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FLEXIBLE CONSTANT FORCE GRINDING OF RARE EARTH METAL INGOT

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The rare earth metal ingots obtained by molten salt electrolysis method have oxide layers, salt layers, and other impurities on the surface, which require polishing processing. However, currently, manual polishing processing has problems such as low processing efficiency and resource waste. By designing a flexible end effector and adopting a parallel fuzzy Proportion Integration Differentiation (PID) control strategy for constant force control of the end effector, automation and high efficiency of rare earth metal ingot grinding are achieved.

Keywords: rare earth metal; ingot; grinding processing; constant force control; fuzzy PID control

INTRODUCTION

Rare earth elements in electricity, magnetic, optical and other aspects have a good performance, in the military, aviation and aerospace fields and electronic information fields are playing a pivotal role. Rare earth elements are 17 elements, including lanthanide, scandium, neodymium and so on.[1] Molten salt electrolysis is the most commonly used method for preparing rare earth metal elements and their alloys.[2,3] According to electrolytes, molten salt electrolysis is divided into rare earth chloride molten salt electrolysis process and rare earth fluoride molten salt electrolysis process.[4] The process flow of preparing rare earth metals by molten salt electrolysis of rare earth fluoride is shown in Figure 1.

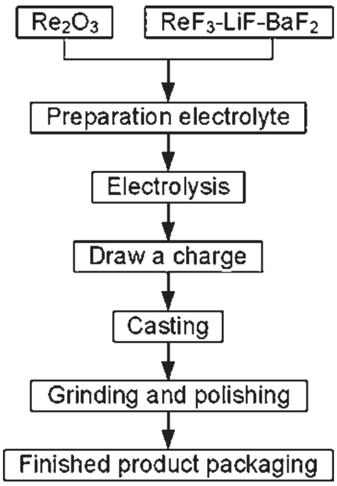

Figure 1 Process for preparation of rare earth metals by molten salt electrolysis.

The process is used to produce rare earth metals with melting point below 1 100 °C. The electrolytic process is carried out in the electrolytic furnace. The rare earth oxide is put into the fluoride melt, after electrolysis, the rare earth cation Re^{3+} is precipitated at the cathode. The electrochemical reaction is as follows:

Cathode reaction: $Re^{3+} + 3e = Re$;

Anodic reaction: $2O^{2-} - 4e = O_2$;

$2O^{2-} + C - 4e = CO_2$;

$O^{2-} + C - 2e = CO$;

When the anode effect occurs, the anode reaction is:

$$4F^- + C = CF_4 + 4e.$$

In summary, the total reaction is as follows:

$$Re_2O_3 + C = 2Re + 3/2CO_2.$$

Because rare earth metal elements have high metal activity (second only to alkali metal elements), the surface of rare earth ingot is easy to form oxide layer. The surface of rare earth ingot obtained by molten salt electrolysis will adhere to metal oxide layer, deposited salt layer and other impurities, as shown in Figure 2.

The rare earth metal ingot needs to be polished to remove the oxide layer, salt layer and other impurities

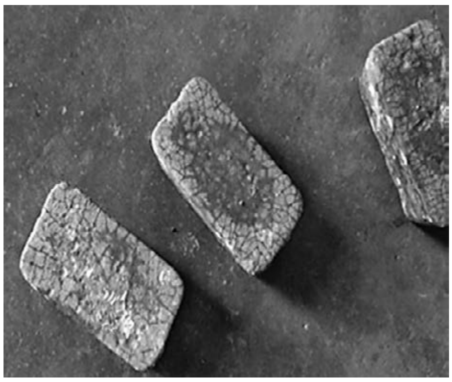

Figure 2 Unpolished rare earth metal ingot

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Figure 3 Polished rare earth metal ingot

on the surface before it can be used. The polished rare earth metal ingot is shown in Figure 3. At present, the surface treatment of rare earth ingot usually adopts the way of artificial grinding, which is difficult to control the grinding amount, resulting in low grinding efficiency, poor processing quality and waste of rare earth metal resources.

DESIGN OF FLEXIBLE END-EFFECTOR FOR RARE EARTH METAL INGOT POLISHING

In order to better solve the grinding problem of rare earth metal ingot, to achieve the requirements of high efficiency and high precision in the grinding process, a flexible floating end-effector was designed. As shown in Figure 4. The device is composed of a motor, a six-dimensional force sensor, a spring device, a distance / Angle detection device, etc. The flexible floating of the end effector of the rare earth ingot polishing is realized by the elastic device in the three columns. The spring device is distributed in a circular array, with 120 degrees between the two pairs, which can realize the floating of different angles. It can solve the problem of rough surface of rare earth ingot and achieve uniformity of grinding. When contacting the surface of the rare earth metal ingot, the spring device achieves flexible contact with the polished surface through elasticity to reduce contact impact. In the process of grinding, the detector detects the output force and feeds back to the control system. It adjusts and controls the output force of the end effector in real time through the control strategy to realize the constant force output of the end effector.

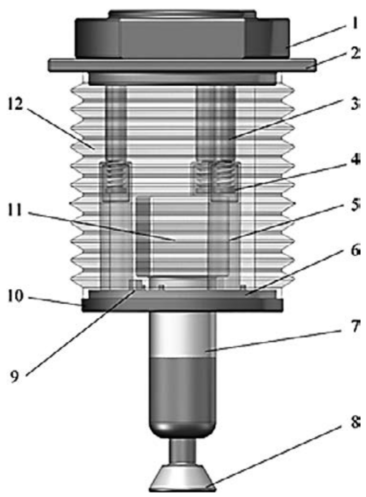

Figure 4 Rare earth metal ingot polishing end effector
1 - connecting flange; 2 - upper connecting plate; 3 - on the column; 4 - elastic device; 5 - under the column; 6 - Angle detection device; 7 - six-dimensional force sensor; 8 - polishing tools; 9 - distance detection device; 10 - bottom plate; 11 - motor; 12 - Outer cover

RARE EARTH METAL INGOT GRINDING CONSTANT FORCE CONTROL

In the process of grinding the surface of rare earth ingot, the contact force between the grinding tool and the surface of rare earth ingot should be kept constant at 25 N to obtain good grinding effect. Parallel fuzzy PID control strategy is used to realize constant force output of end-effector.

The stress of the end-effector was analyzed, as shown in Figure 5.

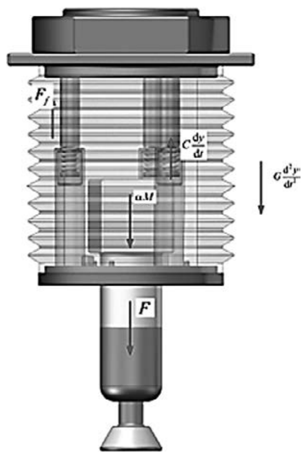

Figure 5 Stress analysis diagram of end-effector

According to the stress of the end-effector, the force balance equation is established:

$$\alpha M - F_f = G\frac{\mathrm{d}^2 y}{\mathrm{d}t^2} + C\frac{\mathrm{d}y}{\mathrm{d}t} + F \tag{1}$$

Where, α is the conversion coefficient of the motor, M is the output torque of the motor, F_f is the resultant force of the system friction, G is the total mass of the flexible floating device of the end-effector, C is the friction damping coefficient, y is the displacement of the spring, and F is the output force.

The response curve of the terminal output force obtained by detecting the terminal output force is shown in Figure 6.

According to the output force response curve at the end of the figure, the mathematical model of the force control device of the end-effector is obtained through Laplace transform calculation:

$$G(s) = \frac{11{,}374}{0{,}01952\ s^3 + 0{,}04784\ s^2 + 0{,}339\ s + 1} \tag{2}$$

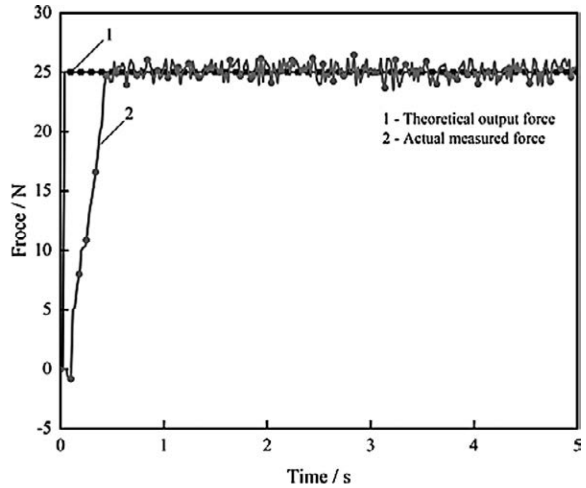

Figure 6 Response curve of terminal output force

The parallel fuzzy PID control strategy is adopted. The fuzzy control and PID control of this strategy are synchronized in time domain. It can not only avoid the steady-state error in fuzzy control but also make up for the shortcomings of PID control, realize the real-time control of terminal output force and achieve the purpose of constant force output.[5, 6] The simulation model is built by Simulink.

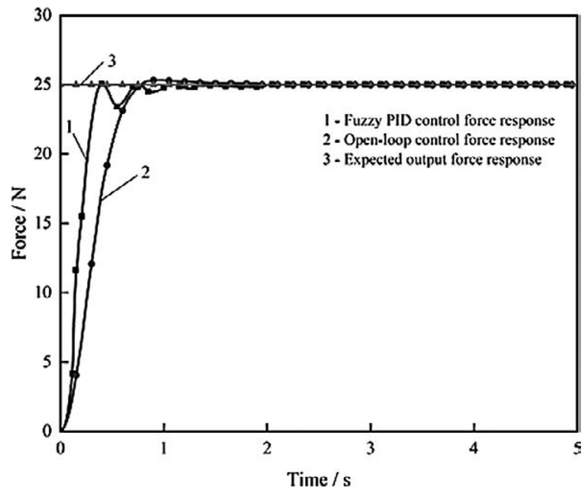

Figure 7 Step response curve of fuzzy PID control

In order to study the performance of the fuzzy PID parallel control strategy, sinusoidal following signals and step signals were input into the Simulink simulation model. When t = 0 input signal F = 25 N, the step response curve of system output force is obtained, as shown in Figure 7. According to the simulation results, the output force step response time of open loop control is 0,86 s and there is an overshoot of 3,2 %. After fuzzy PID control, the response time of the system is shortened to 0,42 s, and the system reaches a stable state after three small oscillations in the early stage. The steady-state accuracy and response performance of the system can be significantly improved by fuzzy PID control.

$$y = \left| 25 \ \sin\left(\frac{2\pi}{25} \ x\right) \right| \quad x \in [0, 50] \tag{3}$$

Input sinusoidal output force signal equation (3), is the expected signal of the control model, and the simulation response curve is shown in Figure 8. Figure 8 shows the first two cycles of the response curve. The open-loop control is very close to the input signal. After the fuzzy PID control is added, the response curve has a slight fluctuation, but the duration is very short, it quickly follows the input signal, and the adjustment delay of the response curve is significantly less than that of the open-loop control.

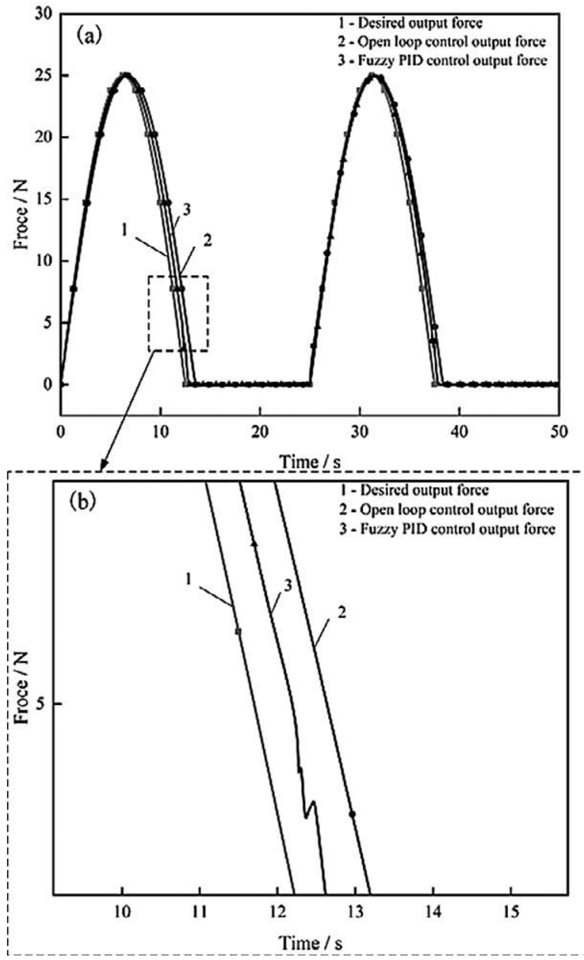

Figure 8 Fuzzy PID control sine response follow curve
(a) - Global image; (b) - Locally enlarged image

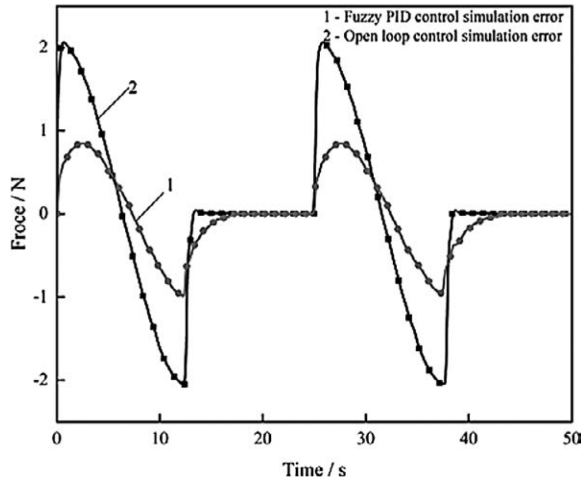

Figure 9 Fuzzy PID control response following error

According to Figure 9, it can be analyzed that after fuzzy PID control, the following error of the end-effector force control device decreases from ± 2,18 N of the original open-loop control to ± 0,9 N of the fuzzy control, and the peak value decreases by 58,7 %. It shows that fuzzy PID control can make the system more stable and solve the steady-state error of the control process effectively.

In conclusion, the parallel control strategy combined with fuzzy PID control can improve the response speed of the control system, reduce the overkill, avoid the steady-state error, and improve the response speed and following robustness of the control system.

CONCLUSION

Aiming at the problems existing in the grinding of rare earth metal ingot, a flexible floating grinding end-effector was designed. The parallel fuzzy PID control strategy can improve the response speed of the control system, reduce the overshot of the control system, avoid the steady-state error, and improve the response speed and the following robustness of the control system. The automation and high efficiency of rare earth metal ingot polishing process have been realized. It has important practical significance to promote the development and progress of rare earth processing industry.

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Note: The responsible translator for English language is Y. BIAN – Hebei Normal University, China