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Article

Optimization strategy of computer numerical control machining process parameters in biomanufacturing mold

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Abstract: With the rapid development of biomanufacturing technology in the medical and pharmaceutical fields, the demand for high-precision and high-quality molds has surged. When Computer numerical control (CNC) machining biomanufacturing molds, the optimization of process parameters becomes the key to improve efficiency and quality. The purpose of this study is to explore the optimization strategy of CNC machining process parameters to achieve the best surface quality, dimensional accuracy and machining efficiency. Through literature review, the spindle speed, feed speed and cutting depth are selected as the key parameters, and the multi-objective optimization model is constructed by response surface method, which is solved by genetic algorithm. The experiment shows that the process parameters of CNC system in mold manufacturing are cutting speed 100 (m/min), feed rate 0.2 (mm/rev) and cutting depth 0.5 (mm), which will effectively reduce the manufacturing cost, and effectively control the alarm times within 35 times in different processing equipment, greatly reduce the risk. The optimization strategy can significantly improve the surface quality and productivity of the mold and reduce the cost. The comparative analysis verifies the effectiveness of the method, which provides new theoretical and technical support for CNC machining in the field of biomanufacturing.

Keywords: biomanufacturing molds; computer numerical control machining; optimization of process parameters

1. Introduction

In order to enhance the international competitiveness of China's biotechnology industry, we should refer to the policies and practices of developed countries in biotechnology industry and closely combine the actual situation of China to formulate appropriate policies and measures [1]. Based on the analysis of grey theory, a set of characteristic evaluation index system and model for China's biomedicine, a strategic emerging industry, is constructed [2]. By summarizing the successful experience of American biotechnology industry, this paper examines the shortcomings in China's biotechnology industry development strategy, investment and financing system, human resource allocation, industrial layout and structural optimization [3]. This paper expounds the conceptual characteristics and development process of green agriculture, emphasizes the necessity of green agriculture for the development of agricultural modernization in China, and puts forward the suggestion that the government should lead the construction of green agriculture system [4]. As agriculture is the only industry of biomass production, biomass energy not only plays a key role in promoting energy conservation and emission reduction and China's transformation to low-carbon economy, but also enriches the connotation of ecological agriculture [5]. Using economic theory, the relevant core issues are deeply demonstrated from four dimensions: growth limit, sustainable development, technological progress, return on scientific research investment and competitiveness [6]. Using the system theory method, the characteristics of bio-industry are analyzed, and combined with the achievements of industrial biotechnology, the practical application cases and remarkable results of system theory in biological processes are demonstrated [7]. The definition, classification, statistical objectives and methods of China's bio-industry are preliminarily explored, which provides a reference for the construction of China's bio-industry statistical system [8]. Through the multi-angle analysis of economic theory, the foundation of the core discussion of biology is further consolidated [9]. The coefficient of variation method is used to analyze the characteristics of the main economic and scientific and technological indicators of the newly upgraded high-tech zone, follow the innovation-driven development strategy, and focus on exploring a new path to promote the innovation and development of the high-tech zone through the cultivation of innovative clusters [10]. The development of bio-manufacturing industry is of great significance to accelerating China's urbanization process, promoting the prosperity of service industry, protecting the ecological environment and enhancing the international competitiveness of bio-based polymer and chemical manufacturing [11]. In order to cultivate the innovative ability of biotechnology students, the experimental teaching system was reconstructed, a new mode of practice training was explored, and the cultivation of engineering practice ability was strengthened [12]. The application of Computer numerical control (CNC) technology in the field of mechanical manufacturing has significantly improved the overall production quality and is the product of the integration of information technology and numerical control technology [13]. In the research of mechanical design and manufacturing and its automation technology, it is very important to comprehensively analyze the application of computer technology to ensure its maximum efficiency [14]. Modern machinery manufacturing and application with numerical control technology as the core has become a key index to measure the level of science and technology, and plays a decisive role in modern machinery manufacturing [15].

However, although CNC technology has brought unprecedented flexibility and accuracy to biomanufacturing, its processing efficiency, cost-effectiveness and impact on material properties are still one of the main challenges currently facing. Especially when dealing with biocompatible materials such as cartilage and bone, how to choose appropriate process parameters to ensure the best processing results becomes particularly important. Improper spindle speeds, feed rates, or depths of cut can lead to material damage, increased tool wear, or even complete failure to achieve the intended design requirements.

In view of the above problems, this study aims to explore an effective strategy to improve productivity, reduce costs and improve product quality by optimizing the key process parameters in CNC machining. Specifically, we will use response surface methodology combined with genetic algorithm to construct a multi-objective optimization framework, which is used to systematically analyze the influence of different parameter combinations on the processing effect, and screen out the optimal solution from it. This method not only helps to deeply understand the interaction mechanism among various variables, but also provides reliable theoretical guidance for practical operation. By carrying out this work, we expect to not only promote the development of biomanufacturing field, but also provide valuable reference cases for other related industries. In addition, the methodology proposed in this paper has strong universality and can be popularized and applied to a wider range of manufacturing scenarios to further promote the progress and development of intelligent manufacturing technology.

2. Related theories and technologies

2.1. Overview of biomanufacturing molds

Biomanufacturing molds, as the name suggests, are molds used in the biomanufacturing process. These molds may involve many fields such as biology, medicine and manufacturing science, and are used to achieve precise replication and manufacture of living organisms, biological tissues or biological structures. According to different uses and manufacturing processes, biomanufacturing molds can be divided into many types, including but not limited to biomimetic manufacturing molds, biological tissue engineering molds, and the like.

Biomanufacturing molds are manufactured with a wide variety of materials and processes, depending on specific application needs and manufacturing processes. Common manufacturing materials include polymer materials, ceramic materials, metal materials and biocompatible materials. The manufacturing process includes injection molding, 3D printing, laser engraving and other technologies. The selection of these technologies and materials requires a comprehensive consideration of factors such as accuracy, durability, biocompatibility and cost of the mold in **Figure 1**.

Its functions and applications:

Biomimetic Manufacturing: Biomimetic manufacturing molds are able to simulate the structure and function of living organisms to create products or components with similar characteristics. For example, medical devices and implants with excellent mechanical properties and biocompatibility can be manufactured by bionic manufacturing molds.

Biological tissue engineering: In biological tissue engineering, molds are used to guide and promote cell growth and tissue regeneration. These molds often have specific shapes and structures to mimic the morphology and distribution of tissues in living organisms. Through cell culture and tissue induction techniques, biologically active tissue structures can be formed inside the mold for repairing or replacing damaged tissues and organs.

Biomedical research: It has a wide range of applications in biomedical research and can be used to prepare biological samples, conduct drug screening, cell culture and other experiments. The precision and repeatability of these molds help improve the accuracy and reliability of biomedical research.

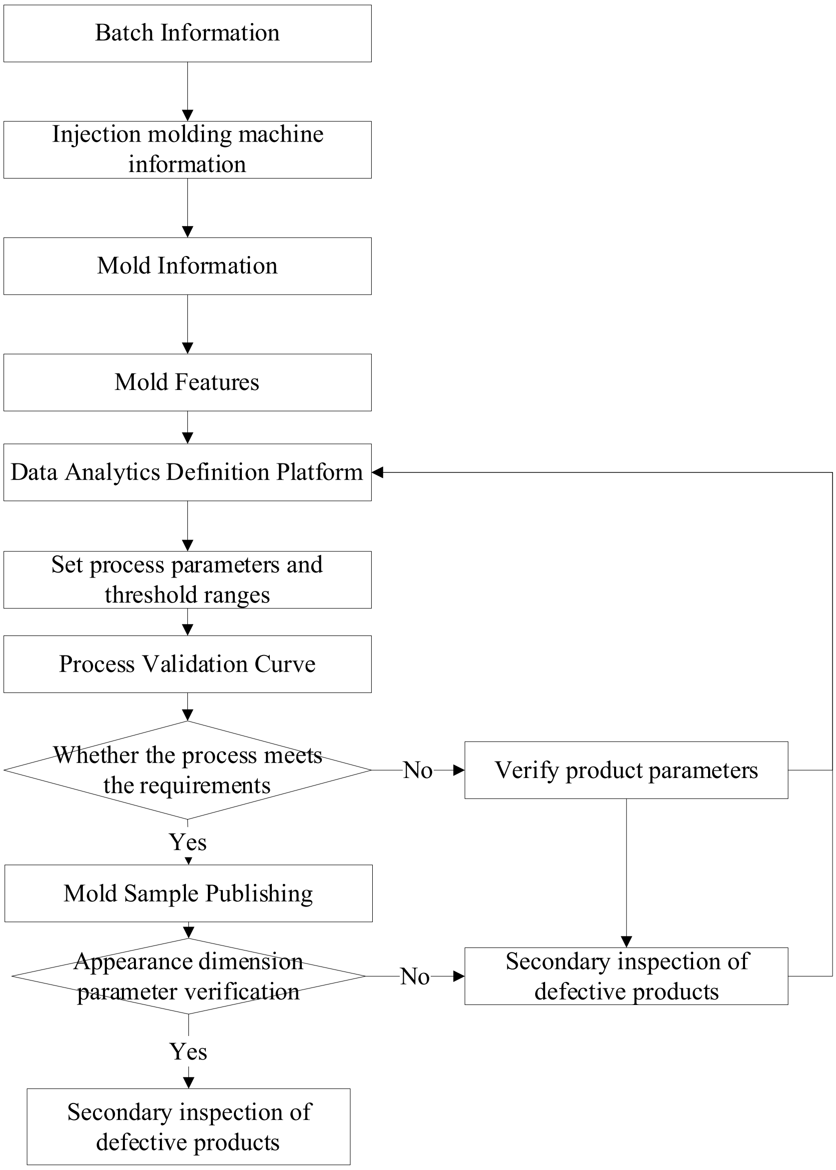

Figure 1. Manufacturing mold production process.

2.1.1. Key elements of mold design and manufacturing

Particularity of biomanufacturing molds

Raw material adaptability: The adaptability of raw materials needs to be considered, that is, the mold design needs to meet the molding requirements of specific biological raw materials. For example, during the biomass solidification molding process, the structure and parameters of the mold need to be optimized according to factors such as the moisture content and particle size of the raw materials.

Molding mechanism and mold parameters: The design of the mold also needs to consider the influence of molding mechanism and mold parameters on the molding process. For example, in the design of biomass hydroforming machine mold, it is necessary to analyze the stress of the mold and determine the most important parameters in the mold structure (such as the length-to-diameter ratio of the large end, the internal diameter ratio of both end faces and cone angle, etc.) to ensure the quality of the product and the wear of the mold.

Temperature and pressure control: In the biomanufacturing process, the control of temperature and pressure is crucial to the molding effect of the mold. For example, in the process of biomass solidification and molding, it is necessary to soften and melt the lignin in the biomass through reasonable temperature and pressure control and act as a binder, while ensuring that the outer surface layer of the molded block is carbonized to reduce motion resistance.

Where biocompatible material selection theory

Surface modification technology: The surface of a material is modified by chemical or physical methods to enhance its biocompatibility. Explain some basic concepts and simple models that may be involved in different types of surface modification processes:

Contact angle measurement: An important parameter used to evaluate surface wettability is the static contact angle θ formed by water droplets on the surface. Equilibrium state [16]:

$$cos\,\theta = \frac{\gamma sv - \gamma sl}{\gamma lv} \tag{1}$$

Electrochemical deposition [17]: By controlling factors such as current density *J*, electrolyte concentration *C*, deposition time and temperature *T*, the film thickness *d* can be adjusted. Faraday's law describes the relationship between the amount of electricity Q transferred through an electrolytic cell and the mass m of matter produced:

$$Q = nF \times m/M \tag{2}$$

With the continuous development of precision machining technology, such as laser machining and ultrasonic machining, the manufacturing accuracy and surface quality of biomanufacturing molds have been significantly improved. These technologies ensure that the tiny details of the mold are machined with precision, improving the quality and consistency of biomanufactured products.

By introducing automation and intelligent technologies, such as robotic processing and intelligent control systems, the manufacturing efficiency and flexibility of biomanufacturing molds can be significantly improved. These technologies can reduce manual intervention and reduce production costs while improving the manufacturing accuracy and reliability of molds.

Introducing on-line monitoring technology can monitor the machining quality and dimensional accuracy of molds in real time. This helps to find and correct problems in the manufacturing process in a timely manner, ensuring that the quality of the mold meets the design requirements. By simulating the actual biomanufacturing process, the performance of the mold can be verified, and its performance in real-world applications can be evaluated. This helps identify potential problems and make improvements, ensuring that the mold can meet real-world application requirements.

2.2. CNC concept and composition

Numerical Control Machine Tools (NC Machine Tools) is a kind of machine tool with automatic control function. It controls the movement and work of the machine tool through digital information to achieve high-precision and high-efficiency machining.

The working principle of CNC machine tool is to transform the mathematical model into the machine tool motion control instruction, and then the computer control system transmits the instruction to each actuator of the machine tool, so that it can be processed according to the predetermined trajectory and speed [18]. The specific process is as follows:

Mathematical model: CNC machine tools need to transform the three-dimensional geometric model of machined parts into mathematical models, including geometric shape, size, position and other parameters.

Programming: According to the mathematical model, a numerical control program is written to convert the instructions that need to be executed in the machining process into machine tool control instructions.

Transmission: Transmit the written NC program to the computer control system of the machine tool.

Control: The computer control system controls each actuator of the machine tool according to the instructions in the numerical control program, so that it can process according to the predetermined trajectory and speed.

Monitoring: The computer control system monitors the movement state of the machine tool in real time, such as position, speed, acceleration and other parameters, to ensure machining accuracy and safety.

The principle of CNC system is mainly based on pre-written programs, which contain all the instructions required in the machining process, such as moving path, speed, depth, etc. After these instructions are processed by the computer, they are converted into signals that the machine can understand, and then control the movement of machine tools. CNC machines are often equipped with multiple axes that allow for precise control in multiple dimensions, allowing for the machining of complex shapes.

CNC system consists of two major systems: hardware and software. The hardware system covers numerical control device, servo system, machine tool body, input and output equipment and auxiliary equipment, and is responsible for executing machining instructions and mechanical movements [19]. The software system includes operating system, programming language, numerical control system software, human-computer interaction software and auxiliary software, which is responsible for data processing, control instruction generation and interaction with operators. These two parts work together to ensure the efficient and accurate operation of the CNC system in **Figure 2**.

CNC system is a highly automated closed-loop control system. It receives user instructions through the operation panel and software. After being processed by PLC and CNC devices, it accurately controls the spindle, feeding device and other components of the machine tool for processing through servo units and equipment drivers. At the same time, it uses the monitoring device to feed back the machining status in real time, so as to compensate for errors or adjust machining parameters, and finally ensure the completion of high-precision and high-efficiency machining tasks.

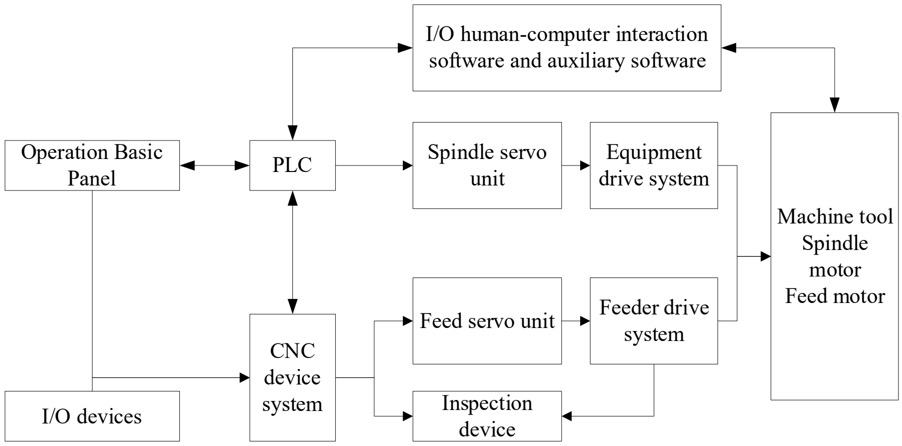

Figure 2. CNC system framework diagram.

CNC working principle and algorithm

The DDA algorithm generates a continuous curve or straight line by accurately calculating the increment of each small step, which can provide a smooth and accurate movement path for the tool. At the same time, the algorithm also has the function of speed control, which can carry out variable speed control according to the machining requirements. However, the DDA algorithm may require higher computational accuracy and more complex algorithm implementation when dealing with complex curves. Therefore, in practical applications, it is necessary to select the appropriate interpolation algorithm according to the specific situation to ensure the machining accuracy and efficiency.

Line segment interpolation [20]:

During CNC machining, the tool needs to move along a predetermined path to cut out the desired shape. The DDA algorithm is able to calculate the straight line segment that the tool should move in each tiny time period based on the coordinates (*X*, *Y*) of the start and end points, and the required feed rate. Plug-in equation [21]:

$$\frac{v}{OE} = \frac{v_x}{X_e} = \frac{v_y}{Y_e} = k \tag{3}$$

K is the scaling factor, and the position amount in a certain time in the incremental direction of the *X* and *Y* axes is:

$$\Delta X = v_x \Delta t = k \Delta X_e \Delta t \tag{4}$$

$$\Delta Y = v_y \Delta t = k Y_e \Delta t \tag{5}$$

When $t = 1$, the displacement of *X* and *Y* is:

$$X = k \sum X_e \tag{6}$$

$$Y = k \sum Y_e \tag{7}$$

The registered functions on each corresponding axis will be accumulated, and the pulse period of each time period drives the overall capacity of *X* and *Y*, and the excess part will be accumulated and accelerated in it, and interpolated in turn [22]. The specific process is shown in **Figure 3**:

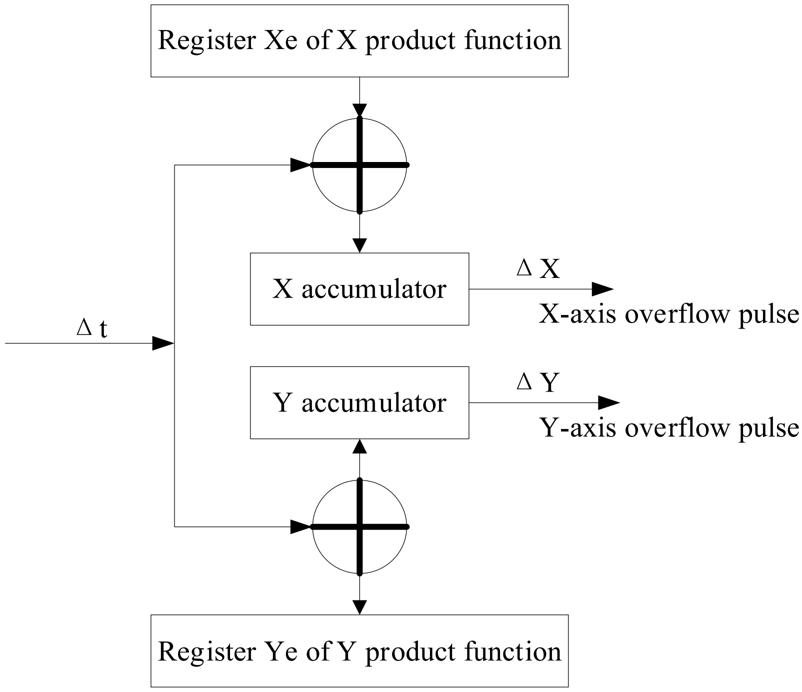

Figure 3. Flowchart of linear interpolation.

After accumulating to m times, the final container will reach the full value, and the corresponding axial direction will also reach the end point, that is:

$$X_e = kX_e m \quad (8)$$

$$Y_e = kY_e m \quad (9)$$

Seek worth it

$$km = 1 \quad (10)$$

The relationship between *m* and *k* is:

$$m = \frac{1}{k} \quad (11)$$

When the capacities of the register and accumulator are equal, the maximum value of each coordinate can be guaranteed to obtain one pulse at a time, so that each increment will not be greater than 1 [23]. The calculation formula is as follows:

$$k(2^n - 1) < 1 \quad (12)$$

Conversion

$$k < \frac{1}{(2^n - 1)} \quad (13)$$

Value

$$k = \frac{1}{2^n} \tag{14}$$

Combined with the cumulative operation of $m = 2n$, the end point of the straight line is reached, thus completing a linear accelerator, and only a simple one-digit accelerator is needed to complete the interpolation work [24]. In addition to linear interpolation, of course, circular interpolation has different starting points. Make a quadrant inverse circular arc, given a constant velocity, that is, the velocity component is:

$$\frac{v}{r} = \frac{v_x}{Y_i} = \frac{v_y}{X_i} = k \tag{15}$$

Since the arc is in the first quadrant and is an inverse arc, the X shift vector over a period of time is negative and Y is positive, then:

$$\Delta X = -kY_i\Delta t \tag{16}$$

$$\Delta Y = kX_i\Delta t \tag{17}$$

In the same way, the X and Y coordinate movement when $t = 1$ is:

$$X = -k\sum Y_i \tag{18}$$

$$Y = k\sum X_i \tag{19}$$

In circular interpolation, the accumulators Jvx and Jvy of X and Y will be stored in the starting point coordinates, and each cycle will exceed the pulse cycle. Through the correction of the coordinate value, it will finally be input to the-X and Y direction, and its coordinate flow chart is shown in **Figure 4**:

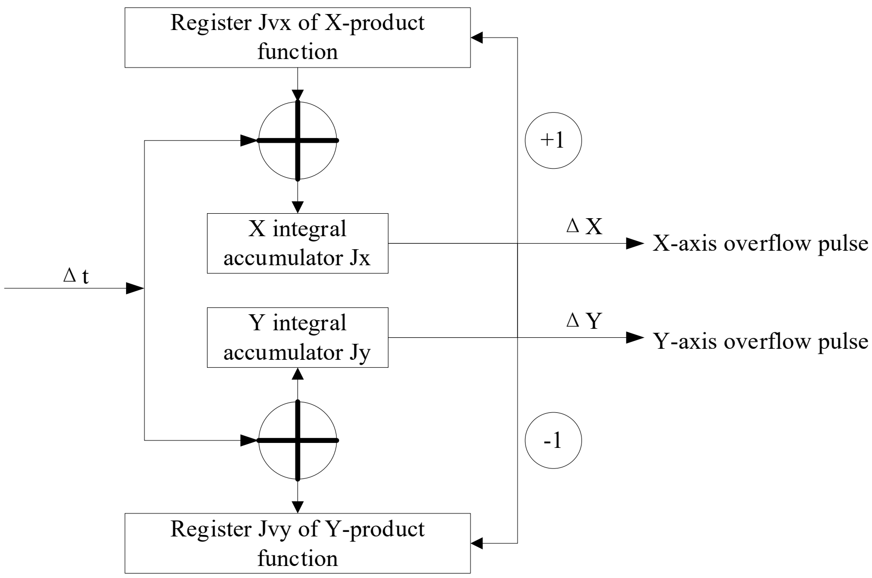

Figure 4. Flow chart of circular arc pin.

The end point judgment mechanism of DDA circular interpolation method can be realized by configuring two counters, which store the absolute value of the coordinate difference between the end point and the starting point of each axis [25]. During the interpolation process, the counter of the corresponding axis decreases by 1 for each feed step. When the counter of a certain axis decreases to 0, the axis stops feeding; If both axis counters reach 0, the interpolation process ends.

3. Hardware and software structure design of CNC system

When building the hardware of CNC system, we first need to choose an appropriate controller as the core component, which is responsible for handling all logic operations and control tasks. Then, the servo motor and its driver are installed to accurately move the machine tool axis, and the accurate position detection is realized by feedback devices such as encoders. In addition, it is necessary to configure appropriate input/output interfaces (such as operator panels, displays) to facilitate human-computer interaction, and ensure that there is a reliable power supply system to support the normal operation of all components. Finally, according to the processing requirements, the corresponding mechanical structures are designed or selected, including bed, guide rails and fixtures, which constitute the basic frame of CNC machine tools in **Figure 5**.

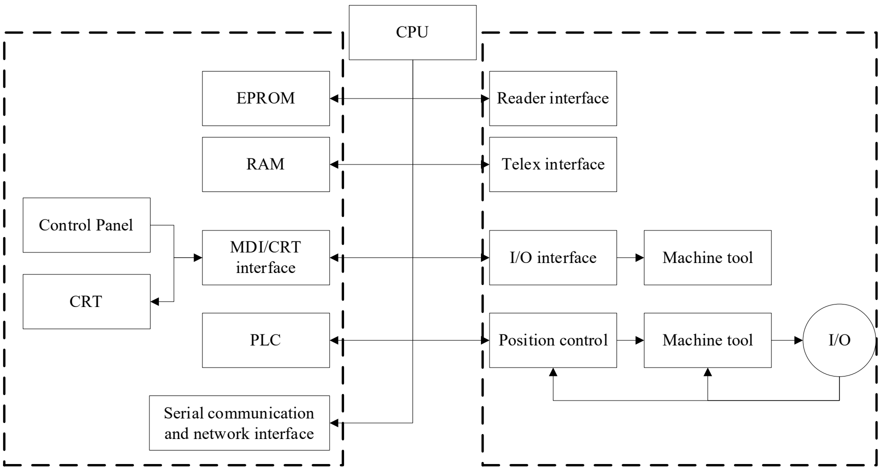

Figure 5. CPU system structure diagram.

The software work begins with selecting an appropriate operating system, which needs to be compatible with the selected controller and provide a stable running environment for the upper application programs. The next step is to develop or integrate control software, which includes functional modules such as decoding G code instructions, interpolation calculation to generate smooth path, and planning speed curve. At the same time, it is also necessary to create an intuitive and easy-to-use user interface, so that operators can easily write programs, set parameters and monitor the machining process. In addition, auxiliary functions such as fault diagnosis and maintenance tools and network communication protocol support should be added to improve the overall performance and availability of the system. As the project progresses, the entire software package is continuously tested and optimized, ensuring its stability and efficiency in **Figure 6**.

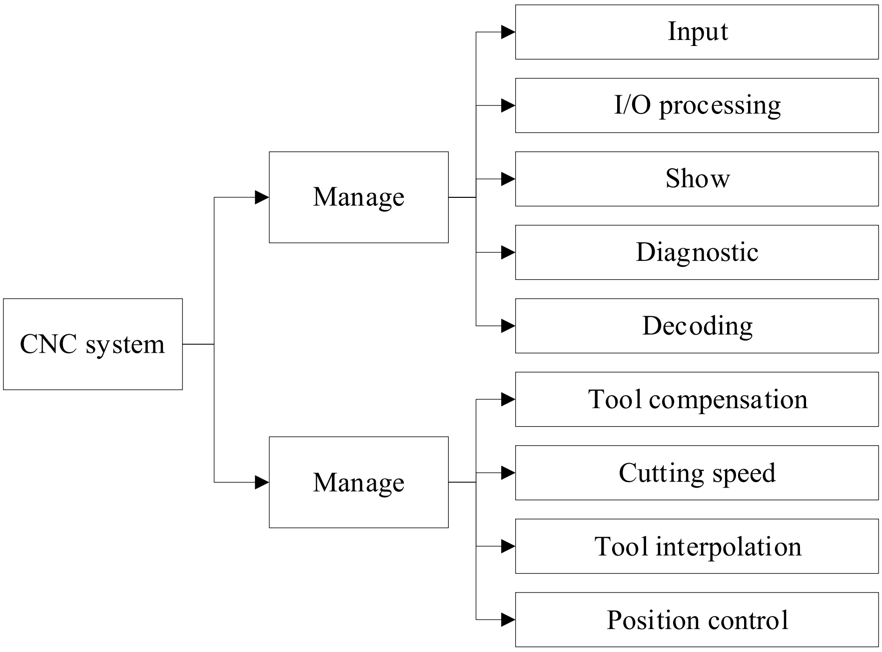

Figure 6. CNC software system structure.

Most NC machining programming is carried out according to the outline of the part, and the radius and length of the tool need to be taken into account in actual operation. At this time, the tool compensation function needs to be used to process the decoding results. The CNC system mainly manages the feed speed in two ways: one is to follow the programming instructions, and the other is to manually adjust the magnification during machining. The speed processing module is responsible for regulating the output pulse frequency according to these two requirements and the selected interpolation algorithm.

On CNC machine tools, the minimum unit of tool movement is pulse equivalent, and the task of the interpolation module is to accurately calculate multiple intermediate position coordinates of the tool from the start to the end of each movement step according to the set feed speed. Interpolation technology is the core component of control logic of numerical control system. For NC simulation, tool compensation, speed processing and interpolation modules are not the key points for two reasons: First, the performance of the computer running the simulation program far exceeds that of the computer used in the NC system, and the time to process these calculations is much shorter than the image rendering time; Second, the algorithms of these modules are quite mature, and the differences between different CNC systems are small, so the implementation difficulty is low. In some numerical control systems, the control program modules may be implemented by hardware, while in numerical control simulation systems, these functional modules should also be considered as elements equivalent to the hardware structure.

4. Application of CNC system in biomanufacturing mold

4.1. Automatic control of biological mold manufacturing by CNC System

CNC hardware and software system is a comprehensive system integrating precision control and efficient machining. The hardware system takes the numerical control device as the core, combined with the motion control system and the workpiece correction system, to realize the precise control and error correction of the machine tool motion. In bio-mold manufacturing, the spindle speed has a direct impact on the processing efficiency, a significant effect on the quality of the mold, and a close relationship with the tool life. The spindle speed not only determines the cutting speed and processing time, but also affects the surface quality, dimensional accuracy of the die and the durability of the tool. Therefore, by adjusting the spindle speed, the processing technology can be optimized, and the production efficiency and die quality can be improved. The reason why the spindle speed is the core of the experimental data of bio-manufacturing mould is that it is controllable, easy to observe and measure, and representative. The spindle speed can be accurately set by the machine tool control system, which is convenient for adjustment and control during the experiment. At the same time, the spindle speed has a significant impact on the machining process, which can reflect the interaction between the machine tool, the tool and the workpiece, and provide an important basis for optimizing the machining process. Therefore, the spindle speed is an indispensable key parameter in the biomanufacturing mold experiment.

The software system guides the machining process through the numerical control program written by engineers and the set machining parameters. By optimizing the motion trajectory, selecting appropriate machining parameters, and monitoring and adjusting the machining process in real time, CNC system can greatly improve the efficiency and accuracy of biomold machining and ensure the machining quality and safety. The realization effects of the hardware control system are shown in **Table 1**.

Table 1. Machine tool parameter setting values of CNC hardware system.

Parameter category	Parameter Name	Set Range/Unit	Set Value
Motion control	Spindle speed	n = 1000~10,000 RPM	n = 5000 RPM
	Feed speed	F = 0.01~500 mm/min	F = 100 mm/min
	Depth of cut	Ap = 0.01~10 mm	Ap = 2 mm
	Positioning accuracy	P = ± 0. 001~± 0.1 mm	P = ± 0.01 mm
	Repeated positioning accuracy	Rp = ± 0. 0005~± 0.05 mm	Rp = ± 0.005 mm
Servo system	Type of servo motor	AC/DC servo motors, linear motors, etc	AC servo motor
	Servo amplifier gain	K = 1~100	K = 50
	Position feedback device	Grating ruler, magnetic grating ruler, laser rangefinder, etc	Grating ruler
Workpiece correction system	Thermal distortion compensation	T = 050 °C, ΔL = ± 0.1 ± 1 mm	ΔL = ± 0.5 mm
	Geometric error compensation	ΔX, ΔY, ΔZ = ± 0.01~± 1 mm	ΔX = ± 0.05 mm, ΔY = ± 0.03 mm, ΔZ = ± 0.02 mm
Other parameters	Coolant system	Q = 550 L/min, P = 0.55 MPa	Q = 20 L/min, P = 2 MPa
	Tool selection and replacement	Tool magazine capacity, tool change time, etc.;	Tool magazine capacity = 30, tool change time = 5 s
	Safety protection system	Protective cover, emergency stop button, safety door, etc	Equipped with complete safety protection system

A three-dimensional model is created or imported using computer-aided design (CAD) software, and the machining path is generated according to the model by using CAM functions. This step determines how the tool moves to remove material and form the final part shape. Based on the machining strategy set in CAM, the software will automatically generate G code, which is a standardized language used to instruct CNC machines to perform specific operations such as movement, rotation, etc. Simulation & Optimization Modern CNC software supports simulating the entire production process, allowing users to check for potential issues such as collision detection and adjust parameters to optimize efficiency and quality in **Table 2**.

Table 2. Software-controlled biomanufacturing value table.

Processing aspects	Software Control Effect Data/Description	Value to biomoldmaking
High-precision programming capabilities	Programming accuracy reaches ± 0. 005 mm	Improve biomold manufacturing accuracy to ± 0.01 mm
Diversified processing strategies	Supports more than 5 machining strategies, including roughing, finishing, five-axis linkage, etc.	Processing efficiency is improved by 30% and quality stability is improved by 20%.
Real-time monitoring and feedback	Monitoring frequency: 10 times per second, feedback response time: < 1 s	Exception handling time is reduced to less than 5 minutes, reducing machining errors
Automation and Intelligence	Automation rate: 90%, intelligent algorithm optimizes processing path efficiency to increase by 15%	Labor costs reduced by 25% and machining consistency improved to 98%
Data processing capabilities	Data processing capability: 1000 pieces of data processed per s, optimization suggestion accuracy rate: 90%	Optimized processing parameters, improved efficiency by 10% and reduced cost by 5%
Flexible parameter settings	Parameter setting range: cutting speed 50–500 m/min, feed speed 0.01–100 mm/rev	Meet different material and processing needs, customized processing
Rich tool library and management	Tool magazine capacity: more than 100 types, tool utilization rate increased to 85%	15% reduction in cutting tool costs and 5% improvement in machining efficiency
Powerful post-processing capabilities	Simulation accuracy: 95%, machining path optimization efficiency improved by 20%	Pre-processing prediction to reduce trial and error costs and improve efficiency
Easy to integrate and scale	Number of integrated interfaces: 10, number of customized development functions supported: more than 5	Improved system flexibility to adapt to different application scenarios
Friendly user interface	User Interface Operation Rating: 4.8/5	Reduce operation difficulty and improve efficiency

CNC hardware and software system speeds up the development cycle of biomold, reduces material waste and cost, enhances production flexibility and safety, and promotes the application of new materials and processes by providing high precision, consistency and repeatability, thus not only greatly improving the technical level of biomold manufacturing, but also bringing significant economic and social benefits to enterprises. In order to improve the stability of the experiment, the experimental analysis is carried out on different environmental variables, which shows that the alarm situation of the processing equipment at different temperatures shows the improvement of processing efficiency, and reveals that humidity has a significant impact on the processing accuracy of machine tools, with the increase of humidity, the processing accuracy of CNC systems, robot control systems and other machine tools generally decreases. When the humidity exceeds a certain range (> 60% RH), the machining accuracy decreases significantly and even can not be processed. The importance of controlling the humidity of the machining environment to improve the machining accuracy of the machine tool is emphasized.

4.2. Best performance of biomold process parameters

For the relevant key parameters, the reason why the spindle speed is the core of the experimental data of bio-manufacturing mould is that it is controllable, easy to observe and measure, and representative. The spindle speed can be accurately set by the machine tool control system, which is convenient for adjustment and control during the experiment. By changing the feed rate, the changes of cutting force and cutting heat in the cutting process can be explored in depth, which provides strong support for optimizing the processing technology. A deeper understanding of the various phenomena in the cutting process, so as to find the best cutting parameters, improve the processing efficiency, while ensuring the high quality and stability of the mold.

CNC machining of biomanufactured molds is the use of CNC technology to accurately manufacture high-precision molds required in biomedical engineering, which are used to produce biocompatible products. When determining the optimal process parameters, background factors such as high precision requirements, material specificity, small batch production and regulatory compliance need to be considered. Optimizing process parameters can improve product quality, enhance production efficiency, reduce costs, and support innovative design and sustainable development. Methods to determine the optimal parameters include experimental research, simulation simulation, data analysis, and intelligent recommendation using expert systems or artificial intelligence.

Table 3 shows that the optimal cutting speed for all control systems is trending upward as the mold accuracy requirements decrease. The recommended speeds of CNC system, robot control system and flexible manufacturing system are relatively close, while the recommended speed of direct digital control system is slightly lower.

Table 3. Optimal cutting speed of different die accuracy.

Mold Accuracy (μm)	CNC system	Robot control system	Flexible manufacturing system	Direct digital control	Monitoring and data acquisition system	Programmable logic controller
0.3	30	32	31	29	30	32
0.4	35	37	36	34	35	38
0.5	40	42	41	39	40	45
1.0	60	62	61	59	60	66
1.5	80	82	81	79	80	82
2.0	100	102	101	99	100	112
2.5	120	122	121	119	120	125
3.0	140	142	141	139	140	143
3.5	160	162	161	159	160	165
4.0	170	175	172	765	170	179

Table 4 reveals the influence of humidity on the machining accuracy of different control systems of the machine tool. In the low humidity environment (< 20%), the machining accuracy of each system has a small fluctuation, but with the increase of humidity, the error has an increasing trend.

Table 4. Machining accuracy of mould under different humidity.

Humidity range	CNC base feed rate (mm/min)	Fixed feed rate	Adaptive control	Time Optimization	Energy efficiency	Surface quality
< 10	± 3	± 3.5	± 2.5	± 4	± 3	± 4.5
10–20	± 4	± 4.5	± 3.5	± 5	± 4	± 5.5
20–40	± 5	± 6	± 4.5	± 7	± 5.5	± 6.5（
40–60	± 12	± 15	± 10	± 18	± 13	± 16
60–80	± 22	± 30	± 25	± 35	± 28	Unable to process
> 80	Unable to process	Unable to process	Unable to process	Unable to process	Unable to process	Unable to process

Programmable logic controllers (PLCs) provide high cutting speeds when high precision is required. It is worth noting that at an accuracy of 4.0 μm, 765 m/min in the "Direct Digital Control" column may be a data error. Generally speaking, different control systems have differences in setting the optimal cutting speed with the same accuracy.

As can be seen from **Table 5**, the CNC base feed speed settings vary for different die geometries, with the flat having the highest base feed speed (1500 mm/min) and the narrow groove having the lowest base feed speed (450 mm/min). When adaptive control is employed, feed rates for other geometries are improved compared to base values except for right-angled interior angles and narrow slots. The feed rate under the time optimization strategy is typically close to or slightly lower than the base speed. In contrast, in pursuit of energy efficiency and better surface quality, the feed rate is significantly reduced, especially most noticeable when dealing with flat and arc radii. This shows that in the actual machining process, according to the different objectives (such as improving productivity, saving energy consumption or ensuring surface finish), it is necessary to adopt corresponding optimal feed parameter settings for dies with different geometries.

Table 5. Optimal parameters of feed speed for different die shapes.

Geometry	CNC base feed rate (mm/min)	Fixed feed rate	Adaptive control	Time Optimization	Energy efficiency	Surface quality
Plane	1500	1500.0	1800.0	1650.0	1350.0	1200.0
Right interior angle	750	750.0	600.0	675.0	525.0	450.0
Arc radius	1150	1150.0	1265.0	1150.0	1035.0	920.0
Bevel	950	950.0	855.0	950.0	760.0	665.0
Narrow groove	450	450.0	315.0	360.0	270.0	225.0

Table 6 shows that under different tool life stages, the recommended cutting depth of all systems shows a decreasing trend as the tool goes from new tool to near failure, indicating that in order to ensure the machining quality and prolong the service life of the tool, it is necessary to gradually reduce the cutting load when the tool is gradually worn. In addition, no matter which tool life stage, the depth of cut of CNC system is usually set to the highest, while the depth of cut of direct digital control

system is relatively lowest, which shows that different control systems have different adaptability and considerations for tool status and machining strategy. CNC systems achieve savings in both raw material and power costs by improving material utilization and reducing energy consumption. At the same time, automated processing greatly improves production efficiency, reduces labor costs, significantly shortens production cycle, and enhances market responsiveness. In addition, the CNC system also significantly reduces the scrap rate, reduces the rework cost and time, and ensures the machining accuracy and quality stability, thereby reducing the quality inspection cost and improving the customer satisfaction. The CNC system brings an overall benefit improvement in the bio-mold manufacturing.

Table 6. Comparison of cutting depths of different tools.

Tool life phase	CNC system	Robot control system	Flexible manufacturing system	Direct digital control	Monitoring and data acquisition system	Programmable logic controller
New knife	0.5	0.6	0.55	0.48	0.52	0.51
Mid-term wear	0.4	0.5	0.45	0.38	0.42	0.40
Late wear	0.3	0.4	0.35	0.30	0.32	0.31
Close to failure	0.2	0.3	0.25	0.22	0.24	0.23

It can be seen from the **Table 7** that different parameter combinations have significant effects on surface roughness, machining time, tool life and material removal rate. Combination E has the most balanced performance at a high cutting speed (100 m/min) and moderate feed rate and depth of cut (both 0.2 mm/rev and 0.5 mm). It not only achieves the lowest surface roughness Ra value (0.17 µm), but also has the longest tool life (16 h) and relatively high material removal rate (2.1 cm ^{3}/min), and the machining time is properly controlled (2.7 min). In contrast, while combination C provided the highest material removal rate (2.4 cm^3/min), it had a high surface roughness (0.25 µm) and the shortest tool life (10 h), suggesting that excessive cutting speeds may sacrifice machining quality and tool durability. Therefore, parameter combination E seems to be an ideal choice for application scenarios that pursue the balance between high-quality surface finish and efficiency.

Table 7. Process parameter combination results chart.

Parameter combination	Cutting speed (m/min)	Feed rate (mm/rev)	Depth of cut (mm)	Surface roughness Ra (µm)	Processing time (min)	Tool Life (h)	Material removal rate (cm^3/min)
A	80	0.15	0.4	0.18	3.2	12	1.6
B	100	0.2	0.5	0.19	2.8	15	2.0
C	120	0.25	0.6	0.25	2.5	10	2.4
D	90	0.2	0.5	0.21	3.0	14	1.8
E	100	0.2	0.5	0.17	2.7	16	2.1

This paper summarizes five typical cases of CNC system in biomedical mold manufacturing, involving biomedical, biological experiments, biotechnology, Bioanalysis, tissue engineering and other fields. Each case demonstrates the ability of CNC system to handle polymer materials, stainless steel, glass and other materials, as well as the advantages of high-precision mold manufacturing. The cycle time varies according to the type and complexity of the mold, but it achieves an increase in production efficiency and a saving in production costs of up to 25%. These cases fully reflect the flexibility and efficiency of CNC system in biomedical mold manufacturing, and provide strong support for the development of biomedical field.

5. Conclusion

This paper analyzes the application status of NC machining technology in biomanufacturing molds, and points out the problems and deficiencies existing in the setting of current process parameters. By comparing the advantages and disadvantages of traditional machining technology and numerical control machining technology, the advantages of numerical control machining technology in improving the accuracy and efficiency of mold manufacturing are defined. Secondly, according to the specific characteristics of biomanufacturing molds, a series of optimization strategies are proposed. These strategies include optimization of cutting parameters, optimization of tool path and adjustment of machining strategy. Through detailed theoretical analysis and experimental verification, the effectiveness of these optimization strategies in improving the quality and efficiency of die processing is proved.

Shortcomings of experiments: Although this paper has achieved some research results in the optimization strategy of CNC machining process parameters in biomanufacturing molds, the experimental data are limited: Due to the limitation of time and resources, the experimental data in this paper are relatively limited and fail to cover all possible machining conditions and mold types. This limits the universality and applicability of the optimization strategy to some extent.

Insufficient theoretical depth: Although this paper systematically discusses the optimization strategy of NC machining technology, the theoretical depth in some aspects still needs to be strengthened. For example, this paper fails to conduct in-depth quantitative analysis and modeling of the effects of complex physical phenomena such as tool wear and cutting heat.

Insufficient technology integration: With the development of technology, the integration of CNC machining technology with artificial intelligence, Internet of Things and other technologies is getting higher and higher. When discussing optimization strategies, this paper fails to fully consider the application of these emerging technologies, which limits the advancement and innovation of optimization strategies to some extent.

By increasing experimental conditions and mold types, more experimental data are collected to validate and optimize the proposed optimization strategy. At the same time, a more complete database can be established to provide more reliable data support for subsequent research and application.

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