

Research on On-Line Control Technology for Machining Size and Deformation of Viscoelastic Small Solid Rocket Grain Processing

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Abstract

Through research on on-line control technology for machining size and deformation of viscoelastic small solid rocket grain processing, the suitable processing parameters are found out. It is proven by experiments that the size of grain can be controlled on-line.

Keywords

Grain, Dimension, On-Line Control

1. Introduction

Small solid rocket propellant is a solid propellant with a certain geometric shape and size [1] [2]. The grain is generally manufactured by casting composite modified double-base propellants. The propellant is directly cast into the core mold, cured, and then pulled out of the mold for shaping [3]-[5]. The grain is the main charge in the combustion chamber of a small solid rocket, and its dimensional accuracy directly affects the engine's working time, combustion chamber pressure, and thrust [6] [7]. A typical grain is shown in **Figure 1**, with a dimensional accuracy of 0.1 mm - 0.2 mm.

Grains are usually purchased externally and returned to the factory as raw materials, requiring secondary mechanical processing to meet design requirements. During the processing, the temperature of the grain increases continuously due to friction between the cutting tool and the grain column. However, as it is a non-metallic viscoelastic material similar to rubber [8], the grain column will undergo corresponding deformation with increasing temperature [9]. In addition,

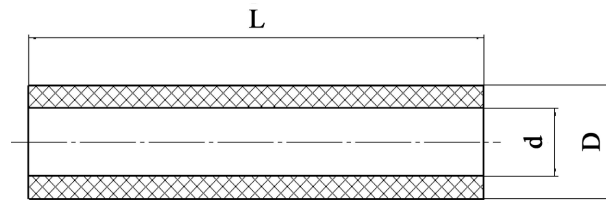


Figure 1. Typical grain structure diagram.

due to the special nature of its material, the deformation generated during the processing is irregular [10] [11], which makes it difficult to control its processing accuracy and often leads to out of tolerance situations.

To ensure the machining accuracy of the grain, operators need to process it face-to-face and perform real-time machining and testing of the grain multiple times during the machining process.

Due to the high energy content of the grain, there is a significant danger in the mechanical processing process.

Additionally, the temperature rise can cause toxic and harmful gases to be emitted from the grain, causing discomfort for operators. Therefore, it is urgent to modify the grain processing process and replace manual processing and testing with automatic processing and testing methods. At present, automatic processing and detection technology is relatively mature, but in order to achieve automatic processing and online detection of grain, the key is to control the size change during the grain processing process, in order to achieve online controllable size and lay the foundation for achieving automatic processing.

2. Problem Analysis

At present, the grain is processed by ordinary lathes, and the steps of grain processing include rough end face, precision inner hole, precision outer circle, and precision end face. Except for the coarse offset end face used for subsequent positioning, all other processing steps are directly processed to form the final size. There are mainly the following difficulties in controlling the dimensional changes during the processing of grain:

1) Deformation occurs during the processing of the grain, which differs significantly from the expected size after processing, resulting in inaccurate measurement

During the turning process of the grain, the turning friction force inevitably causes the grain to heat up. However, due to the creep characteristics of the grain viscoelastic body, the temperature rise causes deformation of the grain size. The longer the processing time, the greater the accumulated temperature rise, resulting in a larger deformation of the grain size. This leads to a significant difference between the processed grain size and the expected processing size value, which can be about 0.2 mm. The smallest tolerance among the three processing elements of the grain outer circle, length, and inner hole is 0.1 mm. The temperature rise during the processing causes the deformation to exceed the tolerance of the grain

size itself, making it difficult to accurately measure the processed grain size.

2) The unquantifiable cutting process parameters of the grain lead to irregular changes in grain size, making it difficult to control the size

The safe temperature of the grain is about 370°C. Currently, due to the limitations of the process, in the machining process of the grain, except for the inner hole machining which uses water cooling, all other processes are not flushed to prevent the powder of the grain from being washed out and scattered by water after cutting. Although the operating procedures specify parameters such as “back feed amount, speed, and feed amount”, these process parameters are set to ensure safety during the machining process and cannot effectively avoid temperature rise during the machining process; At the same time, the deformation caused by temperature rise during the processing of grain of different material types and size specifications is irregularly affected by environmental temperature, raw material characteristics, and processing parameters. At present, only experienced operators can be used for processing.

3) After processing, the first piece needs to be allowed to stand for 2 hours to recover to room temperature and then measured to be qualified before continuing processing, which cannot meet the production schedule requirements.

Before processing each batch of grain, it is necessary to continuously use process parts for process testing and record the turning parameters. After the testing is completed, the grain size should be measured after being left at room temperature of (20 - 35)°C for 2 hours. If the test is not qualified, the test piece should be machined according to the new cutting parameters until it is qualified. Only after passing the test can the turning parameters be used for further processing. Due to the fact that the three processing elements of the outer circle, end face, and inner hole of the propellant are formed in a total of three processes, at least three process tests are required for each batch of propellant processing. In addition, when cutting the propellant, toxic and harmful gases and dust are generated due to temperature rise, causing discomfort to the operator. Currently, the operator can only work for less than four hours a day, and the production efficiency is 15 pieces/person/shift, which cannot meet the production schedule requirements.

This article explores suitable cutting parameters for outer circle and end face machining, as well as inner hole cutting parameters through process experiments. By analyzing and adopting appropriate temperature control measures, the temperature during the grain machining process can be controlled, thereby reducing the deformation caused by excessive temperature rise during the grain machining process. The goal of online size control in the grain machining process is achieved, providing technical support for automatic grain machining.

3. Processing Technology of Solid Small Rocket Grain

From the perspective of the grain processing, temperature is the main factor causing deformation of the grain. The higher the temperature rise during the processing, the greater the deformation of the grain. The main factor causing temper-

ature rise is the cutting parameters during the turning process. If we want to fundamentally reduce the temperature rise during the grain machining process, we need to control the process parameters during the grain machining process, but we need to consider the following aspects:

1) The efficiency of grain processing can not be too low

Due to the fact that the temperature rise generated during the processing of traditional Chinese grain is caused by turning friction, reducing the back cutting amount, feed amount, and speed value during the turning process can effectively reduce the temperature rise. However, considering the efficiency of column processing, too low back cutting amount, feed amount, and speed value can lead to low production efficiency and unnecessary waste. According to production capacity requirements, the processing efficiency of the grain cannot exceed the requirement of 300 S/root. Based on experience, the efficiency requirements for each processing process are shown in **Table 1**.

Table 1. Efficiency requirements for each processing step.

Rough end face machining time	Precision machining time for inner holes	Precision machining time for the outer circle	Precision machining time for end faces
Not exceeding 30 S	Not exceeding 30 S	Not exceeding 120 S	Not exceeding 100 S

2) The processing parameters of the grain need to be within the safety control parameters

The “Safety Operation Regulations for Grain Processing” stipulate that the cutting parameters should not exceed 2 mm for back cutting, 750 r/min for lathe speed, 0.3 mm/r for feed rate, and 450 r/min for drilling speed. During the process of process testing, it is not allowed to exceed the cutting parameter values in the safety operation regulations.

3) The temperature rise value during the processing of the grain should not be too high

In addition, due to the chemical stability test temperature value of 107.5 °C for the grain and the temperature value in the processing workshop being (20 - 35) °C, in order to ensure controllable deformation of the grain during processing without affecting its chemical properties, the internal control setting is that the temperature rise during the grain processing should not exceed 50 °C.

3.1. Processing Parameter Experiment

3.1.1. Process Parameters and Test Specimens

Based on the characteristics of the lathe and considering machining efficiency, process parameters as shown in **Table 2** and typical products (with the highest production capacity and largest volume) as shown in **Table 3** were selected for process testing. During the experiment, the same skilled operator was used for

operation, and the optimization method was used to conduct process tests on single factors separately, obtaining the time and temperature values for grain processing. Based on the actual situation, process parameters that can balance efficiency and safety have been developed through process testing.

Table 2. The process parameters of this process experiment.

Serial Number	Types of cutting parameters	Safety process parameters	The cutting parameter values selected for this experiment		
1	depth of cut	2 mm	2 mm	1.5 mm	1 mm
2	Lathe speed	750 r/min	750 r/min	650 r/min	550 r/min
3	Feed rate	0.3 mm/r	0.3 mm/r	0.25 mm/min	0.2 mm/r
4	Drilling speed	450 r/min	450 r/min	375 r/min	300 r/min

Table 3. Typical product parameters.

Serial Number	Product Category	Product outer diameter × inner diameter × length value (mm)	quantity
1	Product 1	$\Phi 48.6 \times \Phi 10.8 \times 436.5$	10

3.1.2. Test Process and Test Record Requirements

The temperature of the grain was detected by using the FLUKE Ti32 infrared imager. The temperature measurement range was from -20°C to $+600^{\circ}\text{C}$, with an accuracy of $\pm 2^{\circ}\text{C}$. The number of samples in each group was 5. The experimental process is shown in **Figure 2**.

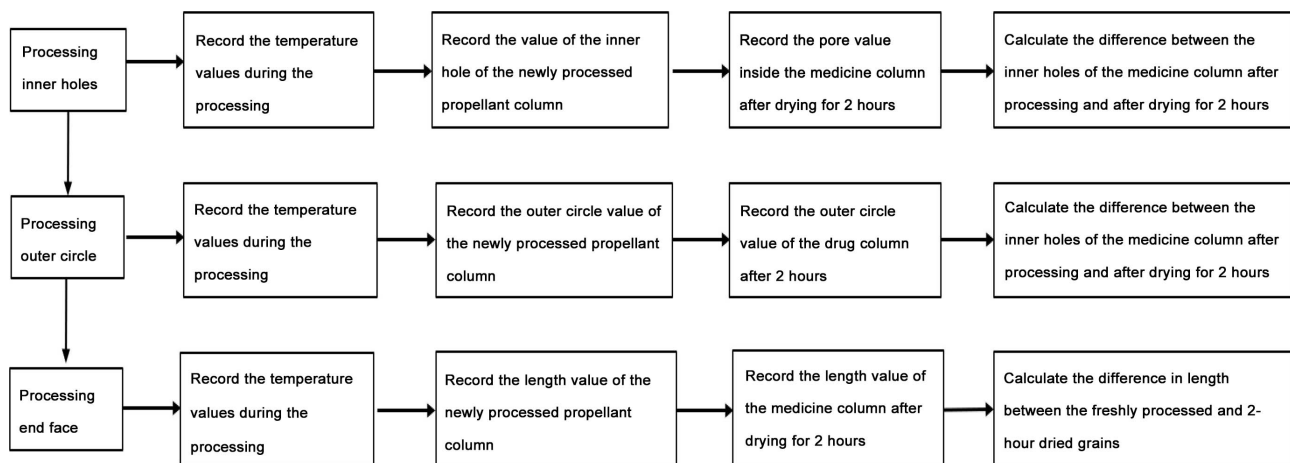


Figure 2. Experimental flowchart.

The specific recording requirements for the experiment are shown in **Table 4**. Partial experimental process is shown in **Figure 3**.

3.1.3. Results and Discussion

Through experiments, the requirements for ensuring efficiency and keeping the deformation of the grain within the tolerance range were explored, and the cutting

Table 4. Test record requirements.

Processing test category	Processing of inner holes		Processing the outer circle		Processing end face process	
	Temperature value	Inner hole value	Temperature value	Outer circle value	Temperature value	end face value
Record requirements	Measure every 5 seconds and calculate the average value	Measure 3 evenly distributed points at each end and take the average value	Measure every 5 seconds and calculate the average value	Measure 3 evenly distributed points at both ends and in the middle of the grain, and take the average value	Measure every 5 seconds and calculate the average value	Measure 3 evenly distributed points on each end face of the grain and take the average value

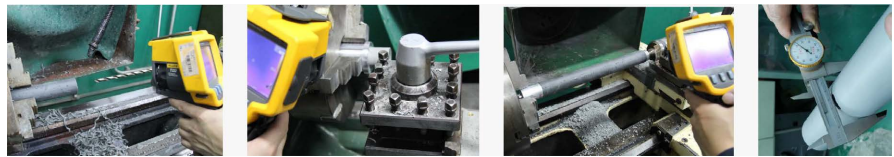


Figure 3. Partial experimental process.

process parameters were determined as back cutting amount of 2 mm, lathe speed of 550 r/min, feed rate of 0.3 mm/r, and inner hole machining speed of 375 r/min. The experimental results obtained according to the process parameters are shown in **Figures 4-6**.

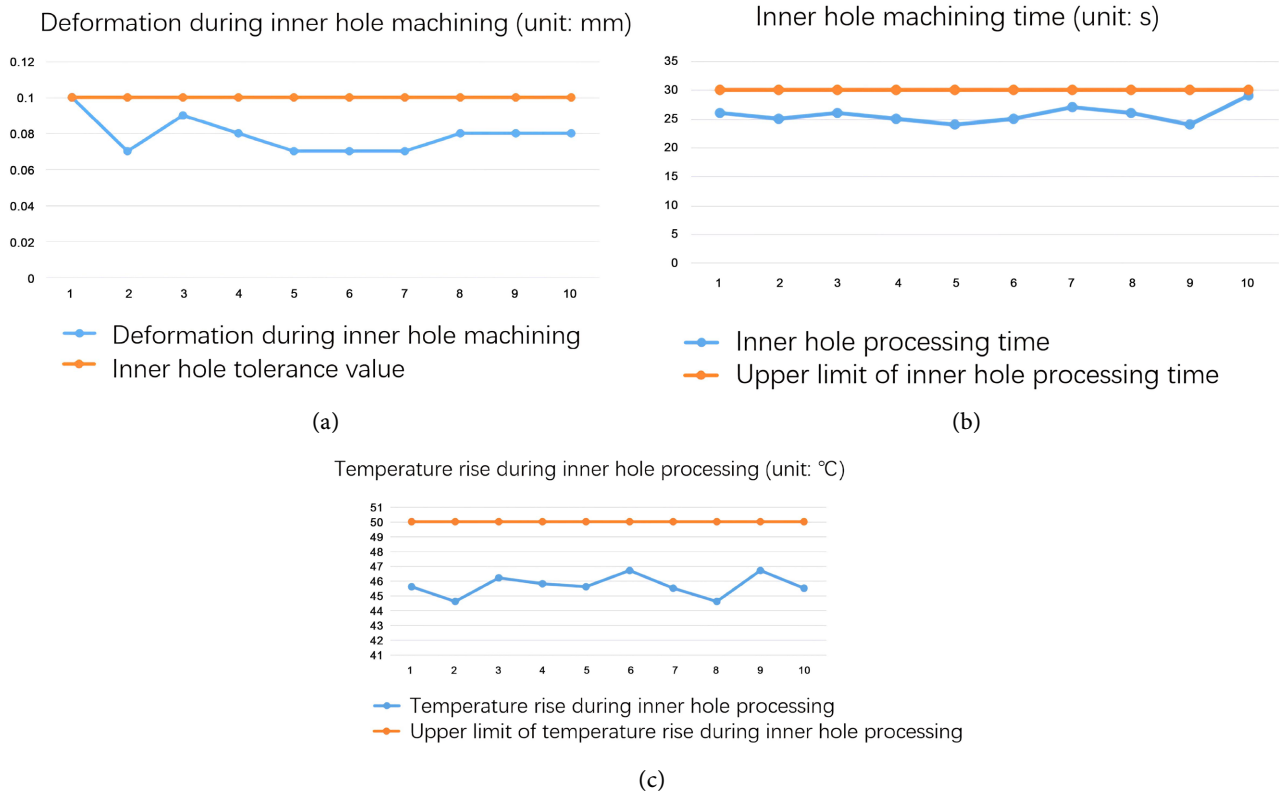


Figure 4. Internal hole processing test results.

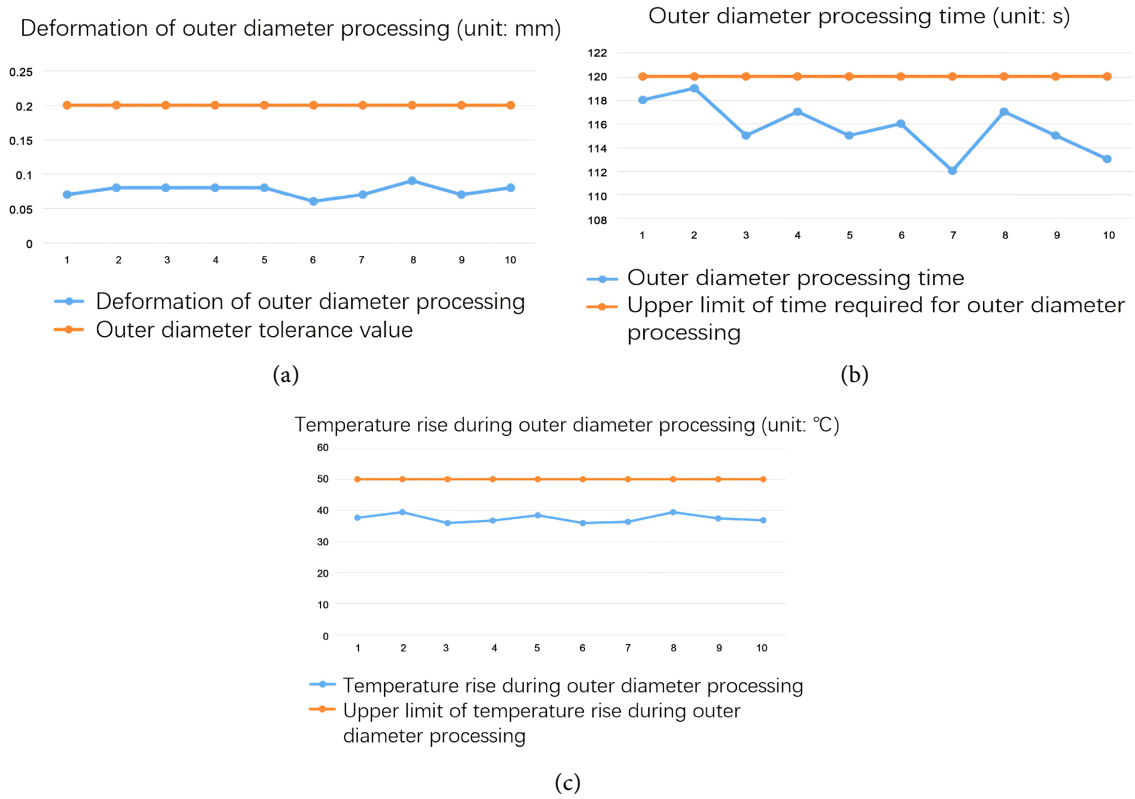


Figure 5. Outer diameter processing test results.

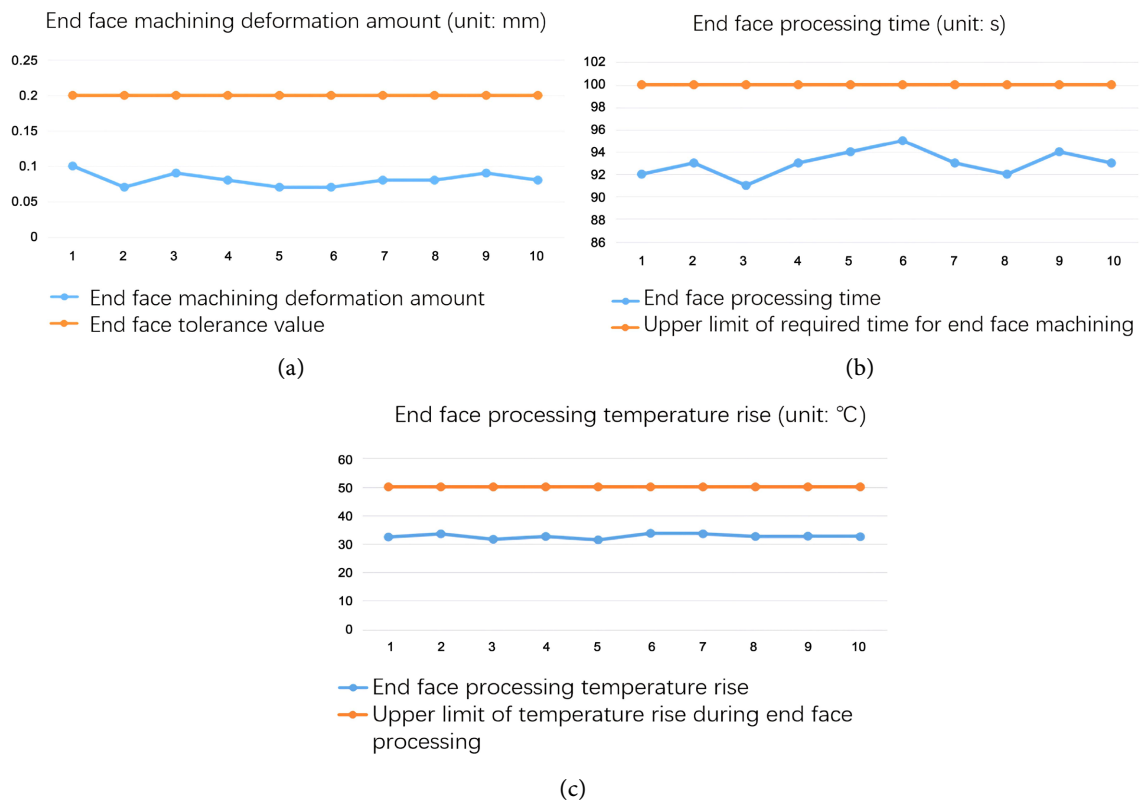


Figure 6. End face machining test results.

From the above experiments, it can be seen that the process parameters obtained through the optimization method can meet the requirements. However, for processes such as inner hole machining, the deformation amount is already equal to or close to the tolerance value of the grain, and there may be a risk of exceeding the tolerance in extreme situations, which brings great trouble to the machining. Therefore, it is necessary to continue studying the adoption of corresponding cooling methods for the grain during the processing, in order to prevent the grain from deforming due to tool friction heating, and thus achieve the goal of online controllability of grain deformation. In addition, the temperature rise values of some links during the processing have approached the upper limit of the set critical value. In order to prevent excessive temperature values from affecting the chemical stability of the grain and reduce the volatilization of toxic and harmful substances caused by temperature rise, and to prevent frequent shutdowns due to approaching the set upper limit of temperature rise (safety control temperature value) during the automatic processing of the grain, corresponding cooling methods still need to be adopted for the grain in the automatic processing process.

3.2. Cooling Method and Parameters for Grain Processing

At present, commonly used cooling media include cutting fluid, water, air, etc. However, using conventional cutting fluids on the market also has a flame retardant effect. The cutting fluid attached to the grain during the machining process will affect the performance of the subsequent grain, so cutting fluid cannot be used as a cooling medium. By comparing and analyzing air cooling and water cooling methods, selecting appropriate cooling media, and determining corresponding parameters based on the characteristics of grain processing.

3.2.1. Water Cooling Method

At present, due to the constraints of processing methods, except for the use of water cooling for inner hole processing, temperature control can only be achieved through air cooling and controlling cutting parameters for other steps in the processing process, which poses certain safety hazards and may result in personal injury or death in case of accidents. When manually processing grain, if water cooling is used to cool the outer circle and end face, the residue of the grain will scatter to the processing workshop as the grain rotates. Long-term use will cause secondary pollution, affect the accuracy of some equipment, and have a significant impact on the health of operators. The automatic processing of grain has achieved human-machine isolation, so it is possible to consider using water cooling to cool down the entire processing process by modifying the equipment.

- 1) The advantages of using water cooling method:
 - a) It can effectively cool down the grain during processing and has process inheritance.
- 2) Disadvantages of using water cooling method:
 - a) When using water cooling to process the outer circle and end face, the residue of the grain will scatter to the baffle due to the centrifugal effect of the lathe rota-

tion when it comes into contact with water. After the water evaporates, the powder of the grain will scatter in the workshop. If not cleaned in time, it is easy to cause dust pollution.

b) After using water cooling for processing, it is necessary to add corresponding mechanisms to control the baffle, and after the grain is processed, corresponding means need to be added to remove water droplets on the grain before detection, which reduces processing efficiency and increases operating costs.

c) Long term use can cause rust on the hydraulic chuck and spindle of CNC lathes, affecting their functionality and increasing the cost of use.

Based on the above analysis, the water-cooled processing method is not suitable for automatic processing of grain.

3.2.2. Air Cooling Method

The process of grain processing has the characteristic of high speed leading to rapid heating, and the use of conventional air as a cooling medium cannot meet the processing requirements. Therefore, cold air can be considered to cool the grain processing process.

As shown in **Figure 7**, the pneumatic spiral cooler is used to cool the entire process of grain processing by introducing air through the pneumatic spiral cooler, thereby reducing the temperature rise during the grain processing. Its working principle is to use the vortex tube to generate vortices in high-speed airflow, separating two cold and hot airflows. The hot airflow is discharged, and cooling is obtained by relying on the cold airflow. Under the premise of dry air, the lowest temperature can reach -46°C . The pneumatic spiral cooler can adjust the gas flow rate at the cold air end by adjusting the valve at the hot air end, and the temperature at the outlet of the cold air end can be adjusted by adjusting the valve at the hot air end.

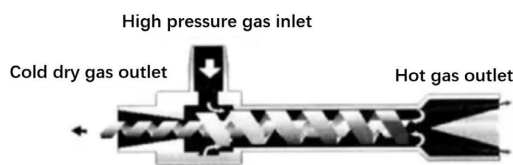


Figure 7. Work principle and physical object of vortex tube.

1) Disadvantages of air cooling method:

a) Due to the first-time adoption of air cooling method, its reliability needs to be verified.

b) Different air volumes and temperatures of cold air correspond to different cooling effects during the processing of grain sizes and specifications. Therefore, it is necessary to explore the required air volume during the grain processing.

2) Advantages of air cooling method:

- a) Compared to water-cooled methods, air-cooled methods can reduce the cost of machine tool mechanisms and usage;
- b) The medicine residue generated by the air cooling method is directly extracted or soaked in water, without generating dust pollution;
- c) Using air cooling method for cooling, there is no need to treat the surface of the grain after processing, and the grain size can be directly detected, which is more efficient than water cooling method.

3.2.3. Experiment on Air Cooling Process Parameters

Due to the processing of the grain at room temperature of 20°C to 35°C, the cold air temperature can be set to a fixed value of 20°C to explore the influence of different air volumes on the processing of the grain.

Calculation formula based on specific heat capacity

$$\Delta T = \frac{Q}{c \times m}$$

Among them, Q is the heat emitted; C is the specific heat capacity, constant value; M is the weight of the grain; ΔT is the cooling value.

There is a formula based on the weight of the grain

$$m = \frac{V}{\rho}$$

Among them, m is the weight of the grain; ρ is the density of the grain, which is a constant value of about 1.7 g/cm³; V is the volume of the grain.

From the above two formulas, it can be concluded that

$$\Delta T = \frac{Q \times \rho}{c \times V}$$

It can be concluded that the cooling value is inversely proportional to the volume of the grain when the heat emitted by the grain is consistent. Under the same air volume and temperature conditions, the larger the volume of the grain, the worse the cooling effect.

Select 20 typical product 1 columns and divide them into 4 groups for testing. Set the air outlet temperature to about 10°C and control the air flow to 0.1 MPa, 0.2 Mpa, 0.3 Mpa, and 0.4 MPa by adjusting the air valve. According to the requirements of **Table 4**, measure and record the temperature rise and column size during the processing of the grain, and measure the size value of the grain after it is left at 20°C to 35°C for 2 hours.

3.2.4. Results and Discussion

The experimental results are shown in **Table 5**. According to the results, after using 0.4 Mpa cold air, the temperature rise of Product 1's grain was well suppressed. Meanwhile, the deformation of the drug column 2 hours after processing was within the allowable range of processing error. Based on the theoretical analysis results that the volume of the grain is inversely proportional to the cooling effect mentioned above, the 0.4 Mpa air cooling parameter is also applicable to grain of

other sizes and specifications. This test verified the feasibility of using air cooling for cooling.

Table 5. Experiment data sheet.

Serial Number	Cold air temperature value	Air volume	Inner-hole processing		Outer diameter processing		End face processing	
			Warm rise value (°C)	Subtraction between processed and left to stand for 2 hours (mm)	Warm rise value (°C)	Subtraction between processed and left to stand for 2 hours (mm)	Warm rise value (°C)	Subtraction between processed and left to stand for 2 hours (mm)
1	About 10°C	0.1 MPa	35	0.08	32	0.08	28	0.07
2		0.2 MPa	23	0.05	21	0.06	19	0.05
3		0.3 MPa	12	0.03	10	0.03	9	0.03
4		0.4 MPa	3	0.01	3	0.01	2	0.01

Note: Workshop temperature 27°C.

Considering the overall economic efficiency and minimizing production requirements, 0.4 MPa of cold air already meets the actual processing requirements, and there is no need to further increase the pressure value. However, when there are larger-sized grain, it may be necessary to further increase the pressure value.

3.3. Small Batch Validation Test

Select 10 pieces from products 1 to 10 with large processing batches according to the “depth of cut of 2 mm, lathe speed of 550 r/min, feed rate of 0.3 mm/r, drilling speed of 375 r/min”. At the same time, use a 0.4 Mpa vortex cooler set at an outlet temperature of about 10°C to strongly cool the grain during the processing process. Measure the deformation of the grain and conduct a deformation test, which basically covers the grain of various sizes and specifications. The experimental results are shown in **Table 6**.

Table 6. Experiment data sheet.

Serial Number	Product code	Subtraction between processed and left to stand for 2 hours (mm)	Subtraction between processed and left to stand for 2 hours (mm)	Subtraction between processed and left to stand for 2 hours (mm)	Is the processing time within 300 s
1	Product 1	0.01	0.01	0.02	Yes
2	Product 2	0	0	0.01	Yes
3	Product 3	0.01	0.02	0.01	Yes
4	Product 4	0	0.01	0	Yes
5	Product 5	0	0.01	0	Yes
6	Product 6	0.01	0.02	0.01	Yes

Continued

7	Product 7	0.01	0	0	Yes
8	Product 8	0	0.01	0	Yes
9	Product 9	0.01	0	0.01	Yes
10	Product 10	0.01	0.01	0	Yes

According to the experimental results, it can be seen that the deformation of each size of the grain processed according to the explored process parameters is basically between 0.01 mm and 0.02 mm, and the processing time is within 300 s. Therefore, the tolerance value can be controlled internally during the machining process to ensure that the size of the grain is within the tolerance range after 2 hours of machining, achieving the goal of online control of grain size.

4. Conclusion

This article analyzes the machining process of viscoelastic solid small rocket grains, and obtains cutting process parameters through experiments that can meet the upper limit of machining temperature rise without affecting the efficiency of grain machining. At the same time, air cooling is selected for cooling during the grain machining process, quantifying the required air volume and air temperature. Through air cooling, the temperature rise of the grain during machining is controllable, thereby reducing the influence of temperature on the deformation of the grain. The deformation of the grain after machining is controlled within 0.01 - 0.02 mm, and the deformation is much smaller than its tolerance value, achieving the goal of online control of dimensional deformation during the grain machining process. Through batch validation experiments, it was found that the quality consistency of the grain processed using this process parameter is high, providing a theoretical and experimental basis for achieving automatic grain processing.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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