Research on green design framework and support system of metal cutting machine

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Abstract. In order to improve the green design level of metal cutting machine tools, the framework and implementation methods for enhancing the green performance of machine tool’s design process were studied. Analysing the environmental impact of design process, studying the green key points in the design process of materials, structures, hydraulics, lubrication and cooling, a green design framework for the metal cutting machine was established. Centering on the machine tool design process; Researching on the machine tool design support technology and implementation tools, a basic support system for green design of metal cutting machine that integrates technical support layer, interaction layer, tool support layer, technical support layer and user service layer was established. The green design support system for gear making machine was developed and applied to verify the guiding role of green framework and support system in the green design process of metal cutting machine tool.

1. Introduction

Manufacturing is not only China's pillar industry, but a major industry for resource consumption and environmental pollution [1]. Machine tools whose green level is of great significance to enhance the sustainable development of manufacturing. [2]. As the main equipment for parts processing of the machinery industry, metal cutting machine tools are widely used in important fields of national construction, such as automobiles, vessels, aircraft, engineering, machinery and other filed. Therefore, the green research of metal cutting machine tools has far-reaching theoretical and practical significance.

Green manufacturing is a modern manufacturing mode which considers the environmental impacts and the resource benefits throughout the product lifecycle, including product design, manufacturing, packaging, transportation, use, and even disposal[3]. As the main link of the product life cycle chain, the design process greatly determines the green performance in the product life cycle [4]. In the process of promoting the green manufacturing in machine tool industry, we need to take green design as the primary link and focus on green manufacturing of machine tools to carry out the further work[5]. The irreplaceable leading role of the design process in life cycle illustrates studying the green design process of metal cutting machine tools is an effective way to improve the machine tools’ green performance.

Currently, the green research of metal cutting machine tools mainly focuses on the green technology research in the using and disposing process of machine tool. And the study of green design process is mainly about the structural optimization and performance analysis of the components[6, 7]. Literature
[8] studied the effect of combination of micro-lubrication technology (MQL) and cutting parameters on tool life. The literature [9] established the heat transfer model of the high-speed dry-cut hobbing process system to verify the green performance of the high-speed dry-cut hobbing process. The literature [10] introduced the dry, semi-dry and low temperature cold air cutting technology and its green performance; The literature [11-13] studied the machine tool remanufacturing process and its performance evaluation.

This paper focuses on the metal cutting machine design process, analyzing its green status, systematically learning the green design framework of metal cutting machine tools, proposed a technical support system for implementing green design, and developed a green design support system for gear cutting machine tools, expecting to promote the green development of metal cutting machine tools in China.

2. Metal cutting machine tool green design frame
The differences of machine type causes the differences of design content, but they keep consistent throughout the overall design direction. Taking metal cutting machine tools as the research object, we studied the environmental and resource impacts produced by the general scheme design of structure, materials, process, packaging and recycling in the life cycle of the machine tool [14], and constructed the global environmental impact of the metal cutting machine design stage, as shown in Figure 1. This figure embodies that the machine tool design stage as the core key link of the machine tool life cycle, plays a decisive role in the green performance of the machine tool.

![Figure 1. Global environmental impact of the metal cutting machine design phase](image)

Guided by the demand of green machine tools and ecological and humanistic attributes, the paper analyzed the resources and environmental impacts of the machine tool design phases, and focused on controlling the key green nodes in the design of each scheme, established a green design framework for metal cutting machine tools covering green design requirements, attributes and top-down three-layer structure. The green design frame is shown in Figure 2. With the green design requirements and attributes as the guiding principle and effective control of key nodes in the design, the green performance of the machine life cycle will be improved.

2.1. Demand layer
The demand layer describes the overall requirements and fundamental principles of the green design process of metal cutting machine tools, including replace, reuse, recycle, and reduce [14] and functional and economical.
2.2. Feature layer
The feature layer puts forward the green attribute requirements of the design phase based on the comprehensive impact of the machine life cycle on the environment, resources and humans. It includes green structure attributes, green process attributes, green material attributes, green energy consumption attributes, green human-machine attributes, green environmental attributes, and green recycling attributes.

2.3. Design layer
The design layer is a concrete measure to guide the implementation of the green design of metal cutting machine tools. The main design content of the integrated metal cutting machine [4] and the impact of each design content on the environment of the rest of the machine life cycle, based on the key points of the structure, transmission, hydraulic and other major solutions, detailing its green design elements.

(1) Structural scheme
Reasonable machine tool structure scheme is an important measure to ensure multi-axis linkage and motion coordination of machine tools, which helps to improve the green performance of metal cutting machine tools. The green structure scheme design mainly uses the lightweight and modular design method to achieve multi-performance coupling of machine tool structure. The lightweight design is used to trade for lighter weight for better operability. Components such as bed, column, large column, workbench, etc., which are in large automatic and complex shape, are the core that affects the green performance of metal cutting machine tools and also the subject of lightweight design of machine tools research. The structure design should be optimized according to layout, the principle of combining new materials and multidisciplinary application [15], and combine with performance analysis software, to study the weight reduction improvement strategy under the performance conditions. Modular design is a research hotspot in the engineering field, which can effectively solve the contradiction between the change and the design cycle and the tedious workload of replacing the parts in the maintenance under the customized production mode. It has practical significance and practical value in the design process. Module division is the basis and precondition of modular design. In the actual design process, the module division work is often carried out according to the differences in performance, function, structure and specifications. Combined the general and special function requirements of the machine tool, and selected reasonably the modules can make a new type of metal cutting machine tool. The modular design simplified the traditional design process, effectively shortened the product design cycle and ensured product interchange ability under the premise of product quality, which is one of the important means of green design of contemporary machine tools.

(2) Transmission scheme
The design of the transmission scheme has a profound impact on the green performance of the machine tool use phase. The complex machine tool transmission chain structure is the fundamental loss of transmission efficiency, and it is also the main cause of vibration, noise and other phenomena during operation. Considering factors such as energy efficient use and human health, it is not a desirable method for green transmission solutions. The green transmission scheme of the metal cutting machine tool mainly simplifies the transmission chain structure, improves the transmission efficiency, and reduces the transmission process loss by adopting measures such as direct drive of the motor and selecting high-efficiency transmission mode under the requirement of multi-axis linkage movement.

(3) Lubrication scheme
The lubrication scheme is an important approach to reduce the friction and wear of the contact surface between the tool and the workpiece, also the main cause of environmental pollution and waste of resources during the use of the machine tool. According to statistics, in metal cutting, cooling and lubrication costs account for 7.5-17% of the total processing costs [10]. The green lubrication scheme achieves green lubrication from three aspects: lubricant selection, lubrication amount control, and lubricating fluid recovery. The first aspect is to replace the traditional lubricants with nitrosamines, polycyclic aromatic hydrocarbons and bacterial decomposition products with new green lubricants that
are non-polluting, recyclable and easy to produce. Secondly, the processing areas are quantified by means of micro-lubrication and quantitative lubrication, reducing lubricant waste; thirdly, the recycle

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**Figure 2. Green design framework for metal cutting machine**

System can be used to effectively separate lubricants and chips, waste, and purify and recycle lubricants, ultimately achieving green lubrication.

(4) Cooling scheme

Cooling is an important guarantee for quickly reducing the surface temperature of the machine, increasing the life of the hob and enhancing the surface quality of the workpiece. Traditional oil jet cooling is likely to cause environmental pollution and waste of resources in the processing area. The green cooling solution mainly includes efficient cooling and clean cooling. Clean and pollution-free high-efficiency cooling technologies such as air-cooling, water-cooling, and low-temperature cooling have made breakthrough research, basically achieving the performance requirements of green cooling.

(5) Cutting scheme

The design of the cutting scheme of the metal cutting machine plays a decisive role in the green performance of the machine tool. The green cutting schemes mainly include three principles: economical, energy saving, productivity. At present, the common metal cutting methods mainly include dry cutting, semi-dry cutting and wet cutting. According to the cutting speed range, they can be subdivided into conventional speed and high speed cutting in detail [10]. High-speed dry cutting is the most ideal cutting solution and the hot spot of current research. Due to technical reasons, high-speed dry cutting technology is only used in specific machine tools, and the technical difficulties in the large-scale popularization of metal cutting machine tools still need to be further overcome.

(6) Hydraulic scheme

Proper design of the hydraulic scheme helps to reduce oil contamination during metal cutting machine processing. The green design of the hydraulic scheme starts with the enhanced hydraulic system oil recycling and waste residue recycling treatment. By separating the oil and waste residue by filtration, the oil can be recycled repeatedly, and the waste residue can be recycled or discarded after disposal, reducing resource waste and environment pollution.

(7) Material scheme

The material is the basis of metal cutting machine tools, especially the large parts such as bed, column and workbench which has great material consumption. Appropriate selection of materials can help reduce material consumption, improve machine tool rigidity and strength performance, and enhance the use and recycling stage green performance. The principles of material selection are as follows: choose materials which is rich and renewable; select new environmentally friendly materials to reduce
environmental hazards; has good performance and small weight, to satisfy the demand of lightweight; non-toxic and harmless to environment and the human body, including materials themselves and the impact of processing and using stages; can be recycled to reduce the environmental burden.

(8) Parts scheme
The complex composition of metal cutting machine parts is the main reason for the long design cycle and the cumbersome repair parts. The green design of component scheme mainly includes three principles: module subdivision, remanufacturable and reuse, and simplify assemble and disassemble. The modular design concept is used to realize component generalization, specialization and differentiated subdivision, which can achieve the design of short-cycle and high-efficiency design of models, solving the problem of repair and interchange. The recycled machine tool components have good aging properties. Parts can be directly applied to the new product design process of the machine tool through processes such as cleaning, inspection, reuse or remanufacturing, reducing waste of resources; Component selection considers the ease of disassembly and assembly, which can effectively reduce the workload of machine tool assembly and disassembly.

(9) Manufacturing scheme
The green design of the manufacturing scheme considers the optimized combination of processing technology, processing parameters and resource allocation to realize energy-saving and scheduling optimization of the manufacturing process, including the rational design of the process route, the optimized combination of processing parameters, and the reasonable scheduling of production resources. Based on the global processing technology of common parts such as metal cutting machine support parts and guide rails, with the goal of reducing carbon consumption and energy consumption in the process, an optimized process route that meets the production requirements of the product is proposed; The optimization of processing parameters is mainly for the specific processing steps. Through the knowledge base, expert database, etc., referring to the existing processing parameter database information, combined with genetic algorithm, ant colony algorithm and other optimization optimization algorithms, taking carbon consumption and energy consumption as the optimization goal, and the workpiece processing precision, roughness and processing time as the constraints, we find the optimal combination of processing parameters; Reasonable dispatching of production resources mainly refers to the rational allocation of equipment, personnel and tooling in the actual processing tasks.

(10) Packaging scheme
The metal cutting machine tool has high precision, and it needs to ensure the processing precision and internal coordination in the packaging process. Especially in the transportation process, it must be protected from external factors such as transportation vibration. The green demands of the packaging stage are mainly reflected in the selection and recycling of packaging materials and the optimization of packaging structure. Selecting packaging materials during the design phase requires balancing weight and resource attributes; Streamline packaging by reducing the redundancy of traditional packaging structures; recycling of packaging materials by means of re-use and secondary treatment of packaging materials, can effectively reduce environmental pollution of materials.

3. Metal cutting machine green design technical support system
Based on the analysis of the green design framework of metal cutting machine, the green design technical support system for metal cutting machine was established, as shown in Fig. 3. The basic design process of metal cutting machine tools is described from the perspectives of basic resources, technical methods, tool applications, integration interactions and user services, guiding the green design of metal cutting machine tools.

3.1. Basic support layer
The basic support layer is the bottom structure for realizing the green design of metal cutting machine, also a necessary condition for ensuring the development of green design work. The basic layer mainly includes information equipment such as servers, databases, design documents, and manufacturing resources servicing for design process.
3.2. Technical support layer

The technical support layer describes the green technology of metal cutting machine, mainly including lightweight design technology, modular design technology, detachable design technology, human-machine friendly design technology, energy-saving design technology, pollution reduction design technology, remanufacturing design technology, recyclable design technology.

Lightweight design technology aims to reduce the natural resource consumption of the machine tool, and saves the resource consumption of the manufacturing process by simplifying the machine structure, selecting materials, and improving material utilization. Modular design technology uses standardized, interchangeable components to improve component interchange ability between machine tools to reduce work design strength; The human-machine-friendly design technology is designed as a design guideline for operational safety, convenience, and harmlessness to human health, and guides the design of metal cutting machine tools; Processing energy-saving design technology responds to sustainable development from the perspective of energy conservation and the lowest energy consumption of machine tool manufacturing processes; The pollution reduction design technology studies the main pollution sources of waste machines, waste slag, noise and other machine tools, analyzes the pollution emission level of the current design scheme, and reduces the pollution of machine tools through dry cutting, oil filtration cycle, shock absorption and noise reduction; Detachable design technology studies the comprehensive impact of machine tool structure on maintenance, maintenance, and scrapping and dismantling processes, and the results will be applied to improve the structure of machine tool; Recyclable design technology and remanufacturable design technology are based on the difference of machine tool recycling methods, achieving the second use of machine tools through material recovery, component reuse, and remanufacturing. The data shows that remanufacturing technology can save 40%~50% of machine tool cost [16], and parts reuse also avoids environmental pollution and resources and energy consumption during recycling and manufacturing. Applying green design technology in the machine tool design process can effectively improve the green level of the machine life cycle.

3.3. Tool support layer

The tool support layer is specific application means for implementing green design technology. With the perspective of machine tool structure, process and packaging design, analysis and evaluation, the tool set suitable for the green design of metal cutting machine tools that was proposed to assist the design work.

The structural design tool is the basic tool module for machine tool design, mainly for machine structure design and selection. The machine frame is built from the perspectives of machine structure layout, component design modeling, assembly simulation, and auxiliary system design. It mainly includes structural layout design tools, assembly simulation tools, modular design tools, auxiliary system design tools, human-machine safety design tools, and motor selection design tools. At present, conventional computer-aided design software such as Auto CAD, Pro/E, CATIA, Solidworks, etc. can realize machine structure design modeling and assembly simulation.

Process and packaging tools are mainly for machine tool manufacturing solutions, and packaging design. Process routing design tools, processing parameter design tools, and manufacturing resource scheduling tools are used to support the development and optimization of machine tool parts process planning; Packaging design tools can be proposed for machine tool packaging structure and materials High-performance, recyclable, low-cost environmentally friendly packaging solutions [17].

Analytical assessment tools can effectively test and optimize machine performance and green performance, including performance analysis tools, manufacturability analysis tools, resource consumption assessment tools, pollution emission assessment tools, detachability assessment tools, and recyclability assessment tools. The performance analysis tool analyzes the machine, component and material plan in the machine tool design process to check whether the machine tool design meets the dynamic and static performance requirements; The manufacturability analysis tool evaluates the design, manufacturing feasibility and economic benefit of the machine tool design plan to find out the design plan of maximize economic benefits; The resource consumption assessment tool and the pollution
emission assessment tool estimate the machine tool resources, energy consumption, and pollution emissions with the key life cycle of machine tool manufacturing and use. The machine green grade is established based on the same function of the industry green machine tool, so we can compare the green stage of the design plan and improve the insufficient; The detachability evaluation tool addresses the disassembly requirements of machine tool repair, maintenance, recycling, etc., studies the complexity of disassembly of the machine tool, the difficulty of disassembly, and proposes targeted disassembly and rectification measures; The recyclability evaluation tool is based on the manufacturing environment in which the machine is intended to operate, then compute the recycling rate, reuse rate, remanufacturing rate at the time of scrapping, and evaluating whether the machine tool design scheme is conducive to recycling work.

| User layer | structural scheme | parts scheme | material scheme | transmission scheme | cutting scheme | ...... |
|------------|-------------------|--------------|-----------------|--------------------|---------------|-------|
|            | lubrication scheme| cooling scheme| hydraulic scheme| manufacturing scheme| packaging scheme|       |
| Tool support layer | resource consumption assessment tools | pollution emission assessment tools | detachability assessment tools | recyclability assessment tools | ...... |
|            | processing parameter design tools | manufacturing resource scheduling tool | performance analysis tools | manufacturability analysis tools |       |
|            | human-machine safety design tools | motor selection design tools | packaging design tools | process routing design tools |       |
|            | structural layout design tools | modular design tools | assembly simulation tools | auxiliary system design tools |       |
| Integration layer | enterprise service bus |                      |                 |                   |               |
| Basic support layer | server group | basic database | green database | machine file | r&d personnel | manufacturing resources | ...... |

Figure 3. Metal cutting machine green design technical support system

3.4. Integration layer
The integrated layer uses the enterprise service bus to implement information interaction between the tool layer and the base layer to realize resource sharing.

3.5. User layer
The user layer is mainly aimed at the specific design content of the designer, and the design support tool is applied to the metal cutting machine design process in a targeted manner.

The establishment of the green design technical support system will help the green design process of metal cutting machine tools. The rational use of green design methods and tools in the design process is of great significance for optimizing design details, reducing designer workload and reducing design and development costs. At present, the research and application of green design tools are mostly in the theoretical stage, and the market launch needs to be further applied and promoted. The application research of tools will be a hot topic in the future.
4. System application
Through the above research on the green design framework and technical support system of metal cutting machine tools, the gear manufacturing machine is used as the application target, and the green design support system of the tooth-making machine is established. Some software interfaces are shown in Figure 4. Figure (a) shows the design process management of the system for the machine bed, column, hydraulic, cooling, lubrication and other solutions; Figure (b) shows the system software integration interface. The integrated module can realize the comprehensive call of the UG software of the whole machine structure design, the Ansys software of the dynamic and static performance analysis of the machine tool parts, the motor selection software realized by the movement of the machine tool, and the LCA of the green evaluation of the machine tool design. The system has been applied to the design and development department of a machine tool factory in Chongqing to guide the green design process of the tooth-making machine tool. The comprehensive user feedback confirms that the system has a good application effect on improving the green properties of the tooth-making machine.

![Figure 4: Green design support system interface for tooth machine](image)

(a) (b)

5. Conclusion
Focusing on the development trend of green manufacturing industry, this paper studied the environmental and resource impacts of the metal cutting machine design process in the life cycle of the machine tool, established the green design framework of the metal cutting machine tool, and expounded the key elements of the green design process from the perspectives of structure, process and materials. The green design technical support system for metal cutting machine tools including the basic support, technology, realization tools, integration, and user of the green design of the machine tool is proposed to support the concrete implementation of the green design of the machine tool. Research and application of the green design support system for the tooth-making machine tool, confirming that the metal cutting machine tool design framework and technical support system have guiding significance for the green design of the tooth cutting machine tool and other metal cutting machine tools.

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