KES Transactions on Sustainable Design and Manufacturing I
Sustainable Design and Manufacturing 2014 : pp.653-667 : Paper sdm14-076

Development of an innovative ERWC approach to sustainable manufacturing with application to design of an energy-resource efficient CNC centreless grinding

Hui Ding[1] and Kai Cheng[1, 2]

[1] School of Mechatronics Engineering, Harbin Institute of Technology, P.R. China
dhalbert@hit.edu.cn
[2] School of Engineering and Design, Brunel University, UK
Kai.cheng@brunel.ac.uk

Abstract Sustainable manufacturing is becoming increasingly important for modern manufacturing industry, while it is also one of the key challenges to manufacturers all around the world since its connotation is not clear and there are no systematic operational approaches to guide the design and service processes for mechanical products development. In this paper, an innovative ERWC (Energy-Resource-Waste-Carbon-footprint) approach is proposed to address the sustainable manufacturing and provide specific tools and methods to enable sustainable design and machining of machine tools. In the ERWC model, the energy consumption (E), resource utilization (R) and waste generation (W) are all converted to the equivalent carbon dioxide emission that is defined as a sustainable manufacturing attribute to comprehensively analyze the environmental impacts. Based on the ERWC approach, the methodological pieces of the operation process are delivered in order to reduce the environmental impact in terms of energy consumption, resource utilization and waste generation in the design and service stages, and also for the test and calibration of the environmental impact level of machine tools. The proposed methodology in this paper is carried out with the grinding process as an exemplar while it can be applicable to other machining processes, which is of high industrial and scientific significance.

Keywords Sustainable manufacturing, ERWC approach, CNC centreless grinding, Sustainable design

Notation

F_t	tangential force
V_S	speed of the wheel[m/s]
V_W	speed of the workpiece[m/s]
P_S	frequency-converted power of grinding wheel motor
P_D	frequency-converted power of guide wheel motor

R_t	tangential static friction force between the workpiece and guide wheel
V_d	linear speed of guide wheel[m/s]
η	grinding efficiency coefficient
T_{GFU}	grinding fluid usage time[s]
T_{GFR}	mean interval time between grinding fluid replacement[s]
Q_{GFI}	initial quantity of grinding fluid[L]
T_{LOU}	spindle running time[s]
T_{LOS}	mean interval time between lubricant oil supplies[s]
Q_{LOS}	supplement quantity of lubricant oil[L]
$r(t)$	grinding depth[mm](time varying)
d_w	diameter of workpiece[mm]
l	length of workpiece being grinded[mm]
G	the ratio of the metal removal to the lost volume of grinding wheel
C_E	carbon dioxide emission intensity of electricity[g-CO_2/kWh]
C_{GF}	carbon dioxide emission intensity of grinding fluid production[g-CO_2/L]
C_{LO}	carbon dioxide emission intensity of lubricant oil production[g-CO_2/L]
C_{CP}	carbon dioxide emission intensity of workpiece chips disposal [g-CO_2/kg]
C_W	carbon dioxide emission intensity of grinding wheel production[g-CO_2/kg]

1. Introduction

Currently, global warming is extensively discussed as one of the most important global issues because of the rising amount of carbon and carbon dioxide contents emitted from industrial products consuming large amount of energy and natural resources. So sustainability has become a very significant research topic since it impacts many different manufacturing industries. Today, a new industrial revolution is being conceived that will continue forever in the form of sustainable design and manufacture [1]. Worldwide research is in a sharp transition in adjusting to these global trends. Manufacturing and the processes involved consume substantial amounts of energy and other resources and, as a result, have a measurable impact on the environment. It's observed that the average efficiency of energy in machine tools is less than 30% and carbon emissions produced in the machining process is up to 82% during its whole life cycle [2]. Gutowski [3] presented the

results that the carbon emissions produced by one CNC machine tool with 22KW spindle power are equal to that generated by 61 SUV cars. Therefore, manufacturing has huge potential to save energy and reduce carbon emissions.
The US Department of Energy started the plan of Industrial Assessment Centers [4] in order to improve the energy efficiency in the manufacturing enterprise production process. 26 Universities were employed to assess each energy consumption link of machine tools including number of motors, motor power, running time, etc. Gutowski [5, 6] studied the energy consumption characteristic of various processes, proposed distributed models of energy and carbon emissions in manufacturing system and presented energy availability factor in CNC automatic mechanical processing line. Dornfeld [7] investigated the monitoring technology of energy consumption and established the monitoring system of energy consumption during machining process. Sheng [8] proposed an energy consumption model of grinding process and studied the relationships between processing parameters and energy consumption. Behrendt [9] developed an energy consumption monitoring procedure for machine tools, which is useful for companies to establish some standard practices.
The research presented above investigated carbon emissions in machining process only in term of energy consumption and proposed the methods to reduce carbon emissions only depend on enhancing energy utilization, which is limited and not comprehensive. For example, grinding, a widely used precision machining method, does not only consume energy but also utilizes large amount of grinding fluid and generates plenty of wastes. The dissipation of grinding fluid, lubricant and grinding wheels impose severe environmental impact. So not only the energy but also the resource and waste should be all taken in consideraton to investigate the environmental impact of manufacturing. In this paper, a systematic framework to study the environmental impact in design and service stages of CNC machine tools is presented, which is demonstrated by taking CNC centreless grinding process for example. The proposed methodology is essential for scientific understanding and industrial implementation of energy-/resource-efficient manufacturing.

2. ERWC methodology and framework

As we know, the performance parameters and economic costs are the two main indicators to evaluate the mechanical products, the performance parameters are usually mandatory indicators while the economic cost is one of the most important factors of competitiveness. However, the contradiction between economic development and sustainable development has become the consensus of all countries in the world because of the resource shortage and environment deterioration. As a result, manufacturing as the main consumption of resources and the major effect factor of the environmental problems, has to reduce the consumption of resources and energy, and cut down environmental emissions. But there is no ideal method that can guide the design of mechannical products and analyze the environmental impact of machining processes systematically to predict the outcome of the machining operations and optimize the process, while life cycle assessment (LCA) is generally accepted as an effective means to measure the environmental impact, but its use in practical development is somewhat limited due to the large amount of time, data, and resources required to conduct it [10]. Under this background, there is very necessary to propose an innovitive method and define the third indicator as an indispensable product environmental feature to assess the environmental impacts of mechanical products and the manufacturing process, together with which the technical and economic attributes constitute the three attributes of mechanical products and the manufacturing process.

Many researchers attempt to investigate the environmental impacts of manufacturing process. They mainly focus on the consumption of energy during machining process in order to improve energy utilization efficiency and reduce energy consumption, which is very limited since manufacturing process does not only consume energy, but also consumes resources and generates wastes. Therefore, the energy consumption, the resources utilizaion and the wasts generation should be all taken into consideration. In this paper, an innovative integrated methodology is proposed to quantitative analysis of energy consumption, resources utilizaion and wasts generation during manufactruing process. As we know, manufactruing process does not emit carbon dioxide, but the energy (E), resource (R) and waste (W) can be equivalently converted to a standard power station's carbon dioxide emmission. By doing so, different physical quantities can be unified into one dimension, which is very useful to quantitative analysis and comparative evaluation. So the equivalent carbon dioxide emission is employed as an environmental attribute to comprehensively analyze the the environmental impacts of manufacturing process. Furthermore, it is estimated that more than 80% of all product-related environmental impact is determined during the product design and service phases [11]. Hence, the research delimitation in this paper is limited to the design and service phases of machine tools.

The ERWC model approach is an innovative method, which will be introduced in section 3. The following three sections are all based on the ERWC model. Section 4 will guide the design process of mahine tools in terms of energy saving, resource reduction and waste reduction. Section 5 will present the quantitative analysis of the equivalent carbon dioxide emission in the service stage of machine tools. Then section 6 will demonstrate the testing and assessment processes of the mahine tool with the purpose of assessing the environmental impact level of the machine tool. The proposed methodology (see Fig. 1) in this paper is of high industrial and scientific significance, although it is carried out with the grinding process as an exemplar and the methodology is applicable to other machining processes.

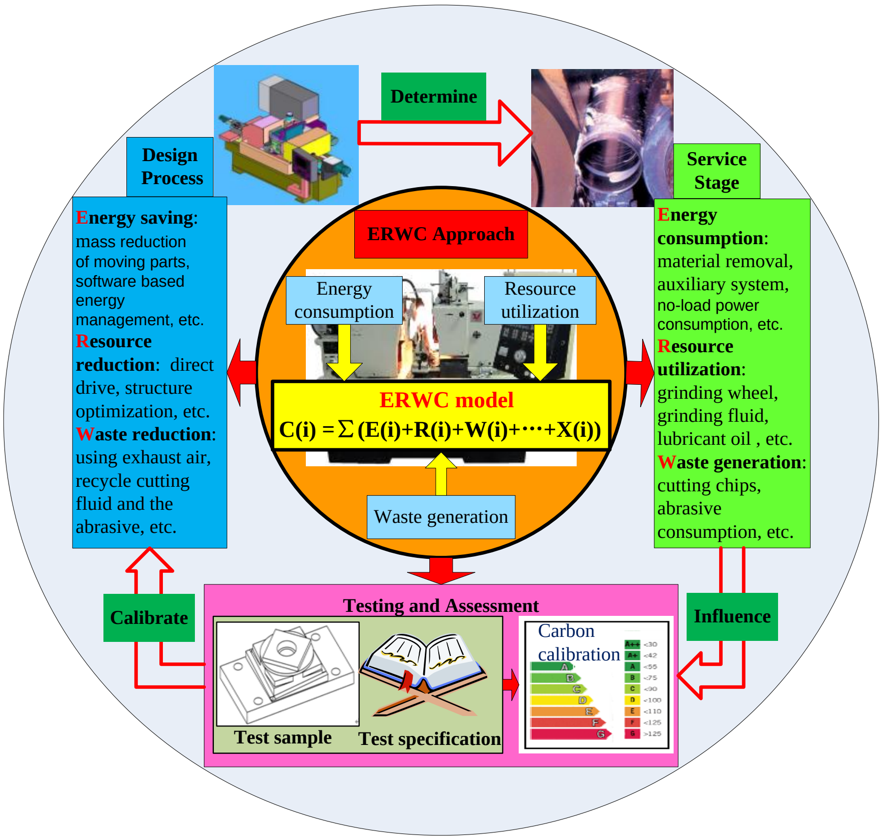


Fig. 1 Methodology for development of energy-resource efficient CNC centreless grinding

3. ERWC modelling approach

Manufacturing process takes resource inputs, including workpiece materials and auxiliary materials such as cutting tools, cutting fluid and fixture, and transforms them into products and wastes. Similarly, the energy inputs into the manufacturing process are transformed into useful work, while some of which is embodied as the form and composition of the products and wastes. So the energy consumption, the resource utilization and the waste generation should all take into consideration to access the environmental impact of manufacturing process. This section will take the CNC centerless grinding for example to show the ERWC modelling approach and process (see Fig. 2).

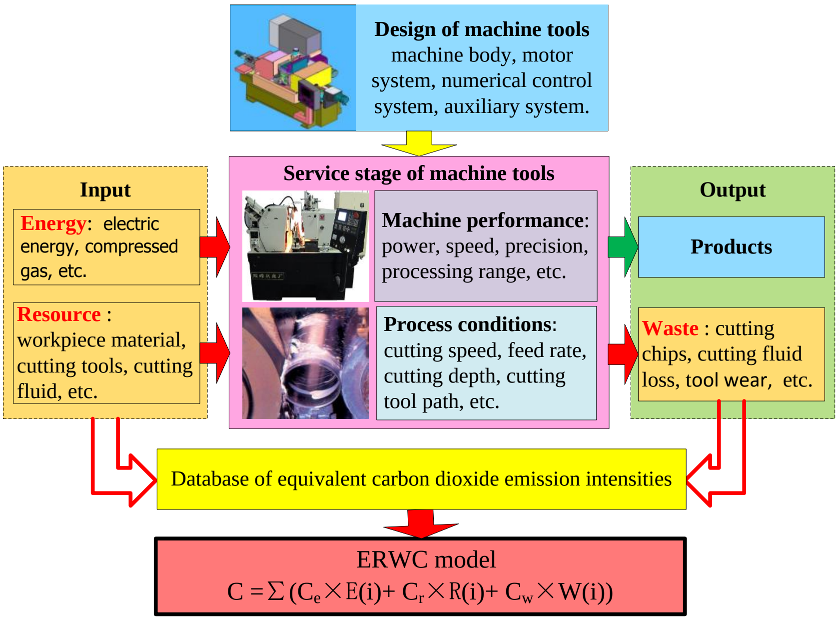


Fig. 2 ERWC modeling method and process

Energy use is one of main causes in the majority of the environmental impact in material removal processes. The energy requirements of a machine tool not only consist of the energy supplied to the tool tip for material removal but also numerous other auxiliary functions. The total energy consumption of grinding process consists of energy consumption in material removal, basic energy consumption, frequency-converted energy consumption and response energy consumption [12]. The energy consumption for material removal is estimated based on cutting force prediction and the basic physical relationship between power and force. The energy consumption caused by grinding force can be calculated as:

$$E_C = \int_0^t F_t \times (V_S \pm V_W) dt \quad (1)$$

Some basic energy consumption is needed to maintain the normal operation of the grinding machine, which includes the energy consumption of coolant pump, lubricant pump and electric cabinet, etc. This part of power consumption can be measured directly.

Besides basic energy, energy consumption of drive motor for grinding wheel and guide wheel in no-load are the indispensable element to make grinding machine function well. The two adjustable frequency motors could change rotate speed by control knobs. According to reference [13], the power of these two motors could be expressed as a quadratic function about rotate speed. So the frequency-converted energy consumption is calculated as:

$$E_{FC} = \int_0^t (P_S + P_D)dt \tag{2}$$

When the workpiece is grinding, the grinding machine needs more energy besides of material removal, basic and frequency-converted energy, which is named response energy. It includes additional guide wheel drive motor power load caused by bearing friction and tangential friction force between the workpiece and guide wheel, etc. The response energy consumption can be calculated as:

$$E_{response} = \int_0^t R_t \times V_d dt \tag{3}$$

Suppose grinding efficiency coefficient is η, the energy consumption of grinding process E is described as follows:

$$E = E_C / \eta + E_{base} + E_{FC} + E_{response} \tag{4}$$

Beside the energy consumption, resoures and wastes, such as grinding fluid, lubricant oil, grinding chips and grinding material, also have environmental impacts. Grinding fluid is an indispensable resource in grinding process, which could not only cool down and lubricate grinding zone but also swash wear debris. In grinding process, grinding fluid should be entirely replaced regularly. The grinding fluid usage is calculated as:

$$R_{GF} = \frac{T_{GFU}}{T_{GFR}} \times Q_{GFI} \tag{5}$$

Many parts of the grinding machine system should be lubricated regularly. The lubrication oil consumption is calculated as:

$$R_{LO} = \frac{T_{LOU}}{T_{LOS}} \times Q_{LOS} \tag{6}$$

The accumulated lost volume of workpiece material is expressed as:

$$W_{CP} = \pi r(t) l d_W \tag{7}$$

The accumulated lost volume of wheel is expressed as:

$$W_W = \frac{\pi r(t) l d_W}{G} \tag{8}$$

As we know, manufactruing process does not emit carbon dioxide, although the energy is primarily from electricity that usually requires fossil fuels and produces huge amounts of carbon emissions while the resources and wastes would also directly or indirectly produce carbon emission during their fabrications. With the help of carbon dioxide emission intensities presented in Table 1[14], the quantitative analysis model of equivalent carbon dioxide emission for CNC centerless grinding can be described as:

$$C_{Grinding}(t) = E(t)C_E + R_{GF}(t)C_{GF} + R_{LO}(t)C_{LO} + W_{CP}(t)C_{CP} + W_W(t)C_W \tag{9}$$

Table 1 Carbon dioxide emission intensities [14]

Carbon Dioxide Emission Intensity	Quantitative Value
C_E [g-CO_2/kwh]	381
C_{GF} [g-CO_2/L]	977.6
C_{LO} [g-CO_2/L]	469
C_{CP} [g-CO_2/kg]	63.4
C_W [g-CO_2/kg]	33747.8

4. ERWC model-based design applied to an energy-resource highly efficient CNC machine

Traditionally, CNC machines have been designed with speed and accuracy as the main objectives. However, a high speed accurate machine is not necessarily an energy-resource efficient machine. While a new industrial revolution is being conceived that will continue forever in the form of sustainable design and manufacture, manufactures will face not only economic and environmental, but eventually statutory challenges as well in the future. Hence, it is necessary to improve the energy-resource efficiency and reduce carbon dioxide emissions by introducing energy-resource efficiency as one of the criteria in the design and development process of CNC machine tools. In this section, the design of energy-resource efficient CNC machines will be demonstrated based on the ERWC model in terms of energy saving, resource and waste reduction.

4.1 Energy efficiency

Due to the continuously increasing demands of accuracy, productivity and reliability, extremely stiff mechanical systems of machine tools are implemented with the capability to absorb arising inertia forces. In consequence, the masses of the machine structure like moving machine components have to be increased. The high amount of masses, in turn, requires motors with high torque output which are able to raise the forces needed during acceleration and deceleration. Therefore, high energy consumption arises. In order to reduce machine masses and realize energy savings, two strategies can be pursued at the same time:

- Replacement of materials of moving components with lightweight alternatives. The usage of lightweight materials in principle is possible for all machine tools with moving parts as long as reliability and performance are not hampered.
- Structure optimization of moving components which allows mass reduction. Mass reduction, i.e. mass optimization, in principle is possible for all machine tools. Besides the potentially additional design efforts there are no additional

costs of implementing this option. On the contrary, material savings are directly related to cost savings.

4.2 Resource reduction

Machine tools consume high amounts of resource and consist of large number of components to realize the function and maintain the performance. In order to reduce the resource utilization, three aspects in design of mahine tools should be payed much attention as follows.

- Lightweight is the trend of the development of machine tools. We can save the material by optimizing the structure of machine tools and employing low density and high strength materials.
- With the help of new technologies, such as direct drive technology that can be used to replace ball scew drive system, the structure of machine tool is simplified and the components of machine tool system will be drastically reduced.
- The renewable materials is employed for major parts of machine tools, which carrys out the reuse of resources, and is the important way for machine tool industry to the reduce the environmental impact.

4.3 Waste reduction

Manufacturing processes utilize energy and other resources to transform raw materials and intermediates into final products, but also generate derivatives that should be recycled and reused in order to improve the energy-resource efficiency of machines, which should take into consideration in the design stage of machine tools.

- Cutting fluids, as an important source of chemical pollution and waste in machining, should be reuse after recycling. So, the filter and circulatory system should be included in machine tools.
- The material removed from workpiece and cutting tools is the indispensable derivative in machining process, which should be recycled and sorted for reuse especially when the material is rare and precious.
- Exhaust gas can be introduced into the cutting area, used for cooling and taking away chips. Also, for applications which are in need of multistaged levels of pressure, it is considerable to reuse the exhaust air from high pressure levels as supply air for those at lower levels.

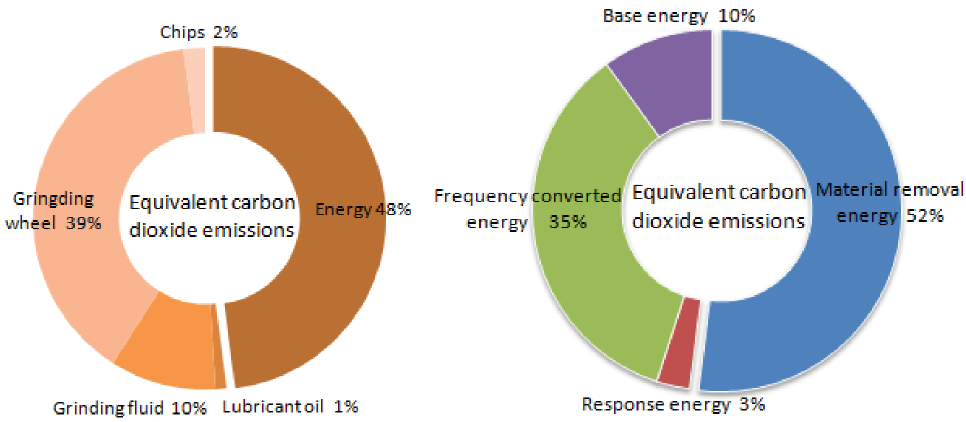
5. Application of ERWC modelling in the operation of a centreless grinding machine

Machining process utilizes energy and other resources to transform raw materials and intermediates into final products and wastes, which is the main consumption of energy and resources, and also the major effect factor of the environmental problems. The environmental impact of the machining process is determined by two main influence factors that are the machine performance and the processing conditions. The first one is discussed in section 4 that introduces some approaches to improve the energy-resource efficiency of the machines, while the latter one will be investigated in this section to study the environmental implication of processing conditions since it's observed that carbon emissions produced in the machining process is up to 82% during its whole life cycle [2].

The centreless grinding process is taken as the application exemplar to study the environmental implication of processing conditions through grinding trials. The modelling and simulation focus on the ERWC approach to quantitatively analyze the collective energy consumption (E), resource utilization (R) and waste generation (W), and the resultantly equivalent carbon dioxide emission in the grinding process. The grinding trials are completed on the centreless grinding machine MK1080. The diameter of cylindrical workpiece is 20mm and the material is 45 gauge steel. And the grinding depth is 0.2mm.

Figure 3 (a) shows the five compositions and their proportions of carbon dioxide emissions during the centreless grinding process. It’s clear that energy consumption and grinding wheel dissipation are two main factors resulting in equivalent carbon dioxide emissions in the grinding process, followed by the loss of grinding fluid, chips and lubricant oil. The results demonstrate that the energy consumption is the most influential factor (48%) but not the only one, more than a half equivalent carbon dioxide emissions are caused by the resoures utilization and wastes generation during the grinding, which also indicates that ERWC modelling approach is a systematical tool that can evaluate the environmental impact of the machining process comprehensively. In other words, only considering energy without resource and waste during the mahining process is incomplete and segmentary to access the environmental impact.

Figure 3 (b) illustrates equivalent carbon dioxide emissions proportion of the four kinds of grinding energy consumption. The energy used to remove workpiece material is 52%, the largest proportion, which is a little different from the range of 0 to 48.1% reported by Kardonowy[15] and Rajemi[16]. This may indicate that the grinding process consumes more specific energy than that in turning or milling. The rest of the energy is consumed in other parts inside the machine, which has a large energy saving potential.



(a) Composition and proportion of equivalent CO_2 emissions (b) Equivalent CO_2 emissions proportion from energy

Fig. 3 Quantitative analysis results of equivalent CO_2 emissions in equivalent grinding process

From the analysis above, it's found that in order to reduce the equivalent carbon dioxide emissions during the machining process, the three aspects in terms of energy saving, resource and waste reduction should all pay much attention. As we know, the energy consumption, the resource utilization and the waste generation are all determined by the process conditions. So the quantitative relation between process parameters and equivalent carbon dioxide emissions, which can be establied based on the ERWC model, can be applied to optimize the process conditions. In additon, the optimization algorithm can be embedded into the controller of machine tools to achieve low carbon manufacturing automatically, which is our ongoing work.

6. Experimental testing and assessment

Because of the market and legislative requirements in the future, manufacturers will have to provide customers with information on the energy-resource efficiency and equivalent carbon dioxide emissions performance of the machine tools and/or guidelines to help minimise their environmental impact during use phase. This is like household appliances, such as air conditioning, refrigeration and so on, that are demarcated with the level of energy consumption. So the testing and assessment method of energy-resource efficiency and equivalent carbon dioxide emissions of machine tools should be developed (see Fig. 4).

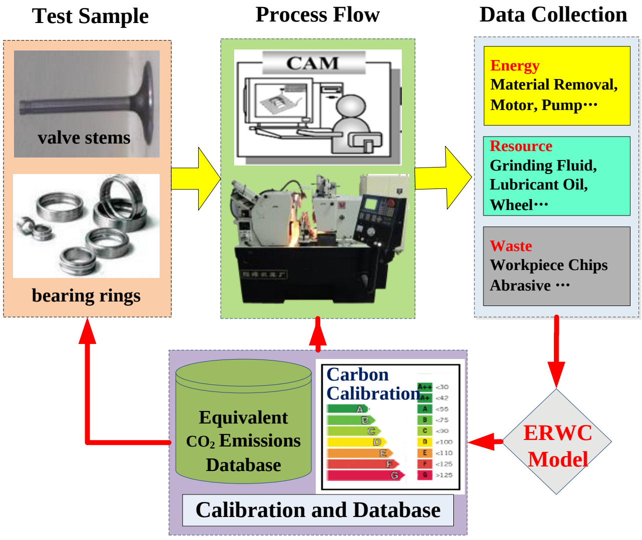


Fig. 4 Testing and assessment method and process

The equivalent carbon dioxide emissions of CNC machine tools depend on the running status that can be classified into six conditions: off, standby, extended standby, ready for operation, warm up and processing [17]. The equivalent carbon dioxide emission in the first five conditions is easy to calculate since it consists of only the energy consumption without the resource utilization and waste generation, while during the machining process it can vary and present greatly different characteristics with various manufacturing strategy and process parameters. Therefore, test samples and test process flow should be standardized in order to test and calibrate the level of the equivalent carbon dioxide emissions of machine tools under the same process condition. Only in this way, the test results are comparative. The standard test samples and standard test process flow should meet the following requirements:

- can reflect the commonly used process conditions of the machine tool
- can reflect the main components of equivalent carbon dioxide emissions of the machine tool
- can be commonly used in the same kind of machine tools
- convenient for the operation and measurement

According to the test object, choose the suitable test device and set up test system. Then the corresponding experimental tests are performed to investigate the equivalent carbon dioxide emissions characteristic of machine tools including the main components and their proportions, the boundary and the level of carbon emissions and so on. Then with the result data, database can be established covering equivalent carbon dioxide emissions of typical machining process, typical machine tools, typical materials and so on, whicn can be used to access the level of equivalent carbon dioxide emissions of machine tools and also provide guidelines to optimize the process conditions to minimise the environmental impact during the machining process.

7. Conclusions

The proposed ERWC approach for the energy-resource efficiency of machine tools is characterized by the integration of energy, resource and waste. And the equivalent carbon dioxide emission is defined as an environmental attribute to comprehensively analyze the the environmental impact of manufacturing process. ERWC modelling process is demonstrated by taking CNC centreless grinding process for example. Based on the ERWC model, some methodological pieces of advice for the design, use and test of machine tools are provided, including how to reduce the environmental impact in terms of energy consumption, resource utilization and waste generation in the design and service stage, and how to test and assess the level of the equivalent carbon dioxide emission of machine tools.
Further research should, on the one hand, concentrate on the smart adaptive machining to achieve low carbon manufacturing automatically, including developing the optimizatioon algorithm using the quantitative relation between process parameters and equivalent carbon dioxide emissions, and embedding the algorithm into the controller of machine tools. On the other hand, a larger data base should be created, particularly in terms of equivalent carbon dioxide emissions of typical machining process, typical machine tools, and typical materials. This would not only contribute to the evaluation of the equivalent carbon dioxide emissions level of of machine tools but also provide guidelines to choose the process conditions to minimise the environmental impact during the machining process.

Acknowledgements

This research was supported by ‘the Fundamental Research Funds for the Central Universities’ (grant no. HIT. NSRIF. 2014057). The authors would like to thank Xianfeng Machine Tool Company for the provision of the centreless grinding machine and the grinding process as needed.

References

[1] S.T. Newman, A. Nassehi, R. Imani-Asrai, V. Dhokia. Energy efficient process planning for CNC machining. CIRP Journal of Manufacturing Science and Technology. 5 (2): 127-136 (2012)
[2] Thurston D, Gutowski T, Murphy C, Allen D, Bauer D, Bras B, Piwonka T, Sheng P, Sutherland J, Wolff E, US National Science Foundation Panel Report on International Environmentally Benign Design and Manufacturing,

Proceedings International Conference on Engineering Design (ICED), Glasgow, Scotland, August 2001
[3] Gutowski T, Dahmus J and Dalquist S. Measuring the Environmental Load of Manufacturing Processes, International Society for Industrial Ecology (ISIE), 3rd International Conference, Stockholm, Sweden, June 12-15 (2005)
[4] http://iac.rutgers.edu/ Industrial Assessment Centers Field Manager
[5] Gutowski T. Thermodynamic Analysis of Resources Used in Manufacturing Processes, Environmental Science and Technology. 43: 1584-1590 (2009)
[6] Gutowski T, Dahmus J and Thiriez A. Electrical energy requirements for manufacturing processes. In Proceedings of 13th CIRP International Conference on Life Cycle Engineering , Leuven, Belgium. 30 May-02 June pp: 623-627 (2006)
[7] Vijayaraghavan A, Dornfeld D. Automated energy monitoring of machine tools, CIRP Annals-Manufacturing Technology, 59(1): 21-24 (2010)
[8] Bauer D J, Thurwachter S, Sheng P S. Integration of environmental factors in surface planning: part 1 -- mass and energy modeling, Transactions of NAMRI/SME, 26: 171–176 (1998)
[9] Behrendt T, Zein A, Min S. Development of an energy consumption monitoring procedure for machine tool. CIRP Annals-Manufacturing Technology, 61(1):43-46 (2012)
[10] Oliver Ioan Avram, Paul Xirouchakis. Evaluating the use phase energy requirements of a machine tool system. Journal of Cleaner Production 19 pp: 699-711 (2011)
[11] Dahmus, J. B., Gutowski, T. G. An Environmental Analysis of Machining, Proceedings of ASME International Mechanical Engineering Congress and R&D Exposition. pp: 13–19 (2004)
[12] Hui Ding, DY Guo, K Cheng and Q Cui1. An investigation on quantitative analysis of energy consumption and carbon footprint in the grinding process. Proc IMechE Part B: J Engineering Manufacture. DOI: 10.1177/0954405413508280
[13] Zhang, H.P. Research on prediction techniques of carbon emission during NC milling processes. MS thesis: Harbin Institute of Technology (2012)
[14] H.Narita, H.Kawamura, .Norihisa, .Y.Chen, H.Fujimoto, T.Hasebe. Development of Prediciton System for Environmental Burden for Machine Tool Operation. International Journal of the Japan Society of Mechanical Engineers, Series C, 4: 1199-1195 (2006)
[15] Kardonowy, D.N. A power assessment of machining tools. Bachelor of Science Thesis in Mechanical Engineering, Massachusetts Institute of Technology, (2002)
[16] M.F. Rajemi, P.T. Mativenga, A. Aramcharoen. Sustainable machining: selection of optimum turning conditions based on minimum energy considerations. Journal of Cleaner Production. 18: 1059–1065 (2010)

[17]Environmental evaluation of machine tools — Part 1: Energy-saving design methodology for machine tools. ISO/TC 39/SC N0035e. pp: 3 (2010)