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Article

Research on the Dynamic Compensation System of the Cathode Electrode Wear for a Short Electric Arc Machine Tool

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Abstract: A methodology of on-line monitoring of the diameter of the cathode electrode is put forward in light of the issue that the diameter of the cathode electrode cannot be detected in an accurate manner in short electric arc machine tools. The monitoring methodology is capable of precisely determining the wear amount of the cathode electrode and uses the bus module in the numerical control machine tool to feed the wear amount of the cathode electrode back to the numerical control system (CNC system). The CNC system dynamically adjusts the position of the cathode electrode by driving the compensation shaft to ensure that the discharge gap between the cathode electrode and the anode electrode is within the control range and attain smooth machining. On this basis, a dynamic compensation system for cathode electrode wear for a short electric arc machine tool is developed, which has the potential to automate short electric arc machining and improving the machining performance of the machine tool. The feasibility of this methodology is verified by a machining experiment.

Keywords: Short electric arc machine tool; cathode electrode; wear monitoring; dynamic compensation

1 Introduction

With the continuous development of industry and technology, there are numerous fields, particularly in the aviation, military special industries, that put forward different kinds of performance indexes for their utilized materials. Short Electric Arc Machining (SEAM) has emerged under such circumstances [1]. Short electric arc milling technology is a type of electrical cutting methodology that is based on the working medium of a certain proportion of gas and liquid, making use of the activated short electric arc discharge group generated between the work-piece and the tool electrode for the elimination of conductive materials, which are difficult to machine [2]. In comparison with traditional electric discharge machining (EDM), the arc column of a short electric arc discharge has a higher internal temperature, coupled with more energy distributed on the work-piece. Accordingly, the short electric arc milling has the potential to obtain a higher machining efficiency, aimed at compensating for the lacking traditional EDM technology [3].

There are currently several investigations dealing with SEAM and compensation control. Zahiruddin and Kunieda made use of two-electrode processing together with introducing a specific pressure gas flow in the discharge gap between the electrodes to improve the removal efficiency [4]. Marafona et al. put forward a discharge model, followed by employing the same model to calculate the maximum temperature as well as the surface quality of the model [5]. Jang and Chung proposed a Neuro-Fuzzy Controller for DC Motor Friction Compensation that can be put to use for the precise driving of robots [6]. In accordance with Yadav, ANSYS finite element software was employed to simulate thermal stress fields in machining [7]. A moving arc was proposed, which removes the workpiece surface material at a higher moving speed [8].

Zhou, Xu, Liang, and Zhou determined that the smaller the discharge gap, the larger the machining current, which results in a higher discharge intensity and a higher processing efficiency [9]. Li et al. investigated a novel anti-swing control strategy for an overhead crane, wherein a high-gain observer was introduced [10]. As suggested by Hashemi et al. [11], the impact of temperature on a CDPS output was identified and compensated for the use of a Support Vector Machine for Regression (SVR) methodology. Yue et al. talked about the methodologies of fast processing UAV images and extracting crop disease information for the purpose of developing a monitoring system [12]. Zhao et al. primarily investigated the impact of a working medium on short arc discharge channels by means of experiments and simulations with the use of finite element software [13]. Zhang et al. analysed the impact of electrical and non-electrical parameters on the surface integrity of the workpiece [14]. Non-conductive ceramic single-pulse discharge experiments were employed to analyse the impacts of various processing parameters on the short arc machining efficiency [15]. Yang et al. made use of a time series and chaos theory of phase space reconstruction in order to demonstrate that the BP neural network and RBF neural network were both effective in monitoring information prediction [16]. Xu et al. made use of orthogonal experiments for the purpose of investigating the factors impacting the surface roughness of the workpiece [17]. Zhang et al. combined the discharge experiment in a bid to study the association existing between the discharge channel and the pit volume, followed by discovering the differences between the short arc discharge and the spark discharge [18]. The short arc machining surface quality model can be predicted by the BP neural network based on the L-M algorithm [19]. Ai et al. realized the function of the remote video monitoring and displaying module statuses on webpages based on the UP-Magic 6410 development board [20]. Wang et al. performed an investigation dealing with the discharge performance of electrode materials for short arc milling tools [21].

Even though the short electric arc machine tool has great advantages in processing high-hardness and high-strength materials, the short electric arc machine tool is still at a semi-automated level and requires manual control. The key issue faced during the automation development of the short electric arc machine tool indicates that the wear of the cathode electrode cannot be automatically compensated, and manual adjustment based on experience is required to ensure the smooth progress of the machining. Liu, Zhou, and Xu put forward a short arc milling machining feed motion control based on the fuzzy PID [22].

SEAM deals with eliminating metal and other conductive materials with the use of the activated short electric arc discharge group between two electrodes or mixed with the spark discharge group, resulting in the cathode tool electrode ceaselessly burning wear, while the anode work-piece electrode is removed during machining. The loss rate of the cathode electrode is between 5% and 15% in the SEAM process. For the purpose of making it certain that the discharge gap between the cathode tool electrode and anode work-piece electrode is not going to suddenly increase, it is deemed essential that the position of the cathode electrode be adjusted to ensure that the discharge gap is within the control range [23].

Currently, the artificial observation methodology is employed for the manual adjustment of the position of the cathode electrode through the observation of the wear of the cathode electrode by the naked eye. The accuracy of this methodology is low, and the location of the cathode electrode cannot be adjusted in real time, leading to an excessive discharge gap in SEAM impacting the surface quality of the machined parts. A new cathode electrode detection method is discovered in the current paper. The diameter of the cathode electrode is monitored by a laser sensor to calculate the wear amount of the cathode electrode. The numerical control system drives the compensating shaft in a bid to adjust the position of the cathode electrode, aimed at completing the respective compensation. On this basis, a dynamic compensation methodology of the cathode electrode wear for a short electric arc machine tool is put forward. The feasibility of this methodology is verified by experiments, and the automation level of the short electric arc machine tool can be enhanced using this compensation scheme.

2 On-Line Monitoring System of the Cathode Electrode

2.1 Working Principle of the Monitoring System

The function of the cathode tool electrode involves conveying the processing pulse, and the tool electrode in the ideal state deals with removing the workpiece with minimum loss. The monitoring system of the cathode electrode diameter adopts a closed loop control for the calculation of the cathode electrode wear value for a specific time in accordance with the difference between the distance detected by the sensor and the setting distance detected. The laser sensor is connected to the HIO-1073 module in the bus module of the CNC machine. When the HIO-1073 module attains the wear amount of the cathode electrode, the numerical control system drives the compensating shaft to compensate the cathode electrode accordingly. The working principle of the monitoring system is presented in Fig. 1.

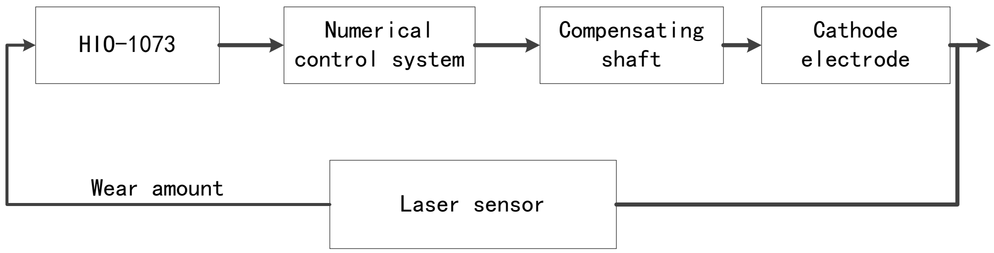


Figure 1: Working principle of the monitoring system

The laser sensor uses a Baumer sensor. The specific model together with the associated working parameters is presented in Tab. 1. The laser sensor is installed in the plane of the cathode electrode, as presented in Fig. 2. The output of the laser sensor is a standard analogue signal. Both the distance between the laser sensor and the edge of the cathode electrode can be manifested on the sensor's working interface. When the processing has not started yet, the laser shoots from the laser sensor and is projected onto the edge of the cathode electrode, and then the distance between the two is set as K_m during SEAM. The cathode electrode has wear when the laser sensor manifests the distance being greater than K_m ; in this case, the distance between the two is set as K_n , and the wear amount of the cathode electrode in the process is set as K . The mathematical model is presented as hereunder:

$$K = K_n - K_m \tag{1}$$

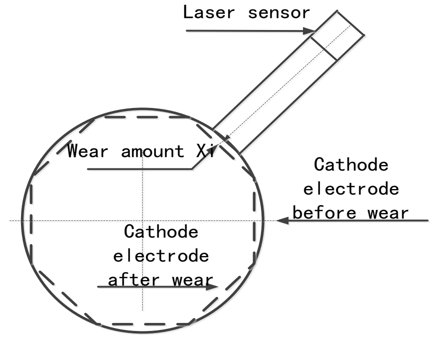
Table 1: Working parameters of the laser sensor

Sensor model	21I6481/S14F
Measuring distance	200–1000 mm
Resolution	0.02–0.4 mm
Laser grade	2
Output circuit	Analogy quantity
Output signal	0–10 VDC

2.2 Processing of the Monitoring Data

After the cathode electrode is worn, its cross-section is expected to turn into a non-standard circular interface. Accordingly, a series of discrete wear amount is going to be attained all through the monitoring process of the laser sensor. This is deemed as essential to process the wear amounts for the purpose of obtaining the correct cathode electrode wear value. Fig. 2a is the laser sensing installation site picture, of which the B shaft constitutes an adjustment shaft of the laser sensor, which is primarily meant for adjusting the initial installation distance between the laser sensor and the cathode electrode, further aimed at adapting to the different size of the cathode electrode. Fig. 2b is a schematic diagram for the laser sensor installation. As seen from the diagram, the cathode electrode changes to a non-standard cylinder following the wear. The wear amount attained by the laser sensor is a series of discrete data that needs to be processed.

a Site Picture



b Schematic Diagram

Figure 2: The laser sensor installation diagram

Based on the relevant statistics principle, the monitoring data is processed by taking the weighted average and the standard variance. The wear deviation is set as X_{ij} and the average wear deviation as $\overline{X_i}$. The mathematical model is presented as:

$$\overline{X_i} = \frac{1}{m}\sum_{j=1}^{m} X_{ij} \tag{2}$$

where i denotes the wear moment (i = 1, 2, 3, …, n); and j represents the wear amount obtained at i.

The wear condition of the cathode electrode for the short electric arc gradually becomes serious. In the preliminary mechanism, the wear condition is light, and the wear deviation value X_i is close to 0. If the wear amount is attained merely by the weighted average, the precision of the compensation is going to be impacted as if the error is too large. In combination with the uncertainty evaluation principle, a more precise wear amount can be attained through the evaluation of the wear deviation. On the basis of the Bessel method, the estimated value of the wear deviation uncertainty is set as S_i, and the standard uncertainty caused by the repeatability of wear amount as U_i. The mathematical model is as:

$$S_i = \sqrt{\frac{1}{m-1}\sum_{j=1}^{m}\left(X_{ij} - \overline{X_i}\right)^2} \tag{3}$$

$$U_i = \frac{S_i}{\sqrt{m}} = \sqrt{\frac{1}{m(m-1)}\sum_{j=1}^{m}\left(X_{ij} - \overline{X_i}\right)^2} \tag{4}$$

That is, why the wear amount of the cathode electrode is set as K_{ij} when wearing at i, for which the mathematical model is as:

$$K_{ij} = \overline{X_i} + U_i \tag{5}$$

2.3 Composition of the Monitoring System

The short electric arc machine tool applies to the Huazhong Type 8 CNC system. The "Huazhong Type 8" CNC makes use of the open CNC system structure and the all-digital control technology for supporting the NCUC bus transmission. The open CNC enhances the stability of the system as well as the scalability of the system. The hardware PLC module, matching the CNC system, is the bus I/O product of the Huazhong CNC HIO-1000 series. The analogue signal conversion module HIO-1073 in the HIO-1000 selects AD7265 as the AD conversion chip. The HIO-1073 holds the responsibility for the completion of the A/D conversion signal input from the machine tool to the CNC system and the D/A signal output from the CNC system to the machine tool. Each A/D-D/A module provides 4 channels and 12 digits' difference of analogue signal inputs and 4 channels and 12 digits' difference of analogue signal outputs. The voltage analogue signal output by the laser sensor is between 0-10 V. The voltage analogue input signal attained by the HIO-1073 module is also between 0-10 V, which is consistent with the signal access requirements. The voltage analogue signal line of the laser sensor is connected to the No. 5 interface in the XA interface. The signal connection diagram of the laser sensor is demonstrated in Fig. 3. The HIO-1073 module is installed as shown in Fig. 4.

The monitoring system is designed for the detection requirements of the cathode electrode diameter. The numerical control system is used as the data processing unit in order to monitor the diameter of the cathode electrode combined with the PLC of the CNC machine tool. The laser sensor transfers the wear amount of the cathode electrode to the voltage signal; subsequent to that, the HIO-1073 module converts the voltage signal into the standard digital quantity for the feedback to the numerical control system, accordingly, completing the online monitoring function of the cathode electrode.

2.4 The Position Compensation of the Cathode Electrode

SEAM is a type of new non-contact non-traditional machining, corroding the excess materials on the work-piece surface by the electric arc generated between the anode work-piece and the cathode tool, in addition to taking the removed materials away from work-piece with the help of a gas-liquid mixing device. Currently, SEAM is primarily applied to the rough machining and semi-finishing of the excircle as well as the end face for the high strength and high hardness materials. The key movements of the short electric arc CNC machine tool counts on the horizontal direction (direction of the Z shaft) and longitudinal direction (direction of the X shaft) movement of the cathode electrode, in addition to the principal shaft movement of the cathode work-piece and the principal shaft movement of the anode work-piece; the auxiliary movements include the motion control of the control shaft of the laser sensor and the compensation shaft of the cathode electrode.

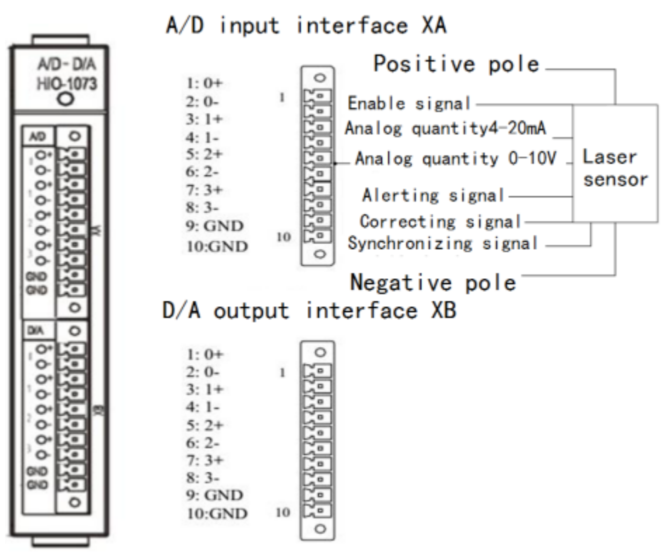


Figure 3: The connecting diagram of the laser sensor and the CNC system

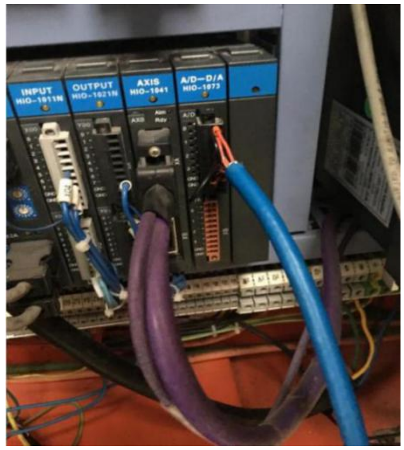


Figure 4: The HIO-1073 board card wiring diagram

All through the short electric arc machining mechanism, the metal on the surface of the work-piece material is going to melt and gasify when subjected to the high temperature, followed by splashing when departing from the electrode. The majority is taken away from the machining area with scouring of the liquid medium, and some being adsorbed on the electrode surface for compensating the electrode. Nevertheless, this compensation effect is low and is accordingly still deemed as essential to compensate for the position of the cathode electrode in real time for the purpose of ensuring smooth machining. The CNC system can obtain the wear condition of the cathode electrode with the on-line monitoring system in real time. The cathode electrode wear is primarily produced in the direction of the X shaft, so the position of the cathode electrode in the direction of the X shaft can be adjusted by setting the compensation shaft (Y shaft), for which the adjustment distance is the wear amount of the cathode electrode within the unit time attained by the CNC system. Fig. 5 shows a diagram of the compensation principle of the cathode electrode.

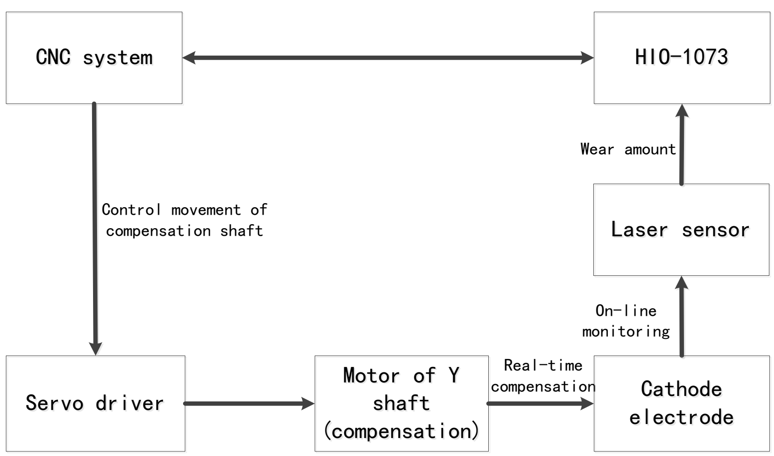


Figure 5: The compensation principle diagram of the cathode electrode

The on-line monitoring system of the cathode electrode makes use of the HIO-1073 module for feeding back the wear amount to the CNC system. In addition, the CNC system is expected to attain the wear amount of the cathode electrode by processing the data. Since the wear amount of the cathode electrode is relative to the preliminary diameter of the cathode electrode, the value is an accumulated value. Nevertheless, the compensation of the compensation shaft is relative to the compensation required by the last wear. The compensation amount is set for the mathematical model as:

$$Y_{\mathrm{i}} = K_{\mathrm{ij}} - \mathrm{K}_{(\mathrm{i}-1)\mathrm{j}} \tag{6}$$

where i indicates the wear moment (i = 1, 2, 3, …, n); and j suggests the wear amount attained at i.

The HIO-1073 module sends a wear signal to the PLC. Due to the short electric arc machining field in the complex environment, which is aimed at avoiding the detection error caused by external factors, the PLC of the CNC machine tool is set to refresh the wear signal three times, suggesting that the cathode electrode wear appears and the PLC sends the compensation signal to the CNC system after that. The CNC system is going to drive the compensation shaft (Y shaft) subsequent to receiving the compensation signal. The compensation axis drives the cathode electrode to be transversely adjusted, and the adjustment distance is the wear amount attained by the CNC system all through this period. See Fig. 6 for part of the PLC ladder diagram.

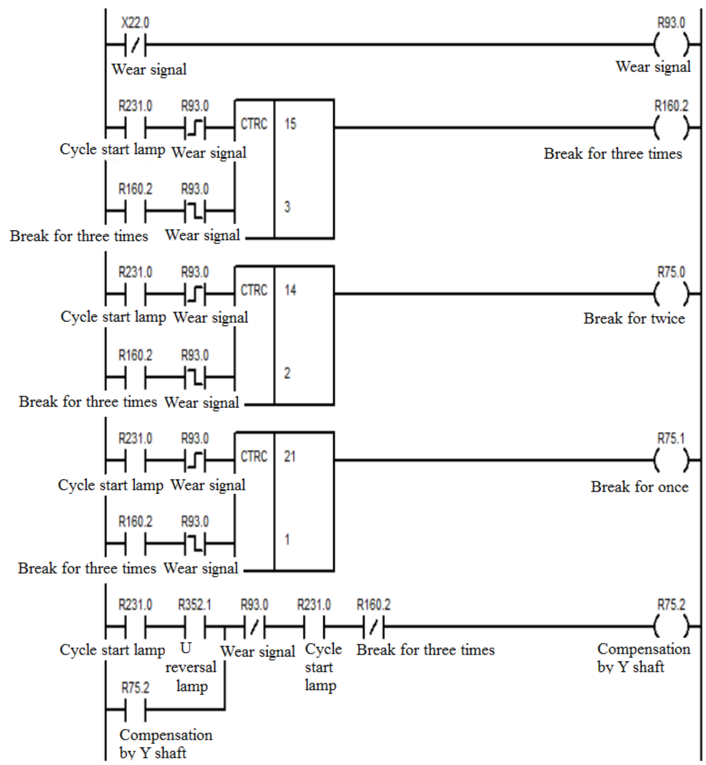


Figure 6: Part of the PLC ladder diagram

2.5 *The Dynamic Compensation Scheme of the Cathode Electrode Wear*

2.5.1 The Overall Design of the Compensation Scheme

The ordinary short electrical arc machine tool is incapable of automatically adjusting the position of the cathode electrode, instead requiring manual adjustment. Accordingly, automatic machining cannot be realized. By means of the automatic compensation methodology of the cathode electrode position highlighted earlier, a dynamic compensation scheme of the cathode electrode wear can be designed and aimed at improving the automation level of the short electric arc machine tool.

The automatic machining of the CNC machine tool typically requires a background program, PLC, a G code interpreter and an interpolator for the purpose of running simultaneously. The background program sets the parameters required for this machining. The PLC reads the associated switch quantity and analogue signal and feeds it back to the CNC system. The “Huazhong Type 8” CNC system has the G code interpretation function. The interpreter divides the G code interpretation into a number of points. The interpolator performs a differential operation on the interpreted G code. With regards to the fully automatic machining of the short electric arc CNC machine tool, there are 5 basic parameters; machining parameter, discharge parameter, work-piece parameter, tool parameter and medium parameter, which shall be first set in the background program. The PLC reads out the basic switch quantity and the analogue quantity signals.

In the meantime, the HIO-1073 module sends the wear amount of the cathode electrode to the CNC system in real time, together with completing the online monitoring of the cathode electrode; the G code the interprets the inputted G code; and the interpolator completes the differential operation. When the cathode electrode has not yet been worn out, the CNC machine tool is expected to typically perform the machining in accordance with the requirements of the G code. When the cathode electrode is worn out, the CNC machine tool is going to drive the compensation shaft (Y shaft) to ensure normal machining. Fig. 7 demonstrates a compensation machining swimlane of the short electric arc machine tool.

2.5.2 The Key Technology in the Dynamic Compensation Machining

The key technology of automatic machining of the short electric arc machine tool involves realizing the information interaction among the background program, PLC, G code interpreter and the interpolator. The user macro variable, which is provided by the Huazhong CNC system, is capable of attaining the data transfer of the G code interpreter as well as the background program. In the G code, the command can be sent to the PLC with the help of the self-defining M code aimed at accomplishing the data transfer between the G code and the PLC by means of the special macro variable of the Huazhong Type 8. The PLC and G code interpolator make use of the F and G registers to realize the data interaction. The background program is capable of obtaining the values of F and G registers with the API interface function.

Key Technology in Dynamic Compensation Machining

The G code interpreter accomplishes the scheduling of the PLC with the use of the self-defined M code. The self-defined M code includes M76, M77 and M78, of which M76 implies making the PLC in order to obtain the wear signal, and M77 suggests that the wear amount attained by the PLC is fed back to the CNC system. The M78 reveals that the PLC stops sending the wear amount to the CNC system. Fig. 8 illustrates the G code design flow chart of the online monitoring module.

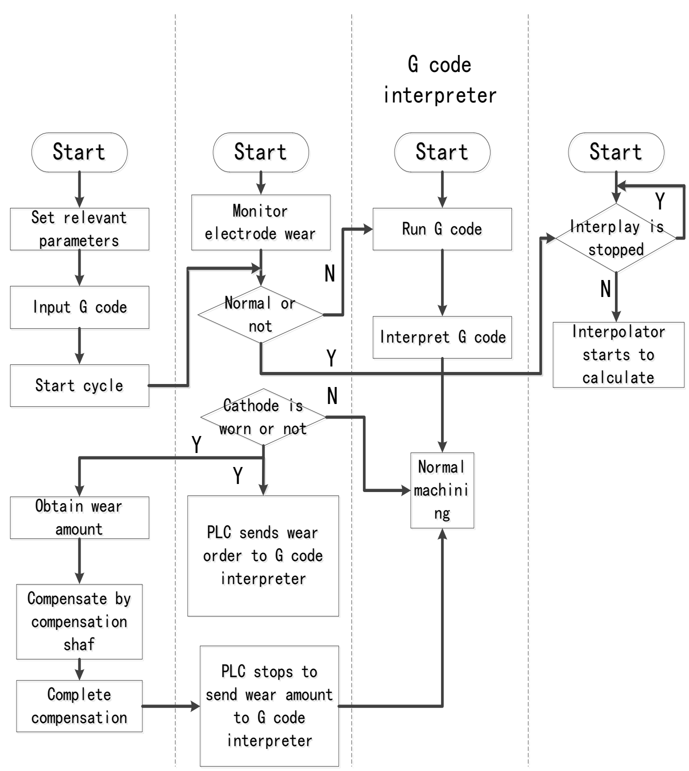


Figure 7: The compensation machining swimlane of the short electric arc machine tool

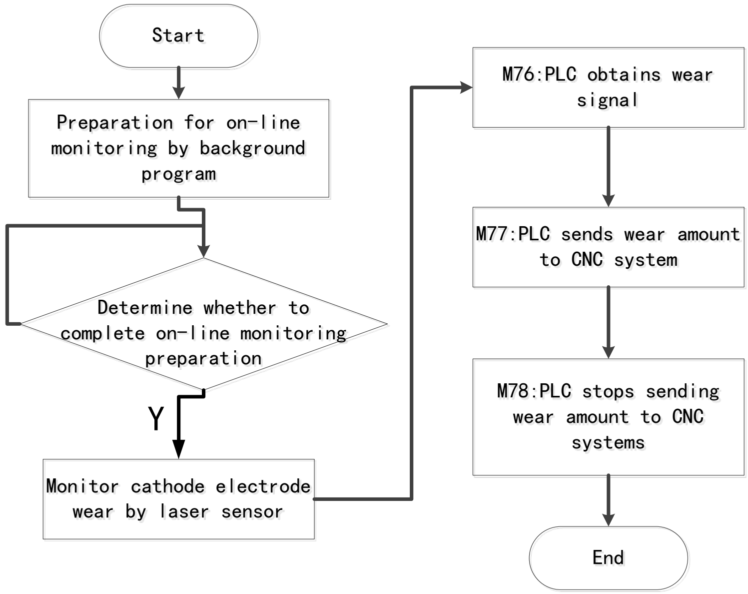


Figure 8: The G code design flow chart of the online monitoring module

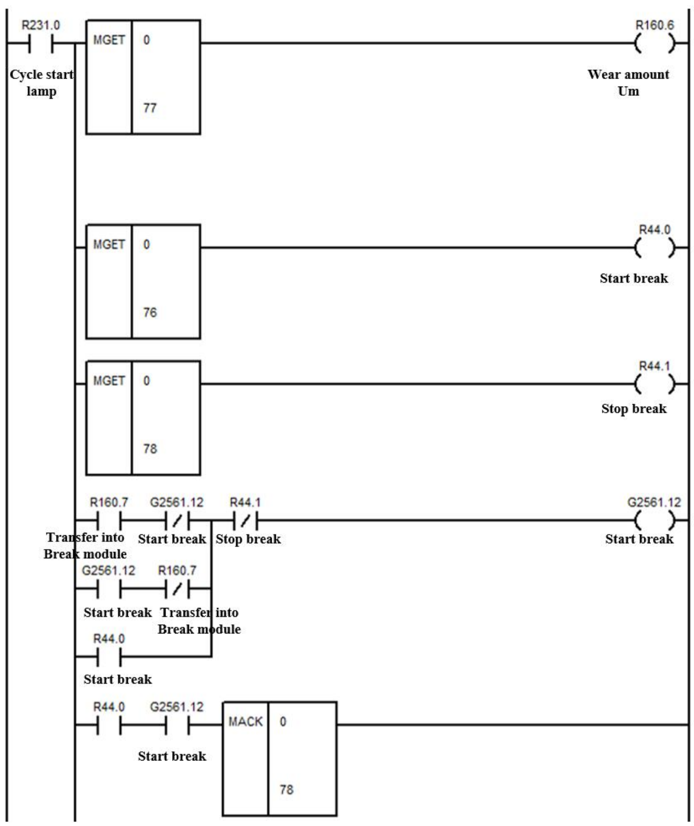


Figure 9: The specific implementation mode of the M code in the PLC

In the Huazhong CNC system, the G code interpolator attains the data interaction with the PLC by means of the F and G registers, in addition to observing the monitoring scenario by setting the register of the G2561.12 in Fig. 9. When G2561.12 is equal to 1, the PLC sends the wear order to the G code interpolator. When G2561.12 is equal to 0, the PLC sends an order to stop transferring the wear order to the G code interpolator. Fig. 10 sheds light on the specific implementation of the M code in the PLC. In the diagram, the MGET module is set by two parameters, wherein the first parameter is the channel number and the second is the M code.

The Information Interaction Technology between the G Code and the Background Program

The Huazhong Type 8 CNC system provides 5000 global macro variables, which include #50000-#54999, using them together for the purpose of writing the G code programs. The global macro variable #50040 is used for the realization of the information interaction between the G code as well as the background program. When #50040 is no. 1, the G code interpreter sends the command for dealing with the wear data to the background program; thereafter, the G code interpreter enters a cycle. When the background program processing is completed, the wear data and #50040 is no. 2, and the real-time compensation module is leapt out of the loop.

The information interaction between the background program and the G code can be realized with the use of the interface function of the CNC system. The laser sensor is expected to transfer the wear amount to the D register in the PLC. The interface function has the potential of obtaining the position data of each shaft of the short electric arc machine tool. The HNC_RegGet Value is capable of attaining the value in the D register and the sprint function is expected to write the wear amount into the interface of the CNC system for the purpose of achieving the display function.

3 Experiment

The feasibility of the dynamic compensation methodology for the dynamic compensation machining of the cathode electrode wear will be verified with the help of the machining experiment.

Based on the Huazhong 8 CNC system, the servo algorithm is designed. According to the feedback current, voltage, temperature, water pressure and air pressure of the processing state acquisition system, the feed servo execution strategy is synthetically evaluated. The short arc machining process can be divided into four states, including: the stop alarm, open circuit, normal discharge and short circuit alarm. The algorithm flow is as follows in Fig. 11.

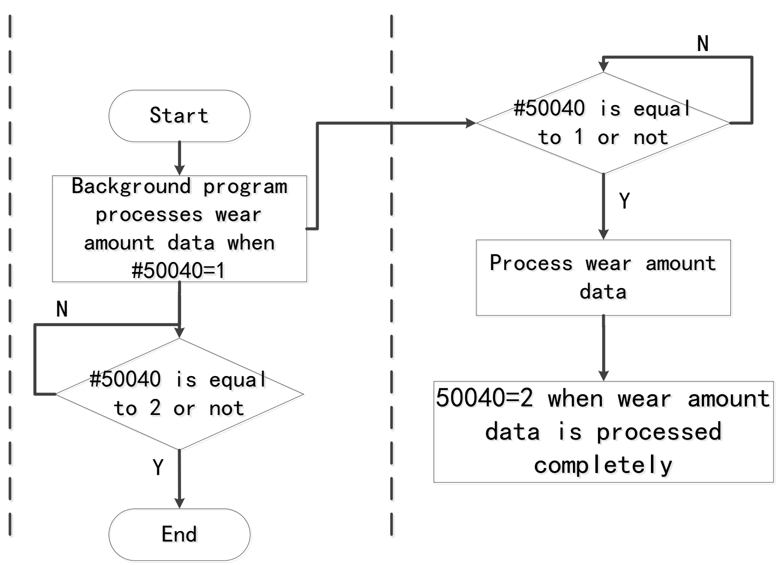


Figure 10: The information interaction flowchart between the G code interpreter and the background program

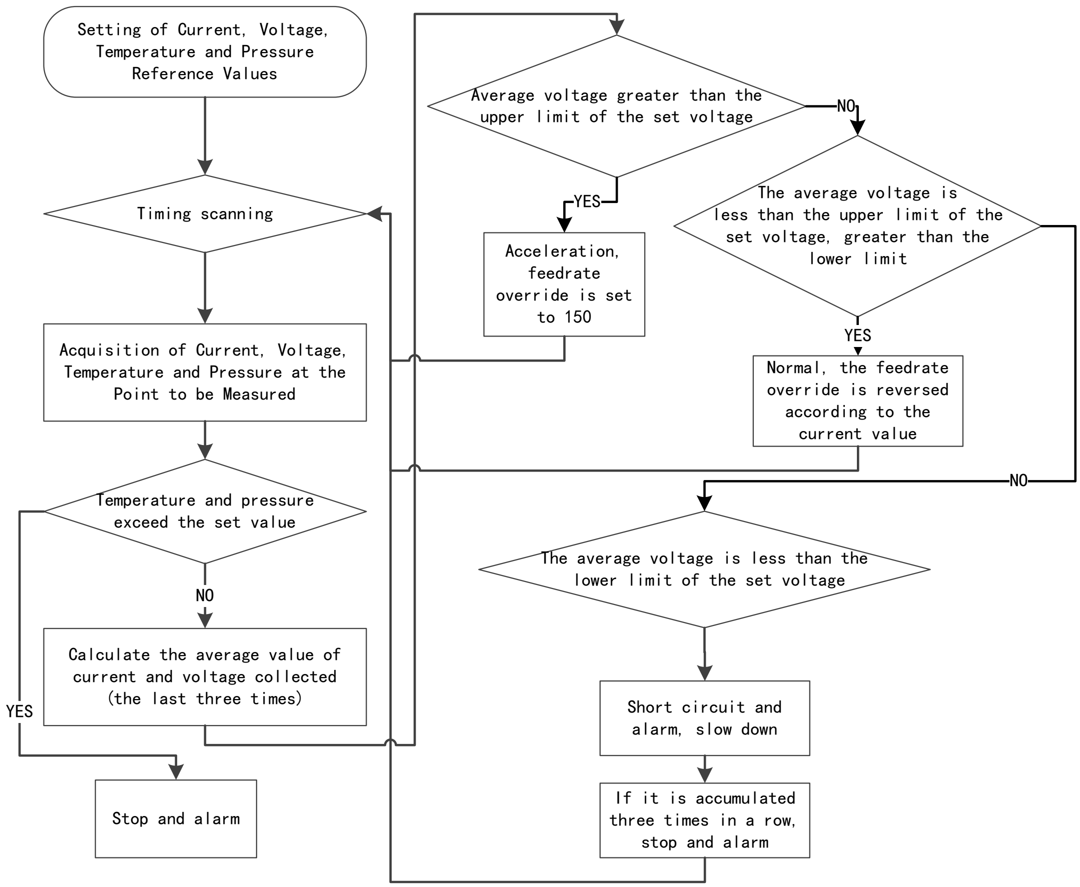


Figure 11: The feed servo control flow

This work-piece selected for this experiment is a cylindrical roller with a diameter of 800 mm, 9Cr material and a total grinding amount of 25 mm. The machining mode is set as rough machining, the axial feed speed is 5 mm/min, the single side cutting axial feed is 1 mm, the working voltage is 20 V, and the rotational speed of the work-piece is 50 r/min. The relevant parameters are presented in Tab. 2.

The processing site is shown in Fig. 12 and following the observation of the machining experiment, it is evident that with continuous machining the cathode electrode is worn to a specific extent, while the compensation shaft adjusts the position of cathode electrode for the purpose of ensuring smooth machining. Following the period of 17 minutes, the workpiece is accomplished. The measured diameter of the workpiece is 74.36 mm, which is consistent with the machining requirements. Tab. 3 shows a table of the changes in the cathode electrode obtained all through the machining.

Table 2: Table of the set experimental parameters for short electric arc compensation machining

No.	Parameter name (mm)	Parameter value
001	initial diameter of workpiece	800.000000
002	Final diameter of workpiece	775.000000
003	Margin of rough machining	25.000000
004	Margin of semi-finishing	0.000000
005	Margin of finish machining	0.000000
006	Retreating distance of Z after cutting	15.000000
007	Retreating distance of X after cutting	30.000000

008	Feed amount per step of X for rough machining	1.000000
009	Feed amount per step of X for semi-finishing	0.000000
0010	Feed amount per step of X for finish machining	0.000000

Table 3: Table of changes in the cathode electrode

Machining time/min	Diameter of cathode electrode/mm	Wear amount/mm	Compensation amount/mm
0	380.41	0	0
1	380.41	0	0
2	380.41	0	0
3	380.40	0.01	0.01
4	380.12	0.29	0.28
5	379.44	0.97	0.68
6	375.87	4.54	3.57
7	373.34	7.07	2.53
8	371.66	8.75	1.68
9	370.55	9.86	1.11
10	368.45	11.96	2.1
11	368.22	12.19	0.23
12	366.59	13.82	1.63
13	365.67	14.74	0.92
14	363.76	16.65	1.91
15	362.12	18.29	1.64
16	361.58	18.83	0.54
17	360.81	19.60	0.77

Figure 12: The machining experiment site picture

As evident from both Fig. 13 and 14, the change in the diameter of the cathode electrode during the initial machining is small. The change at the middle section of the machining is larger, whereas the change at the end of the machining is inclined to being stable. As suggested by Fig. 15, it is known that the position of cathode electrode is adjusted at the beginning of machining. In addition, the compensation amount undergoes a sharp increase when the machining time is at 6 minutes; nonetheless, the compensation amount undergoes a gradual decline when the machining time is at 13 minutes.

As revealed by the empirical findings, the wear amount of the cathode electrode can be precisely attained by this compensation methodology. Furthermore, the cathode electrode can be precisely compensated rather than the original cathode electrode artificial observation methodology, which accordingly improves the automation level of the short electric arc of the CNC machine tool.

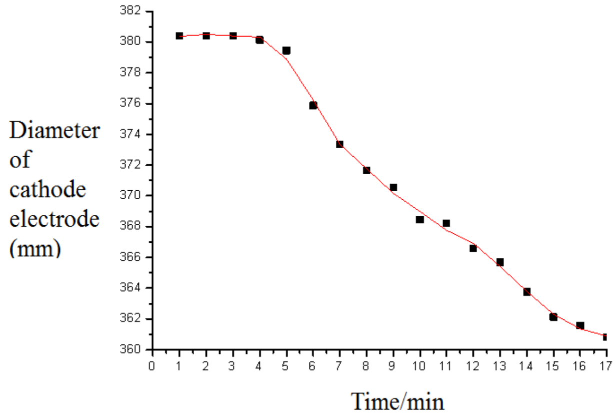


Figure 13: The diameter change diagram of the Cathode Electrode.

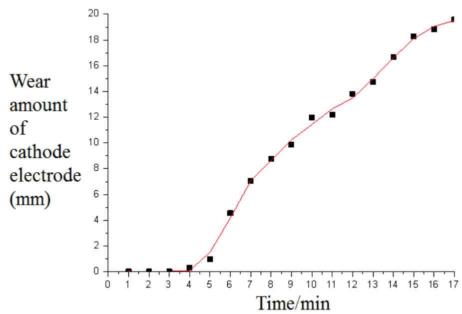


Figure 14: The wear amount change diagram of the Cathode Electrode

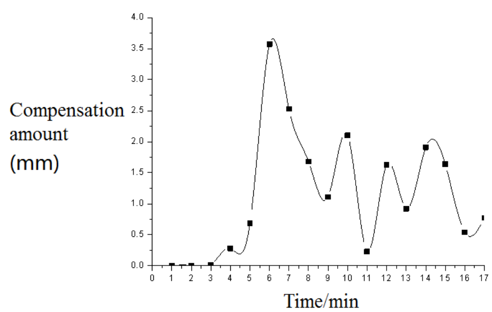


Figure 15: The compensation amount change diagram

4 Conclusion

In this paper, the necessity of the cathode electrode compensation is highlighted first, and then followed by analysing the shortcomings of the current cathode electrode compensation methodology, which is aimed at designing a new compensation methodology. The cathode electrode is monitored on-line by a laser sensor, and the wear amount is fed back to the CNC system for the purpose of driving the compensating shaft in a bid to adjust the position of the cathode electrode, together with completing the position compensation of the cathode electrode. On this basis, a dynamic compensation system of the short electric arc cathode electrode wear is put forward. In accordance with this scheme, the function of automatic machining of the short electric arc machine tool can be realized instead of traditional manual processing in order to enhance the automation level of the short electric arc machine tool.

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Conflicts of Interest: The authors declare that they have no conflicts of interest to report regarding the present study.

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