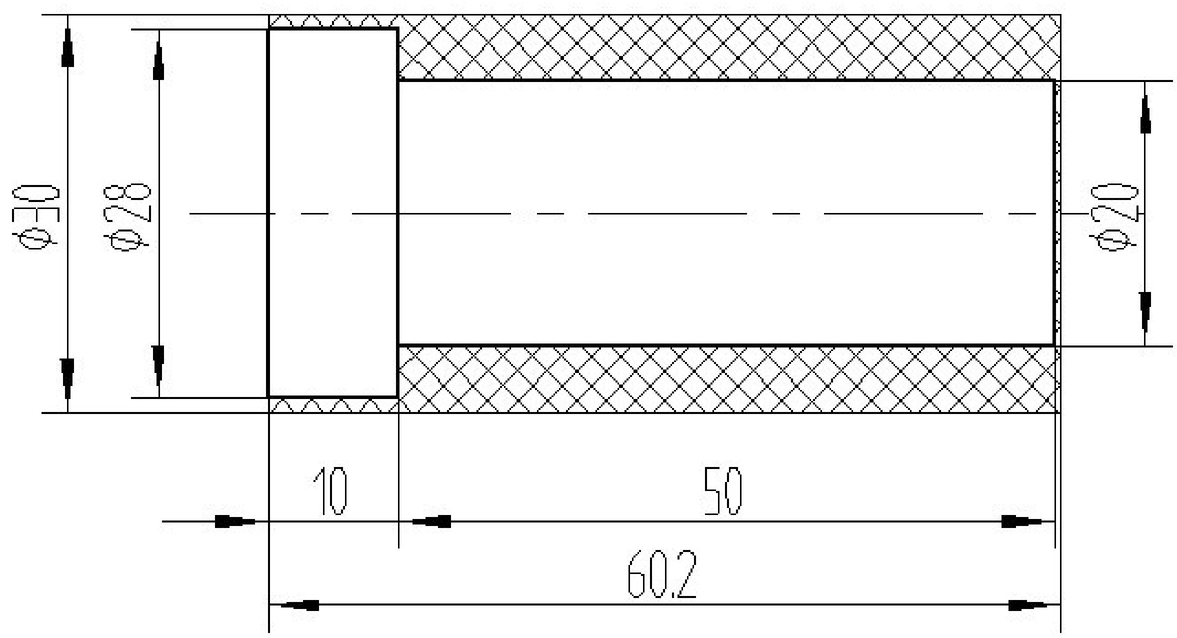

Fig. 1. The blank drawing of the workpiece

The power schematic diagram of the whole machining process is shown in Fig.2, which reveals that the process of energy consumption consists of three kinds of periods.

start-up period: (1)

idle periods: (2) (4) (6) (7) (9) (10) (12)

cutting periods: (3) (5) (8) (11)

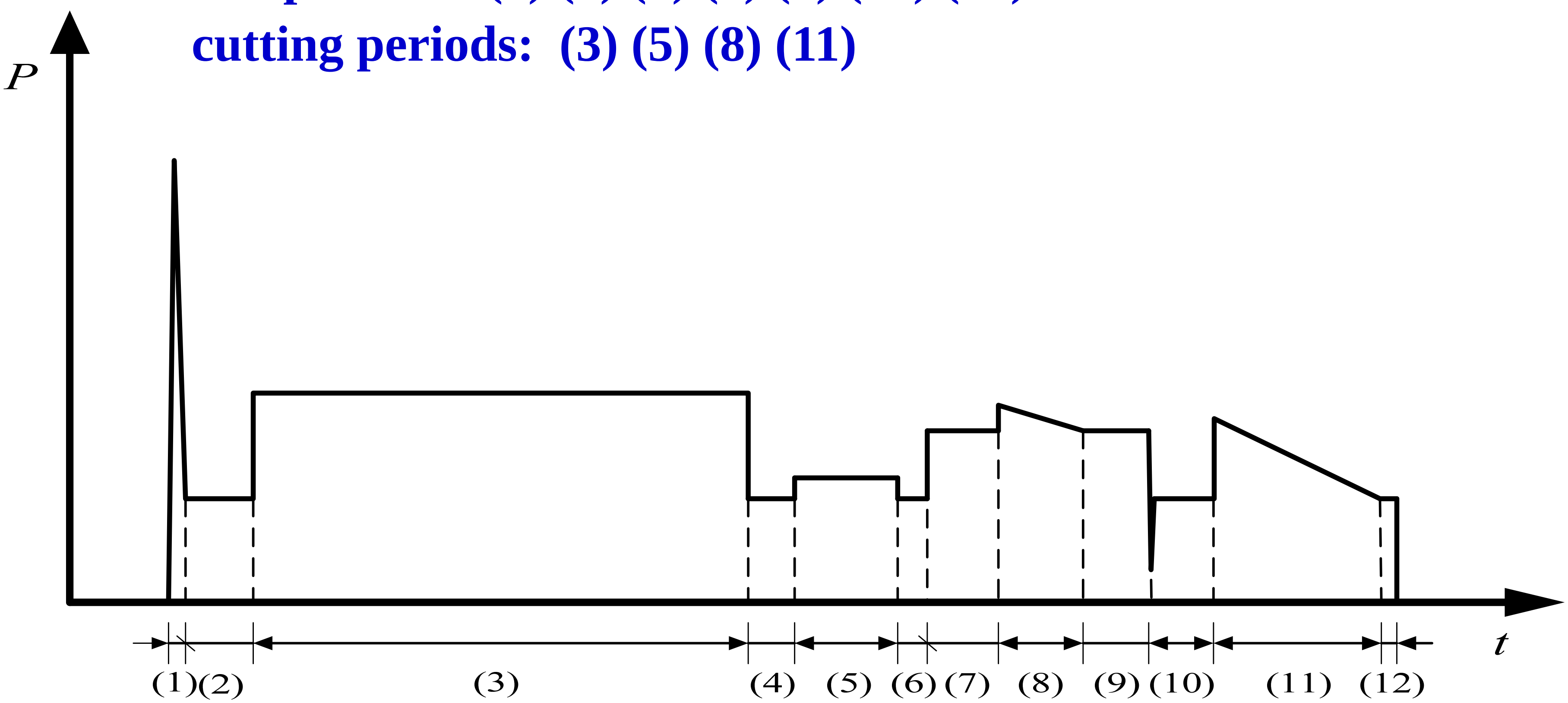

Fig. 2. The power schematic diagram of the machining process of the workpiece

There are different energy consumption characteristics in the three kinds of periods.

Start-up periods: The power process changes sharply and the law of energy consumption is complicated.

Idle periods: The power is almost constant.

Cutting periods: They can be divided into constant load cutting shown as period (3) and (5), and variable load cutting shown as (8) and (11). Both of their power is larger than that in the idle periods.

The authors have established a transient model in the early studies

$$P_i\left(t\right)=P_{le}\left(t\right)+P_{lm}\left(t\right)+P_c\left(t\right)+\frac{dE_m}{dt}+\frac{dE_k}{dt} \quad (1)$$

The model (1) has different forms corresponding to the three kinds of periods in machining process.

Start-up periods：

$$P_i\left(t\right)=P_{le}\left(t\right)+P_{lm}\left(t\right)+\frac{dE_m}{dt}+\frac{dE_k}{dt} \quad (2)$$

Idle periods：

$$P_{\mathrm{u}}(\mathrm{n})=P_{\mathrm{ue}}(n)+P_{\mathrm{um}}(n) \quad (3)$$

Cutting periods

$$P_i = P_u + P_a + P_c \quad (4)$$

Where, P_i is the input power of the motor; P_c is the cutting power; P_{u} is the idle power or unproductive power of MDS at a specific rotate speed; P_{ue} is the power loss of the motor and P_{um} is the power loss of the mechanical transmission system when MDS is idle; P_a is the total loading loss in MDS.

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The model framework for predicting the energy consumption of a machining process

$$E = \sum_{j=1}^{Q_s} E_{sj} + \sum_{j=1}^{Q_u} E_{uj} + \sum_{j=1}^{Q_c} E_{cj} \qquad \textbf{(5)}$$

Where，E denotes the total energy consumption in MDS in the machining process; Q_s ,Q_u and Q_c respectively denote amount of start-up periods, idle periods and cutting periods ; The subscript s, u and c denote start-up, idle and cutting separately.

Energy consumption prediction of start-up periods

It is very difficult to use the theoretical model (2) to predict energy consumption of start-up periods.

But the start-up energy of a machine tool (MT) at a certain speed n should be a constant, which means there is functional relationship between energy consumption and spindle speed, so that we can predict energy consumption of start-up periods by establishing the energy consumption database for common MT or function library for CNC MT in advance.

The detailed method for function library : first, measuring energy consumption at several selected speeds, and then constructing energy consumption function with speed as variable, and finally get the predict model just like formula(6), which can be used to predict the energy consumption of the start-up period at any speed n

$$E_s = x_1 n^2 + x_2 n + x_3 \qquad (6)$$

Energy consumption prediction of idle periods

Theoretically, the idle power at a certain rotating speed n is a constant, which means that an idle power database or function library could be also constructed in advance as

$$P_u = g(n) \qquad (7)$$

Thus, energy consumption of idle periods is

$$E_u = P_u \times t_u \qquad (8)$$

Energy consumption prediction of cutting periods

Energy consumption prediction model of cutting periods

$$E_c = \int_0^{t_c} \left(\alpha_2 P_c^2 + (1 + \alpha_1) P_c + P_u \right) dt \qquad \textbf{(9)}$$

$$= \alpha_2 \int_0^{t_c} P_c^2 dt + (1 + \alpha_1) \int_0^{t_c} P_c dt + t_c \times P_u$$

P_u has been obtained by**(7)**. The key issue of energy consumption prediction of cutting periods is to obtain the cutting power P_c and the parameters α_1 and α_2 .

Calculating of the cutting power P_c

Cutting power can be calculated by means of some cutting manuals with the cutting parameters, cutting depth a_p, feed rate f, and cutting speed v_c.

$$P_c = F_c \times v_c = C_{F_c} a_p^{x_{Fc}} f^{y_{Fc}} v_c^{n_{Fc}} K_{F_c} \times v_c \qquad (10)$$

Obtaining of parameters α_1 and α_2

For each transmission chain, taking k ($k > 2$) groups of different cutting parameters and measuring the corresponding P_i, P_u and P_c, we can get

$$\begin{cases} \alpha_2 = \dfrac{\sum P_{ij} P_{cj} \sum P_{cj}^3 - \sum P_{uj} P_{cj} \sum P_{cj}^3 + \sum P_{uj} P_{cj}^2 \sum P_{cj}^2 - \sum P_{ij} P_{cj}^2 \sum P_{cj}^2}{\left(\sum P_{cj}^3\right)^2 - \sum P_{cj}^2 \sum P_{cj}^4} \\ 1 + \alpha_1 = \dfrac{\sum P_{uj} P_{cj}^2 \sum P_{cj}^3 - \sum P_{ij} P_{cj} \sum P_{cj}^3 - \sum P_{uj} P_{cj} \sum P_{cj}^4 + \sum P_{ij} P_{cj} \sum P_{cj}^4}{\sum P_{cj}^2 \sum P_{cj}^4 - \left(\sum P_{cj}^3\right)^2} \end{cases} \qquad (11)$$

Total energy consumption prediction model of MDS

After predicting energy consumption of all periods, the total energy consumption prediction model of MDS can be obtained based on the model framework (5) as follows.

$$E=\sum_{j=1}^{Q_s}\left(x_1 n_j{}^2+x_2 n_j+x_3\right)+\sum_{j=1}^{Q_u}\left(P_{uj}\times t_{uj}\right)+ \quad \textbf{（12）}$$

$$+\sum_{j=1}^{Q_c}\left[\int_0^{t_{cj}}\left(\alpha_{2j}P_c^2+\left(1+\alpha_{1j}\right)P_c+P_{uj}\right)dt\right]$$

Machine tool and workpiece

C2-6136HK/1
CNC lathe

Machined
workpiece

Preparation of fundamental database of the lathe

Table 1 Related parameters of CNC lathe

Type：C2-6136HK/1
Speed range of low gear (rpm)：0-1000
Speed Range of high gear (rpm)： 300-2100
Main motor rated power (kw)：5.5

With measuring start-up energy consumption of high gear and low gear at respective different speeds, the fitting function of the start-up periods is obtained as follows.

$$\begin{cases} E_{sl} = 0.0045n^2 + 0.1024n + 70.393 \\ E_{sh} = 0.0024n^2 - 0.2862n + 164.28 \end{cases}$$

In the same way ,the fitting function of the idle periods is obtained as follows.

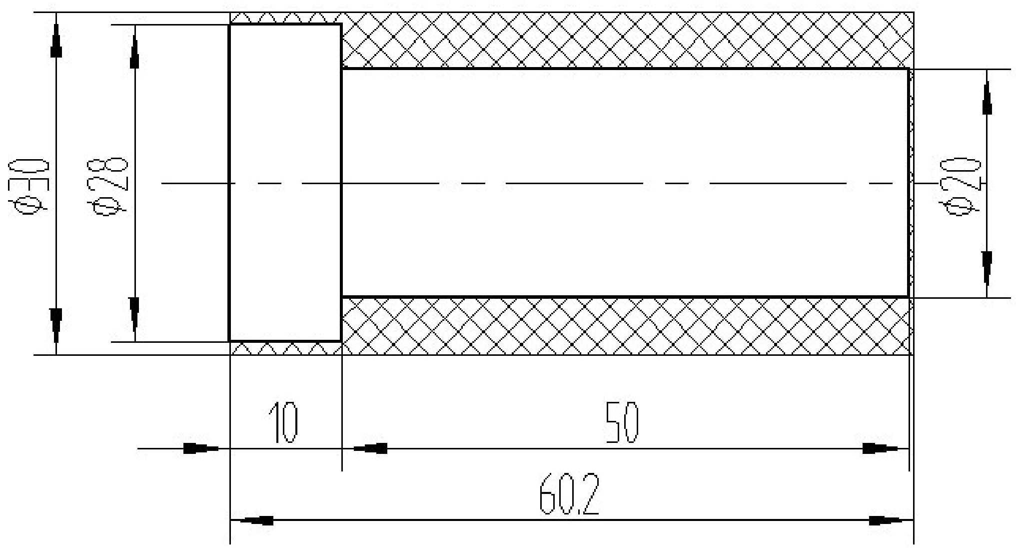
$$\begin{cases} P_{ul} = 0.00002n^2 + 1.2426n + 90.115 \\ P_{uh} = 0.000005n^2 + 1.0232n - 0.6835 \end{cases}$$

Several groups of input power P_i and cutting power P_c, and idle or unproductive power are measured, the values of α_1 and α_2 are obtained according to the model(11).

$$\begin{cases} \alpha_{1l} = 0.1939 \\ \alpha_{2l} = 3*10^{-6} \end{cases} \qquad \begin{cases} \alpha_{1h} = 0.1574 \\ \alpha_{2h} = 8*10^{-6} \end{cases}$$

Energy consumption prediction

The energy consumption prediction of the machining process of the workpiece shown as follow is taken as an example.



The information about cutters and blank material are shown in table 2, the machining steps and parameters are shown in table 3. The whole machining process is divided into 12 periods which are listed in table 4.

Table 2 Information of cutters and blank material

Type of cutter 1: 90° cylindrical-cutter
Material of Cutter 1: YT15
Type of cutter 2: MGMN400-M cut-off tool
Material of Cutter 2: NC3020
Blank material：45 steel

Table 3 Machining steps and parameters

Machining steps	Machining parameters		
	n(rpm)	f （mm/min）	a（mm）
cylindrical turning of front part	400	40	5
cylindrical turning of rear part	400	40	1
end-face turning	1000	48	0.2
cut-off	400	35	4

Table 4 Machining process

step	Type	Contents	speed	time (s)	energy(J)
1	Start-up	Start-up	400	—	E_{s1}
2	Idle	Plunge	400	10.5	E_{u1}
3	machining	cylindrical turning of front part	400	75	E_{m1}
4	Idle	Withdrawal	400	6	E_{u2}
5	machining	cylindrical turning of rear part	400	15	E_{m2}
6	Idle	Withdrawal, fast moving	400	3.6	E_{u3}
7	Idle	accelerate、approach	1000	9.1	E_{u4}
8	machining	End-face turning	1000	12.5	E_{m3}
9	Idle	Withdrawal, tool-changing	1000	10	E_{u5}
10	Idle	decelerate、fast moving、approach	400	8.75	E_{u6}
11	machining	Cut-off	400	24	E_{m4}
12	Idle	Fast moving, shutdown	400	2.74	E_{u7}

Take the parameters in the tables into the models separately, the results obtained as follows:

$$E_{s1} = 831J \qquad E_{u6} = 5259J$$
$$E_{u1} = 6311J \qquad E_{u7} = 1647J$$
$$E_{u2} = 3606J \qquad E_{m1} = 114388J$$
$$E_{u3} = 2164J \qquad E_{m2} = 12648J$$
$$E_{u4} = 12048J \qquad E_{m3} = 20146J$$
$$E_{u5} = 13240J \qquad E_{m4} = 29718J$$

By adding up energy consumption of all periods, the total energy consumption E can be obtained.

$$E = \sum_{j=1}^{1} E_{sj} + \sum_{j=1}^{7} E_{uj} + \sum_{j=1}^{4} E_{cj} = 222006J$$

In the machining process of CNC lathe, the actual energy consumption measured by electricity meter is 240716J, thus the prediction error is

$$error = \frac{|E - E'|}{E'} = 7.773\%$$

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5 Conclusions

- Machining processes have great amounts and usually have very low energy efficiency, so they have great potential for energy saving.
- A method for predicting the energy consumption in machining of a workpiece is proposed, so that the energy consumption can be obtained before practical machining only based on the basic data of the machine tools, workpiece and process planning.
- The method is capable to provide supports for evaluating energy efficiency in machining systems , setting workpiece energy consumption quota, optimizing the cutting parameters and the process planning to reduce energy consumption. So the method may have good application prospect .

Thank you!