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Dynamic Calibration of the Cutting Temperature Sensor of NiCr/NiSi Thin-film Thermocouple

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Abstract: In high-speed cutting, natural thermocouple, artificial thermocouple and infrared radiation temperature measurement are usually adopted for measuring cutting temperature, but these methods have difficulty in measuring transient temperature accurately of cutting area on account of low response speed and limited cutting condition. In this paper, NiCr/NiSi thin-film thermocouples(TFTCs) are fabricated according to temperature characteristic of cutting area in high-speed cutting by means of advanced twinned microwave electro cyclotron resonance(MW-ECR) plasma source enhanced radio frequency(RF) reaction non-balance magnetron sputtering technique, and can be used for transient cutting temperature measurement. The time constants of the TFTCs with different thermo-junction film width are measured at four kinds of sampling frequency by using Ultra-CFR short pulsed laser system that established. One-dimensional unsteady heat conduction model is constructed and the dynamic performance is analyzed theoretically. It can be seen from the analysis results that the NiCr/NiSi TFTCs are suitable for measuring transient temperature which varies quickly, the response speed of TFTCs can be obviously improved by reducing the thickness of thin-film, and the area of hot junction has little influence on dynamic response time. The dynamic calibration experiments are made on the constructed dynamic calibration system, and the experimental results confirm that sampling frequency should be larger than 50 kHz in dynamic measurement for stable response time, and the shortest response time is 0.042 ms. Measurement methods and devices of cutting heat and cutting temperature measurement are developed and improved by this research, which provide practical methods and instruments in monitoring cutting heat and cutting temperature for research and production in high-speed machining.

Key words: thin-film thermocouple, cutting temperature sensor, dynamic calibration, one-dimensional unsteady heat conduction, response time

1 Introduction*

In high-speed cutting, 95% of cutting heat will transmit to the chip, which will be local melted on the interface contacting with rake face, and a layer of extremely thin liquid film will be formed. The chip will be instantaneously cut off from the work piece during cutting without traditional plastic deformation, so it is very important to accurately measure the temperature of the cutting area. Thin-film thermocouples(TFTCs) are advanced sensors for transient temperature measurement and the measurement principle is the same as normal thermocouples. Because of the small thermal capacity and fast response, TFTCs can measure transient temperature accurately[1–2]. The dynamic calibration of TFTCs is used to measure the response process of temperature sensors versus temperature signal. There are three methods for the dynamic calibration of ordinary wire-type thermocouple: step response, impulse response and slope response. These methods all consider dynamic calibration of thermocouple as a first order inertial loop. The dynamic response time is calibrated with dynamic calibration curve and larger errors will occur while it is calibrated by the ordinary calibration methods. Currently, more advanced methods are basically based on laser dynamic calibration for dynamic time of TFTCs[3–4]. CHOI, et al[5], adopted K model thin-film thermocouple scattered around the laser path to observe the conversion of laser welding energy, in order to monitor the distribution of energy in laser welding process. YANG[6] used a continuous carbon dioxide laser and neodymium-doped glass pulsed laser as the excitation heat source for static and dynamic calibration of transient high-temperature sensors, by drawing on their predecessors using laser heated TFTC for dynamic calibration technique. The system was designed

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by using integration of static and dynamic. The systematic errors generated by the differences of heat radiation coefficient and location movement were eliminated. Other heat equipments which produce transient temperature rise can also be used for incentives dynamic heat in the system of dynamic calibration of TFTCs except adopting laser as heat source for experiment of dynamic calibration. QIAN, et al[7], carried out a certain amount of research work using heating circuit as the heat source in the dynamic calibration experiment.

In this research, the fabrication of TFTCs is introduced and the compositions are measured by electron probe firstly. Then, dynamic performance of TFTCs is researched by the combination of calculation with measurement. The time constants of the TFTCs with different thermo-junction film width are measured at different sampling frequency. Finally, the shortest response time is given.

2 Fabrication of NiCr/NiSi Thin Film

NiCr/NiSi is a widely used cheap metallic thermocouple material. The highest temperature can reach 900 ℃ for long-term use and 1 200 ℃ for short-term use. The anti-oxidation ability and corrosion resistance of this thermocouple material are strong as thermoelectric properties, good linearity, and high sensitivity, etc. NiCr/NiSi is chosen as thin-film electrode materials in this study, which can meet the requirement of cutting temperature testing.

Several methods can be used to prepare NiCr/NiSi thin-films, for example, vacuum evaporation, sputter deposition, and ion plating method [8–9]. NiCr/NiSi thin-films are prepared by means of advanced twinned microwave electro cyclotron resonance (MW-ECR) plasma source enhanced radio frequency (RF) reaction non-balance magnetron sputtering technique [10]. Without considering the proliferation of alloy composition caused by the increasing temperature of target and the re-evaporation on the substrate, the sputtering thin films can be obtained, whose components are the same as the targets. The composition of NiCr/NiSi thin films measured by electron probe is shown in Table 1. It can be seen from Table 1 that the composition of sputtering thin films is nearly the same as the composition of the targets.

Table 1. Comparison of the compositions of thin films and targets (%)

Component	NiCr		NiSi	
	Ni	Cr	Ni	Si
Target	88.93	9.50	95.15	2.50
Film	88.95	9.38	95.29	2.47

Fig. 1 and Fig. 2 show the scanning electron microscope (SEM) images and atomic force microscope (AFM) images of NiCr/NiSi films, respectively. From Fig. 1, it can be seen that the compactness of the NiCr/NiSi film is uniform and the continuity is good. From Fig. 2, it can be seen that the surface of NiSi thin film is much more smooth than that of NiCr thin film. Mean roughness of the NiCr thin film is 4.84 nm, and the mean roughness of the NiSi thin film is 0.33 nm [10]. It can be seen from the results above that the alloy composite elements of the prepared NiCr/NiSi films are closed to the target. They are compact uniform, smooth and continuity good, which meet the fabrication requirement for temperature measurement of cutter sensor.

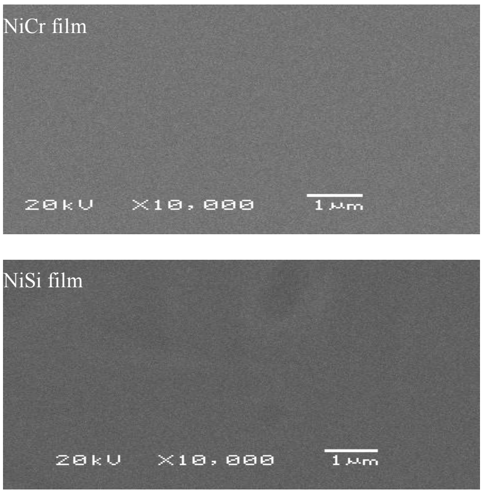

Fig. 1. SEM images of the surface of NiCr/NiSi thin films

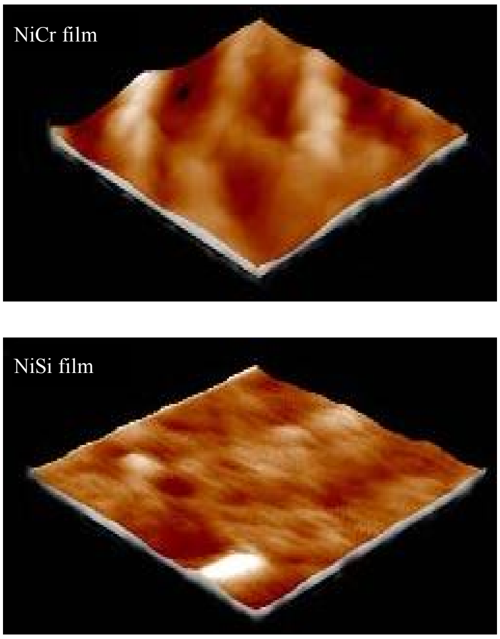

Fig. 2. AFM images of the surface of NiCr/NiSi thin films

3 Theoretical Analysis of Dynamic Performance

TFTCs were deposited on the surface of high-speed steel substrate coated with silicon dioxide insulating film. Because the thickness of matrix is very large compared with that of thin-film, it can be regarded as a semi-infinite in a one-dimensional unsteady heat conduction process[11].

Silicon dioxide has low thermal conductivity, which is much smaller than that of NiCr/NiSi. The influence of silicon dioxide can be ignored because of multi-layer thickness of the films. Only the influences of NiCr/NiSi thin-film in temperature conduction process were studied and the effects of different thickness of NiCr/NiSi thin-film on the dynamic response time at room temperature were calculated. We assume that the physical properties of materials do not change with temperature, because temperature upper limit of sensor is much lower than the melting temperature of thin-film and substrate materials. The heat transmission is along x direction (by assumption the vertical direction along the membrane towards matrix-oriented), as is shown in Fig. 3.

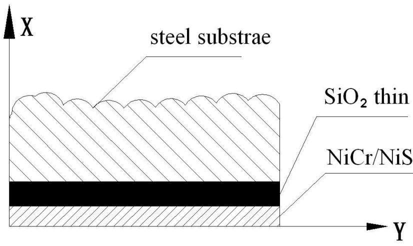

Fig. 3. Heat conduction model

Supposing that the surface of thin-film generates a temperature step [11], $f(t)=\theta_s$ is equal to a constant, the distribution function of NiCr/NiSi thin-film is $\theta_1(x, t)$, we can obtain

$$\frac{\theta_1(\delta,t)}{\theta_s}=e_{rfc}\left(\frac{\delta}{\sqrt{4\alpha_1 t}}\right)-K\left[e_{rfc}\left(\frac{3\delta}{\sqrt{4\alpha_1 t}}\right)-e_{rfc}\left(\frac{\delta}{\sqrt{4\alpha_1 t}}\right)\right], \quad (1)$$

where $\theta_1(\delta, t)$—Temperature distribution function,
θ_s—Step temperature signal,
$e_{rfc}(\bullet)$—Complementary error function,
δ—Thickness of NiCr thin film,
t—Heat transmission time,
α_1—Thermal diffusivity of NiCr thin film,
K—Correlation coefficient.

When $t=\tau$, $\theta_1(\delta, \tau)=0.632\theta_s$, we substitute it into Eq. (1), and can obtain the following:

$$\begin{aligned}&e_{rfc}\left(\frac{\delta}{\sqrt{4\alpha_1\tau}}\right)-K\left[e_{rfc}\left(\frac{3\delta}{\sqrt{4\alpha_1\tau}}\right)-e_{rfc}\left(\frac{\delta}{\sqrt{4\alpha_1\tau}}\right)\right]=\\&1-e_{rf}\left(\frac{\delta}{\sqrt{4\alpha_1\tau}}\right)-K\left[e_{rf}\left(\frac{\delta}{\sqrt{4\alpha_1\tau}}\right)-e_{rf}\left(\frac{3\delta}{\sqrt{4\alpha_1\tau}}\right)\right]=0.632,\end{aligned} \quad (2)$$

where $e_{rf}(\bullet)$—Gauss error function,
τ—Time constant.

When x is small, complementary error function is close to linear, $e_{rf}(3x)\approx 3e_{rf}(x)$, Eq. (2) can be simplified as follows:

$$(1-2K)e_{rf}\left(\frac{\delta}{\sqrt{4\alpha_1\tau}}\right)=0.368, \quad (3)$$

$$K=\frac{-1+\frac{\lambda_1}{\lambda_2}\sqrt{\frac{\alpha_2}{\alpha_1}}}{1+\frac{\lambda_1}{\lambda_2}\sqrt{\frac{\alpha_2}{\alpha_1}}}, \quad (4)$$

where α_2—Thermal diffusivity of matrix,
λ_1, λ_2—Thermal conductivity of thin-film and matrix.

Moreover,

$$\begin{aligned}&e_{rfc}(y)=1-e_{rf}(y)=1-\frac{2}{\sqrt{\pi}}\int_0^x \exp(-\lambda^2)\mathrm{d}\lambda=\\&\frac{2}{\sqrt{\pi}}\int_x^\infty \exp(-\lambda^2)\mathrm{d}\lambda.\end{aligned} \quad (5)$$

When α_1, α_2, λ_1, λ_2 are substituted into Eq. (4), K=0.912. Substituting K, α_1, δ into Eq. (3), we can get that the time constant of thin-film sensor τ is 32.011 ns, as shown in Table 2.

Table 2. Response time of different thickness of thin-films

Parameter	Sample 1	Sample 2
Thickness δ/μm	2.89	3.78
Thermal conductivity λ_1/(cal • cm • s • K)	0.040 842	0.040 842
Response time τ/ns	32.011	152.606

It can be concluded from the above results that the main factors which influence time constant τ of thin-film are thermal diffusivity, thermal conductivity and film thickness of thin-film materials. Moreover, time constant τ is proportional to the thickness δ of hot junction. The response speed of thin-film thermocouple can be obviously improved by reducing the thickness of thin-film.

4 Measurement of Dynamic Response Time and Results Analysis

In order to research the effect of the abrasion of TFTCs impacting on time constant, a series of area of hot junction were prepared. The areas are 1.0 mm×2.5 mm, 0.8 mm×2.5 mm, 0.5 mm×2.5 mm, 0.3 mm×2.5 mm, respectively. The series of TFTCs is shown in Fig. 4.

4.1 Dynamic response testing scheme of TFTCs

In this paper, Ultra-CFR short pulse laser has been used as the incentive heat source. The parameters of laser are as follows: repetition frequency is 1–20 kHz, pulse duration is stationary 8 ns, laser's energy is 0.1–0.5 mJ, and repetition frequency is set at 10 kHz. Energy is selected as high as possible in order to make temperature curve more obviously. According to experiment, 0.3 mJ is chosen as the parameter of laser incentive heat source. Test principle is shown in Fig. 5.

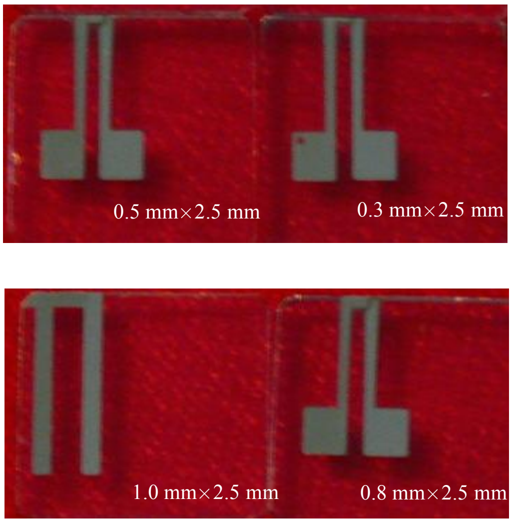

Fig. 4. A series of TFTCs

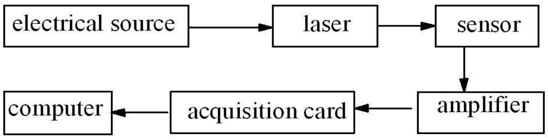

Fig. 5. Scheme of dynamic calibrating for temperature measurement of TFTCs

The output of the laser was absorbed by thin-film thermocouple cutter sensor, the signal was amplified for 1000 times with precision amplifier circuit and thermal electric-potential signal that sensor exported was gathered by DT9800 acquisition card. The sensor and testing system was in grounding to decrease the interference on signal conditioning circuit and recording instruments caused by laser power supply and other electromagnetic devices, in order to ensure the accuracy of dynamic characteristics testing.

4.2 Dynamic response time measurement of thin-film thermocouple at different hot junction width

Ultra-CFR short pulsed laser has been used, the pulse width was 8 ns, repetition frequency was 1 Hz and laser's energy was 0.3 mJ. Data was collected by DT9800 acquisition card, then time constant was measured when hot junction width were 0.3 mm, 0.5 mm, 0.8 mm, 1.0 mm, respectively. The response curve at 1 Hz repetition frequency and at 100 kHz sampling frequency is shown in Fig. 6. The time constant curve with different width of hot junction is shown in Fig. 7. From Fig. 7, it can be seen that when area of thermal contact is reduced to 3.3 times, the difference of response time was small.

Heat capacity is the main factor that influenced the response time of wire thin-film thermocouple, which is obtained by the thickness multiplying the area of thin-film thermocouple, so the thickness and area of the TFTCs are the main factors that influenced the response time. It can be inferred from the formula of heat transfer model that the area has no effect on macroscopic thermal volume when the area changed 3 times or even 30 times, because the thickness of thin-film is 10^{-5}–10^{-3} times smaller than that of block. In conclusion, the thickness of thin-film is the most important factor that influences response time.

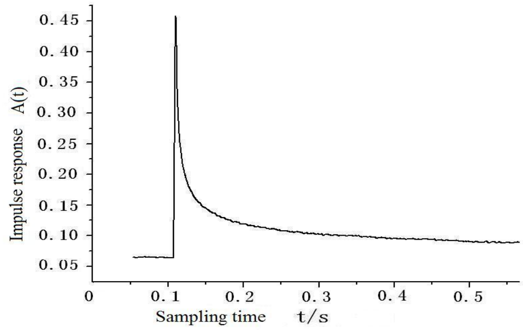

Fig. 6. Impulse response curve

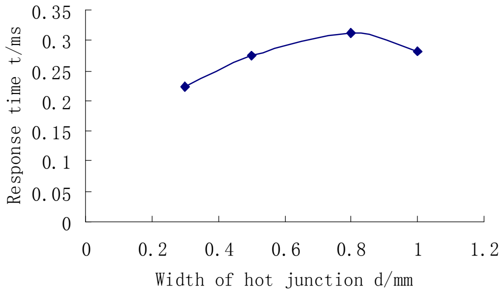

Fig. 7. Time constant curve of four TFTCs

4.3 Dynamic response time measurement of thin-film thermocouple in different sampling frequency

When the sampling frequency were 10 kHz, 50 kHz, and 100 kHz under the same testing conditions, the hot junction width were 0.5 mm and the time constants were 0.224 ms, 0.126 ms, and 0.095 ms, respectively. The relationship of response time and sampling frequency is shown in Fig. 8. Dynamic response time decreased as the sampling frequency in the range of 10 kHz to 50 kHz. The time sampling frequency of the testing system should be larger than 50 kHz in order to obtain the steady test results.

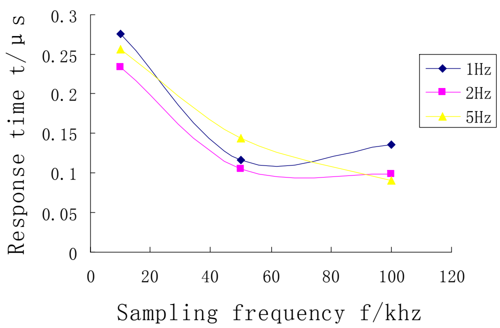

Fig. 8. Relationship of response time and sampling frequency

4.4 Deviation analysis

There is great difference between calculated values and measured values of time constant, the main reasons can be summed up as follows.

(1) The laser on the surface of TFTCs is an extremely complex process, when dynamic character of thin-film thermocouple is regarded as one order inertial link, the time constant precision is poor by output curve estimating.

(2) In this research, the influence of NiCr thin-film in temperature transmission has been investigated, while the influence of silicon dioxide is ignored in calculation. The thermal conductivity of thin –film is substituted by that of block, which influences calculated values, is smaller than measured value.

(3) The electrode of thin-film is alloy material, thermal diffusivity and thermal conductivity coefficient change along with the material composition. The composition of the electrode is an important influence factor to time constant.

(4) Laser modulation is not taken into account to reduce the error of dynamic response time constant as much as possible. The test accuracy could be improved by increasing impact energy and reducing the pulse width of the laser.

5 Conclusions

(1) The time constant of cutter measurement sensor made by means of advanced twinned MW-ECR plasma source enhanced RF reaction non-balance magnetron sputtering technique can reach to microsecond, which is suitable for measuring transient temperature that varies quickly. It can be concluded from the measured values that there was little influence of the area of hot junction of this sensor on the dynamic response time.

(2) It can be learned from the calculated result that time constant τ is proportional to the thickness δ of hot junction, the response speed of thin-film thermocouple can be obviously improved by reducing the thickness of the thin-film.

(3) The system for measuring dynamic response time by means of Ultra-CFR short pulsed laser is constructed and the pulse width of laser is 8 ns. Sampling frequency can reach to 100 kHz. The shortest response time of test is 0.042 ms.

(4) Sampling frequency should be larger than 50 kHz when dynamic response time is measured by short pulsed laser.

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