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Processing Parameters' Multi-objective Optimization for Compound Machining with Ultrasonic Vibration on SiC Monocrystal

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Abstract

Because of SiC monocrystal belongs to difficult-to-process material, improving its processing quality and effect has great significance. This paper carries out a great deal of experimental research of compound processing with ultrasonic vibration on SiC monocrystal, and obtains important factors that influence processing result, i.e., based on relevant regularities of sawing force and processing parameters, processing parameter optimization model is established under the constraints of sawing force, wire saw life, and wire saw tensile stress. Solving the model by means of genetic algorithm, an optimum grouping of processing parameters is obtained. Research result indicates that this method could effectively obtain processing parameters under certain processing conditions, helps to enhance the processing efficiency of SiC monocrystal.

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Keywords: SiC monocrystal; Ultrasonic vibration; Parameter optimization; Genetic algorithm

1. Introduction

Along with SiC monocrystal application domain expands unceasingly, and because of its features of high temperature resistance, good thermal conductivity as well as impact resistance, SiC turns to be the optimal material to produce optoelectronic devices integrating high temperature, high frequency, high

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power, and radiation resistance. It plays an important role in electron and micro-electron fields. As a super hard brittle material, SiC monocrystal's wafer slicing processing is an important manufacture procedure.

As a semiconductor material, SiC monocrystal's cutting processing and method is much less than that of metal. According to the present mature cutting technology of ceramic, glass, stone and other hard brittle materials, diamond wire saw cutting technology is found developing fastest[1,2]. Vibration cutting technology research and the practical application in Japan show that the efficiency of vibration cutting is two to three times more than that of normal no vibration cutting[3]. And vibration cutting can reduce cutting force, improve cutting precision, and prolong tool's life. Therefore, a new cutting technology--electroplated diamond wire saw ultrasonic vibration cutting technology is generated. By means of applying ultrasonic vibration to diamond wire saw to capture the aim of increasing material removal rate, improving work piece surface quality and precise, and extending the service life of diamond wire saw[4]. But as this technology's processing mechanism is not very mature, processing technique remains to be improved, its practical application and promotion are limited. Thus, processing regularities of compound processing with electroplated diamond wire saw ultrasonic vibration, author of this paper exploring and researching, have great significance on the application and development of this new technique.

2. Related research

Effective force during wire saw cutting is the sawing force. It is a very important physical quantity of wire saw cutting processing, and it directly determines the production of cutting heat, affects wire saw's wear, fracture, service life, work piece precise, and processing surface quality. In practical production, sawing force acting on the work piece is essentially the general performance of grits cutting effect within saw cutting area, cutting and other friction effects.

Liaoyuan Zhang[5] in China Changchun University of Technology has designed a set of flexible electroplated diamond wire saw ultrasonic compound cutting equipment. He has carried out such experimental researches as dynamics analysis of electroplated diamond wire saw and grits, investigating processing track of electroplated diamond wire saw and ultrasonic vibration compound processing parameters, and analysis material removal, sawing force, surface quality, wire saw's invalidation forms and mechanism during sawing. Wei Gao[6] et al have carried out studies on cutting processing parameters optimization of circular electroplated diamond wire saw. Through the analysis of diamond granularity, obtained conclusion that the increase of diamond granularity can improve cutting efficiency, but the impact is not big. Jianfeng Meng[7] et al has established vibration equation of circular electroplated diamond wire saw processing, studied wire saw's random vibration under the action of sawing, and concluded the influence regularity of tension and wire saw speed upon wire saw vibration.

Vibration cutting is a new cutting method which is formed in the cutting process added with some physical processes. This method can get some good cutting results that ordinary cutting can't get, which mainly displays in the following aspects[8]: (1) smaller sawing force, (2) lower cutting temperature, (3) higher surface finish quality and processing precise, (4) greatly improved tool durability. However, researches of wire saw cutting parameters optimization under circumstance of ultrasonic vibration have not been found yet. Since choosing different cutting parameter grouping affects cutting effect, getting of the optimal processing parameters will greatly improve tool service life and work piece quality.

Therefore, based on the related regulations of processing parameters obtained from a large number of experimental studies on compound processing with ultrasonic vibration on SiC monocrystal, this research establishes a processing parameter optimization model, achieves the anticipated cutting results through optimal parameter grouping by genetic algorithm.

3. Ultrasonic Vibration Cutting Optimization Model

In engineering application, under the same conditions the smaller sawing force is, the more effectively wire saw's service life and processing surface quality could be enhanced, and the smaller effect on processing material's twisting is. For which, this paper has carried out a lot of sawing force orthogonal experiments on SiC monocrystal, found the main factors impacting sawing force, and obtained the relation model of sawing force and each main cutting parameters through regression orthogonal analysis.

$$F_t=1.305\times10^{-5}\ v_s^{-0.3411}\ v_f^{0.5611}\ n_w^{-0.9786}\ a^{-2.3838} \quad (1)$$

In which, F_t is sawing force (kN), i.e., SiC monocrystal bar bore tangential force, v_s is sawing cutting speed (m/min). v_f is feed speed (mm/min), n_w is work piece rotational speed (r/min), a is ultrasonic wave amplitude (mm).

To obtain good processing effect, the above mentioned four selection of wire saw cutting parameters are particularly important. But since each parameter is limited by machine tool, wire saw, work piece, processing efficiency and other technique conditions, constraint conditions of each parameter optimization should be decided before selecting parameter so as to make the optimization results meet the practical production requirements.

3.1. Machine tool's restriction on wire saw cutting parameter

To ensure the safety and reliability of saw cutting, selection of saw cutting parameter should be within the permitted range of machine tool:

a. Diamond wire saw cutting speed should meet the restriction of machine tool cutting speed:

$$v_{min} \le v_s \le \pi\ d\ n_{max} / 1000 \quad (2)$$

In which, v_{min} is the minimum speed of speed cutting (m/min), d is driving wheel diameter of wire saw, n_{max} is the highest rotational speed of driving wheel (r/min).

b. Feed amount of diamond wire saw cutting work piece should meet the restriction of machine tool feed speed:

$$v_{fmin} \le v_f \le v_{fmax} \quad (3)$$

In which, v_{fmin} is the minimum feed speed of work piece (mm/min), v_{fmax} is the maximum cutting feed speed (mm/min).

c. Power of diamond wire saw cutting is smaller than effective power:

$$F_t\ v_s / 1000 \le \eta\ P_{max} \quad (4)$$

In which, η is driving efficiency of machine tool, P_{max} is driving motor power (KW).

d. Ultrasonic wave amplitude of diamond ultrasonic cutting should meet the restriction of ultrasonic wave vibration processing:

$$a_{min} \le a \le a_{max} \quad (5)$$

In which, a_{min} is the minimum amplitude (mm), a_{max} is the maximum amplitude (mm).

3.2. Diamond wire saw's restriction on wire saw cutting parameter.

a. The maximum tensile stress of wire saw should less than that of wire saw permitted:

$$F_t/(\pi r^2) \leq \sigma_{max} \tag{6}$$

In which, r is wire saw's semi-diameter (mm), σ_{max} is wire saw permitted maximum tensile stress (kN/mm^2).

b. In cutting process, to prevent wire saw's excessive wear affecting work piece surface quality, service life of wire saw should be greater than the processing time of work piece. Through long-term experiments, wire saw's service life calculation formula and its constraint conditions are obtain as follows:

$$C_T\, l \,/\, (\, v_s^{\,m} f^n \,) \geq h \,/\, v_f \tag{7}$$

In which, C_T is grinding factor of processing material, l is wire saw's effective cutting length (m), h is work piece's cutting depth (mm), f is work piece's feed amount (mm/r). $f = v_f / n_w$, m, n are relevant to tool material and processing material.

4. Sawing force minimum based on genetic algorithm

Because it is unable to directly obtained the minimum value and corresponding variables of formula (1) by calculating partial derivative, and especially in a variety of constraint conditions, the optimal solution is difficult to be calculated, the approximate method is adopted to obtain processing parameters. Taking into account all the above restraining analysis, the target functions of genetic algorithm is defined as follows:

$$\mathrm{M\,in(F)} = \mathrm{M\,in}\left(F_t + \alpha\left(F_t/\pi r^2\sigma_{\max} - 1\right) + \beta\left(1 - C_{\mathrm{T}} n_{\mathrm{w}}^{n} l / v_{\mathrm{s}}^{m} v_{\mathrm{f}}^{n-1} h\right) + \gamma\left(F_t v_s / 1000\eta P_{\max} - 1\right)\right) \tag{8}$$

Sawing force, tensile stress constraint, wire saw's service life, and cutting power constraint are added into this function respectively, and a comprehensive optimization target is formed. In which, α, β, γ as respective optimization weights of (0,1), controls their own influence degree.

This research focuses on using genetic algorithm to solve optimization problems, several key procedures of solving process are as follows:

a. Chromosome coding: a chromosome is composed of four genes, they are v_s, v_f, n_w, a.

b. Initial population generating: by adopting roulette, randomly generate each constraint condition meeting parameter within its value range so as to form a chromosome. Repeat the above method, until the chromosome number reaches the required population size.

c. Genetic operation: Simulate biologic evolution, by meaning of copying to realize the superior selecting and the inferior eliminating of population group. Through the mutation and crossover operation, maintain diversity of population group, and generate new chromosome.

- **Copy** Carry out target functions evaluation on each chromosome of the population group, i.e., substitute function value of formula (1). Select chromosome with minimum function value but meets constraint condition (2)-(7), and copy it into the new population group.
- **Variation** Make a gene on a chromosome vary randomly, i.e., randomly change parameter value within the value range. Variation probability is P_m. Put the newly generated chromosome into the new generation group.
- **Crossover** Extract two chromosomes randomly to generate random crossover point. Exchange genes before this crossover point to generate two new chromosomes, and then, put the newly formed chromosomes into new population group. Crossover probability is P_c.

The whole process of this algorithm is as shown in fig. 1 below.

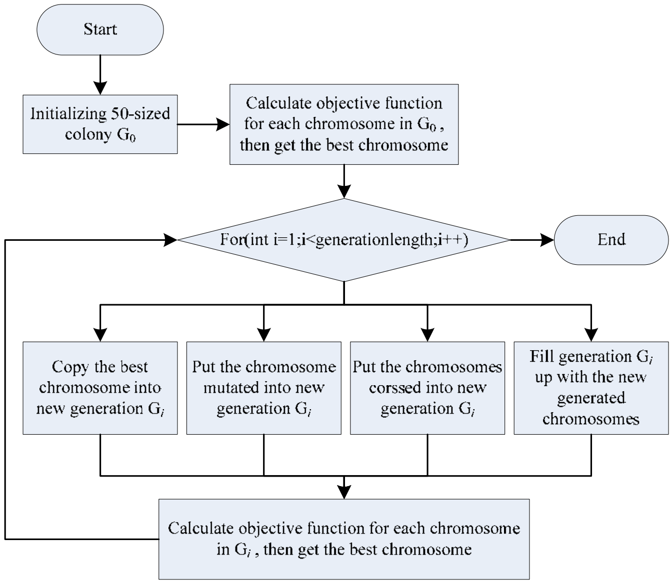

Fig. 1. Genetic algorithm flow chart

5. Case study

Cut SiC monocrystal and exert ultrasonic vibration by diamond wire saw, of which the semi-diameter is 0.15mm and effective cutting length is 45m. According to experiment conditions, obtain table 1 shown parameters value range after normalizing processing parameter constraints. Realize the before-mentioned algorithm program by using Java language. Set population size as 50, crossover probability P_c=0.6, variation probability P_m=0.1. Refer to experiment data's order of magnitude to make sure sawing force is the core optimization factor, and set α, β, γ as 0.05, 0.03, 0.02 respectively.

Table 1. Constraints of processing parameter

v_s	v_f	n_w	h	a	l	C_T	m	n	η	P_{max}	σ_{max}
[1.5,2]	[0.025,0.0725]	[8,20]	30	[0.001,0.005]	45	0.75	0.25	0.8	0.8	0.27	0.65

Iterate 300 times by genetic algorithm, obtained table 2 shown parameters optimization grouping of minimum target functions under the condition of ultrasonic vibration cutting and normal wire saw cutting. Variation trends of target function and sawing force are as shown in fig. 2.

Table 2. Optimization results of processing parameter

Processing Parameters	v_s	v_f	n_w	a	F_t
Normal cutting optimization results	1.9434	0.025	8.2422	/	0.1683
Vibration cutting optimization results	1.9727	0.0254	9.6446	0.0049	0.0441

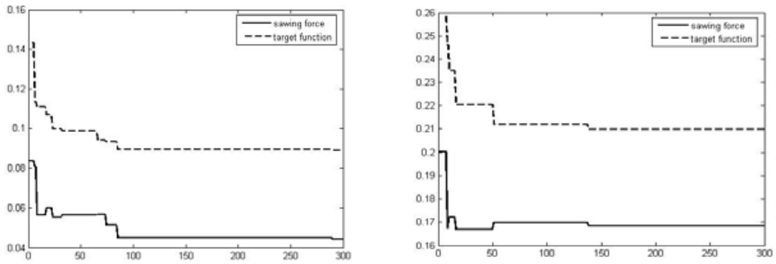

Fig. 2. (a) Variation trends of functions in ultrasonic vibration processing; (b) Variation trends of functions in normal wire saw processing

As is shown in fig. 2 and table 2, along with increase of iterate times target functions tend to optimization rapidly, and sawing force also maintains the trend of minimizing gradually. Analysis of optimization results finds that optimized parameters of normal cutting and vibration cutting under the same constraints condition vary very small, but the minimum sawing force of vibration cutting is about 1/4 of that of normal cutting, which proves that ultrasonic vibration could effectively reduce sawing force of the cutting process. Besides, prompt gaining of optimization parameter by genetic algorithm also proves the feasibility and validity of using this method to carry out parameter optimization.

Therefore, under multi-constraint conditions, using this method can capture processing parameters of SiC monocrystal ultrasonic vibration effectively and rapidly, has great significance to the improvement of SiC monocrystal's machining efficiency and quality.

6. Conclusion

Combined with experimental results, aiming at improving processing efficiency of SiC monocrystal, and under the condition of using ultrasonic vibration, this research solves the established optimization target functions by genetic algorithm, obtains parameter optimization grouping which satisfies kinds of processing constraints. What's more, result issues that this method is available and effective, and provides ways and basis to select parameters for ultrasonic vibration cutting.

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