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Intelligent control of surface quality in super-finish grinding by utilizing WattPilote

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Abstract

As the intelligent grinding machine is required for high-precision grinding, a monitoring system is developed to control the surface quality of nozzle injector, which is stainless steel (DSUS70DH), for automotive combustion engine in super-finish grinding process by utilizing WattPilote to detect the in-process power signals. The in-process control limits of surface finish are determined referring to the experimentally obtained results by examining the maximum and minimum power signals under various samples. The new algorithm is proposed to identify and compare the obtained power signals by WattPilote during the in-process super-finish grinding. The experimentally obtained upper and lower control limits have been proved and verified with the new super-finish grinding tests. It is confirmed that the developed system can be used to monitor and check the quality of the surface finish of nozzle injectors during the super-finish grinding process with high accuracy regardless of grinding conditions. However, the in-process prediction model of surface finish, which can forecast the surface roughness of nozzle injector during high-precision grinding, will be executed in further research work.

1. Introduction

To achieve high surface qualities and geometrical specifications, one of the most important processes in manufacturing is super-finish grinding [1]. Particularly, in the automotive combustion engine, a surface finish is required to enhance quality, performance, and service life of the mechanical parts. The grinding spindle must be operated at higher rotational speeds with a low feed rate [2] to generate the surface temperatures [3], which softens the material surface and results in improved surface finish.

This research proposes a concept to control the surface quality of nozzle injector during the super-finish grinding process, which is a key component of a gasoline injector. It serves to atomize gasoline and mix it with air, thereby providing the fuel necessary for combustion in a gasoline internal combustion engine. The injection system has an important function in delivering decreased consumption of fuel, reduced pollution, and reduced emissions of gases. In the injection system, the most important component is the nozzle injector [4]. The critical parameter is the nozzle opening pressure at the nozzle body seat, which is the minimum pressure required to lift the nozzle needle and initiate the injection. The nozzle body seat is the important area for the opening pressure. It functions similarly to a valve, regulating the leakage of fuel. The nozzle body seat significantly impacts those parameters, influencing the injection system and engine performance throughout its lifespan [5]. The nozzle body seat is an internally conical shape that has been finely ground [6], located inside a hole that is approximately 3.4 mm in diameter and 5 mm in depth. This surface requires a high-quality finish with a surface roughness less than 0.6 µm as shown in Figure 1.

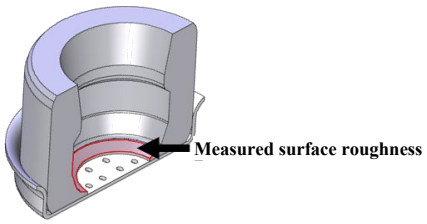


Figure 1. Illustration of nozzle body.

Currently, the inspection of nozzle body seat is time-consuming, making it impractical to inspect the quality of all [7]. It results in reduced performance and operational quality of the gasoline injector, as well as increased production waste, due to the delayed detection of quality issues. To enhance the in-process inspection of surface roughness for nozzle body seat in super-finish grinding by monitoring the power signals measured through the WattPilote sensor [8], providing a basis for controlling surface quality in accordance with specified standards and reducing the likelihood of production defects.

The intelligent machine can monitor and control itself to improve the process capability due to the environmental changes [9]. The internal cylindrical grinding, which is a necessary surface finishing process, is widely utilized for the internal grinding of complex surfaces and for the finishing of small-diameter holes [1]. The cutting mechanism of the grinding process is quite complex and uncertain because the presence of several irregular abrasives that are randomly dispersed over the circle of the grinding wheel [10]. The WattPilote or power sensor employed to monitor the power signal during the process has been developed through extensive researches [11–13]. The advantages include no need for machine modification and widespread industrial acceptance,

as it allows direct measurement of the power of spindle grinding motor [14]. The power sensor is the most suitable option for monitoring in terms of hardware cost, modification of the system, hardware ease of use, and invasiveness of operation [15]. Therefore, quality is controlled during the super-finish grinding process, which focuses on controlling the surface finish of nozzle injector within specified limits by using WattPilote sensor. The monitoring of the power signals which are occurred in the CNC grinding process leads to the development of the in-process quality control of the surface finish in the grinding process. However, an important challenge in the grinding process is the inability to inspect the surface quality during the grinding operation [16]. The poor surface quality during the grinding process will result in instability, leading to an unacceptable surface finish, which causes the rework, rejection and low productivity [17].

The WattPilote is utilized to monitor the power signals during the in-process super-finish grinding. The power variations are correspondent with the feed rate of grinding tool diameter while grinding the workpiece [18]. However, the surface finish has not been examined yet. Hence, an in-process monitoring system has been proposed to realize the intelligent grinding machine with the humanless operation to increase the surface quality of nozzle injector for automotive combustion engine in CNC super-finish grinding process. The in-process monitoring of surface finish in super-finish grinding is developed to control the surface quality, which can help to improve the productivity, reduce the reproduction time, eliminate the reproduction cost and save the energy usage leading to the decarbonization and greenhouse gas (GHG) reduction also by using WattPilote to investigate the power signals during the process as shown in Figure 2.

Normally, the original power signals consist of the static and dynamic power signals. The dynamic power signals, which start from zero baseline, have been considered instead of static power signals to monitor the surface finish due to the theoretical surface roughness. The static power signals have been subtracted out from the original signals. Hence, the (dynamic) power signals in this research are therefore occurred around zero baseline, which have positive and negative values as shown in Figure 2.

The power signals in super-finish grinding have been monitored while the grinding wheel is inserted into the nozzle body seat with inching frequency of 4 times and the stroke of 5 mm. Hence, the power signals will have 4 cycles of strokes with 1.6 s. The sampling rate of power signal is set at 5 ms. The power signals are expected to correspondent with the surface roughness that left on the seat of nozzle injector. It is understood that the upper and lower control limits can be obtained from the experimental results as the surface roughness and power signals are consistent. The experimentally obtained control limits can be used to monitor and check the quality of surface finish of nozzle injector for automotive combustion engine during the in-process super-finish grinding. The acceptable surface roughness is less than 0.6 μm.

2. Experimental setup and procedure

The super-finish grinding experiments are conducted and tested on CNC grinding machine which is setup and employed with the use of Cubic Boron Nitride (CBN) grinding tools. The nozzle injector for automotive combustion engine, which is stainless steel (DSUS70DH) with diameter of 3.4 mm, is ground by using cylindrical CBN grinding tool as shown in Figure 3(a). WattPilote sensor has been installed on the CNC grinding machine to monitor the power signals during the grinding tests as shown in Figure 3(b). The surface roughness tester from TOKYO SEIMITSU (SURFCOM NEX) is adopted to measure the surface finish after the super-finish grinding experiments as shown in Figure 3(c). Figure 4 illustrates the experimental setup to monitor the power signals occurred during the super-finish grinding process which the interaction of the grinding wheel and the nozzle body seat can be monitored.

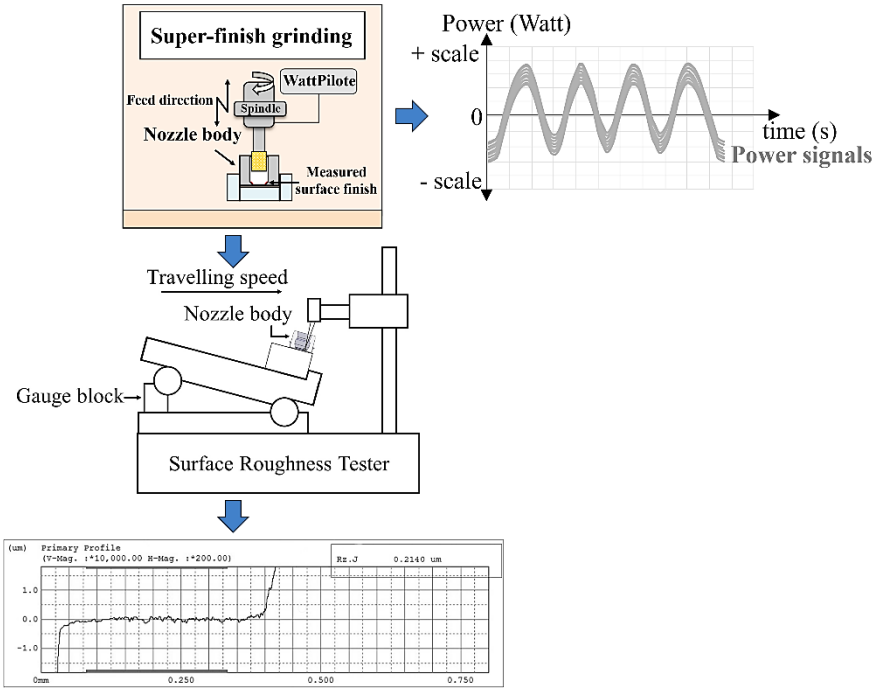


Figure 2. Illustration of in-process monitoring of surface finish and power signal in the super-finish grinding process to control the surface quality.



Figure 3. Illustration of equipment.

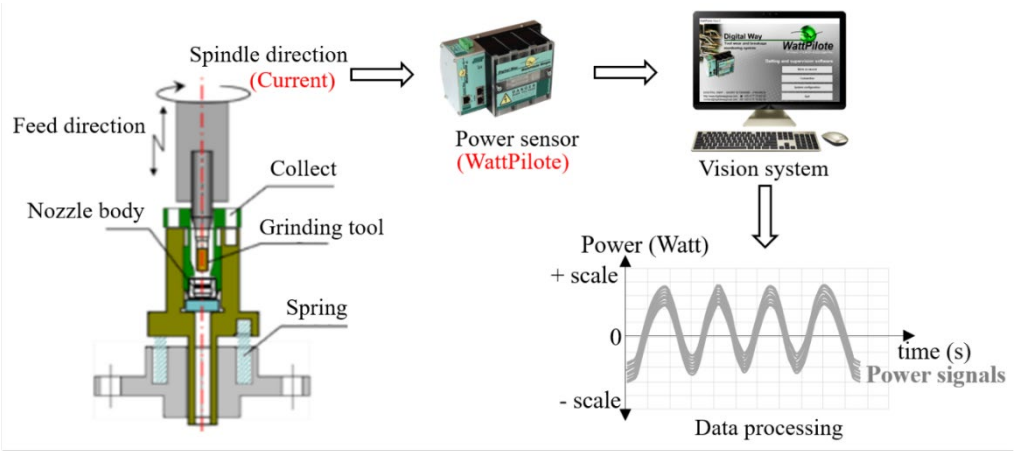


Figure 4. Illustration of experimental setup.

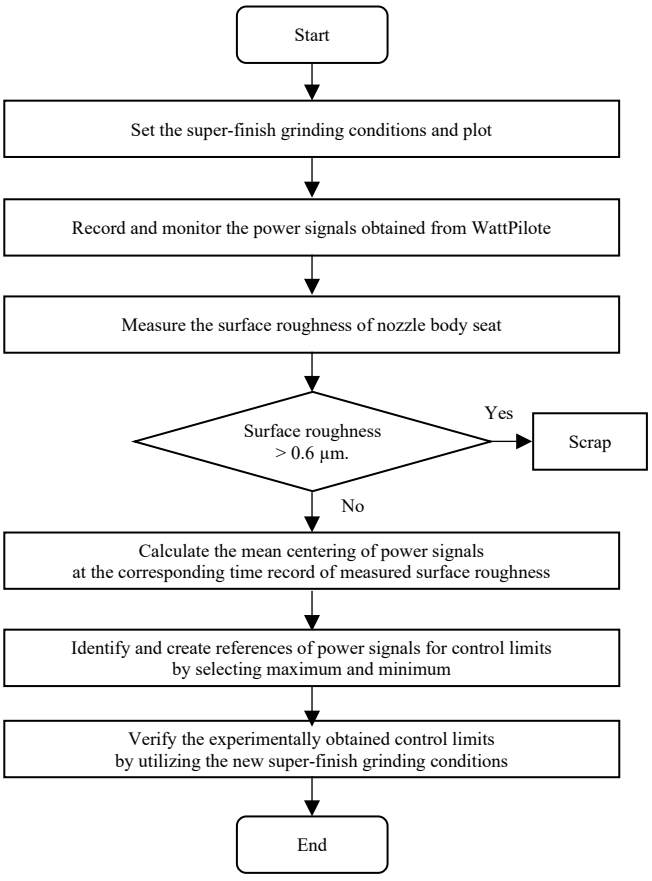


Figure 5. Flow chart to calculate and verify the maximum and minimum power signals.

Table 1. Major grinding conditions.

Grinding tool	Cubic Boron Nitride (CBN)
Workpiece	Stainless steel (DSUS70DH)
Grinding rotation speed (rpm)	5000
Grinding feed rate (mm·s^{-1})	20
Inching frequency (time)	4

A summary of the major grinding conditions is provided in Table 1. WattPilote has been distinguished by its resistive shunt sensor, which provides high accuracy in both amplitude and phase measurements, a response time of 5 ms, power sensitivity that is greater 0.002%, and a measurement accuracy of 0.01%. WattPilote is easy to install on the CNC super-finish grinding machine.

The following flow chart to obtain the maximum and minimum power signals is illustrated as shown in Figure 5.

The experimental procedures to calculate and verify the maximum and minimum power signals are adopted as followed.

(1) Start the super-finish grinding process with cylindrical grinding at a super-finish rotational speed of 5000 rpm and a feed rate of 20 mm·s^{-1}, with an inching frequency of 4 times, as referred to in Table 1.

(2) Record the power signals by WattPilote and measure the correspondent surface roughness with various nozzle injectors.

(3) Calculate the mean centering of each power signal to normalize data from all nozzle injectors which can align those data on the same baseline.

(4) Identify the maximum and minimum power signals at the corresponding time record of measured surface roughness obtained from (2).

(5) Plot the boundaries of the maximum and minimum power signals referring to the measured surface roughness as shown in Figure 7.

(6) Create the references of control limits of power signals by selecting the maximum and minimum power signals at the sampling rate of 5 ms to be the references of control limits.

(7) Verify the control limits of the proposed method by mapping the experimentally detected power signal to the reference control limits.

The maximum and minimum power signals are identified to plot the graph boundaries referring to the corresponding time record of surface roughness under various samples, which are proposed to develop the in-process control of surface quality in super-finish grinding. A new algorithm to obtain maximum and minimum power signals is proposed and shown in Figure 6.

It is known that the cutting forces of the power signals can be used to monitor the surface finish as they have the relations on the surface roughness which the cutting area has been ground and resulted in power signals [16]. Hence, the power signals are proposed to monitor and control the surface finish during in-process grinding. It is understood that the peak-to-valley amplitudes of power signals are correspondent with the upper-and-lower surface roughness which are obtained to calculate the upper and lower control limits.

3. Experimental results and discussions

In order to control the in-process surface finish during the super-finish grinding process, the relation of the power signal in super-finish grinding and the surface finish has to be investigated to obtain the control limits. The examples of experimentally measured surface roughness on nozzle body seats during the super-finish grinding process are shown in Figure 8.

According to Figure 8, it is shown that the measured surface roughness is less than 0.6 µm, which is controlled limit of surface finish. Figure 8 illustrates the better surface roughness obtained from experimental number 17 to 30 because the new grinding tool is installed. It is well known that the tool wear affects the surface finish which results in higher (dynamic) power signals. However, Figure 8 illustrates the experimentally obtained examples of surface roughness from worn and new grinding wheels, which are still less than the acceptable specification of 0.6 µm. Hence, the control limits are proposed to monitor both worn and new grinding wheels during the process. Once the wear on the CBN grinding wheel progresses, it may cause the poor surface finish, and consequently the dynamic power signals will exceed the upper and lower control limits as shown in Figure 9. However, the experimentally obtained results of surface roughness are accepted even though the grinding conditions have been changed under various samples. It is understood that the experimentally obtained power signals can be used to monitor and control the surface finish of nozzle injectors during the in-process super-finish grinding. Hence, the power signals obtained from the experiments are adopted to establish the control limits to monitor the surface roughness in term of power signal instead during the super-finish grinding process.

Figure 9 illustrates the experimentally obtained power signals in super-finish grinding process. The experimentally obtained power signals of super-finish grinding, surface roughness, control limits are collected at the same time. The power signals have been obtained by WattPilote, which is utilized to monitor the surface finish. The power signals in super-finish grinding have been monitored while the grinding wheel is inserted into the nozzle injector with inching frequency of 4 times with the stroke of 5 mm, which affects the surface roughness of the nozzle injector.

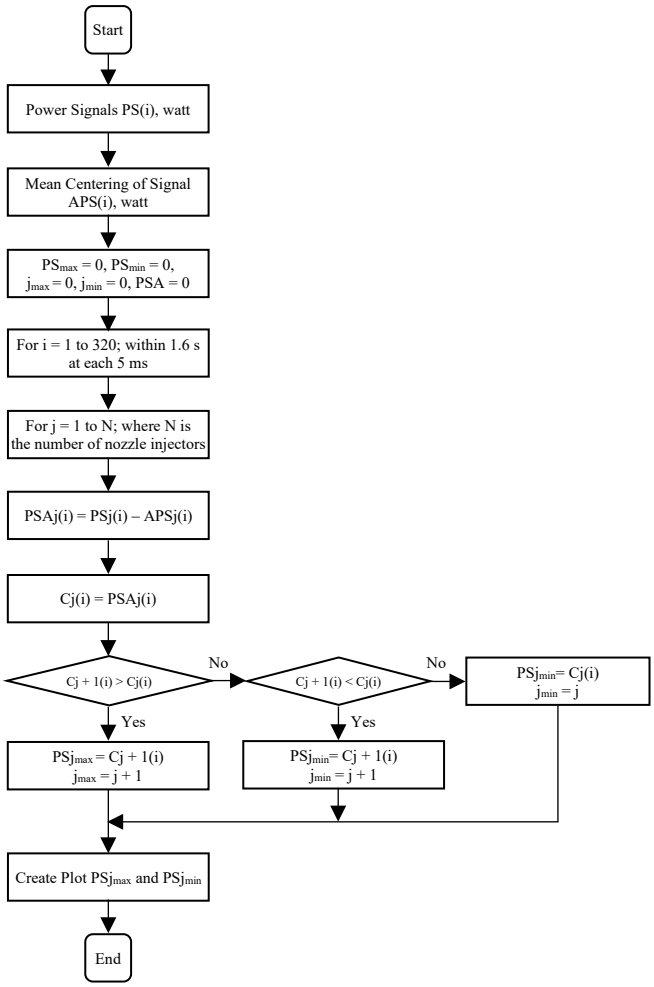


Figure 6. Illustration of proposed algorithm to create the maximum and minimum control limits.

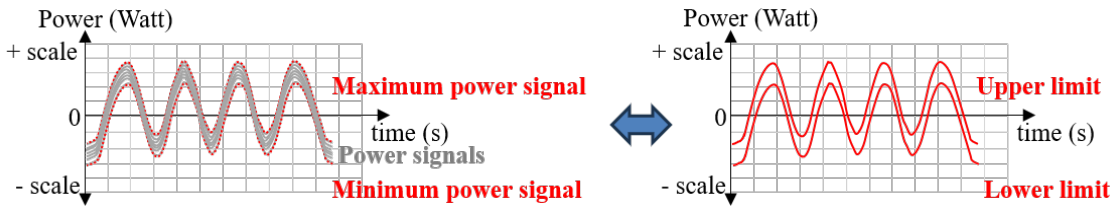


Figure 7. Identification and creation of maximum and minimum power signals obtained during super-finish grinding process.

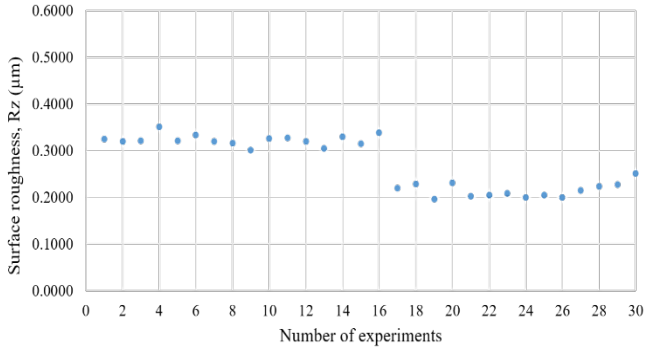


Figure 8. Example of experimentally measured surface roughness on nozzle body seats.

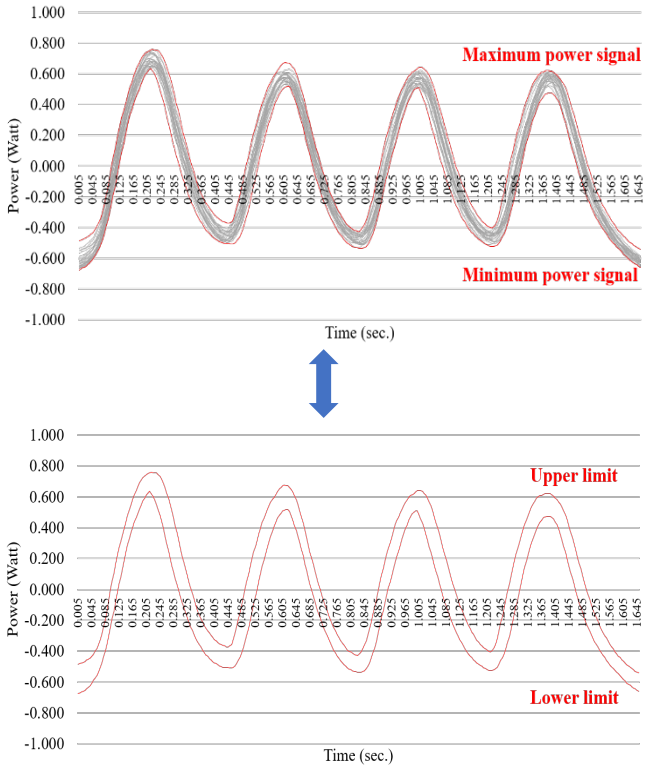


Figure 9. Illustration of experimentally obtained power signals in super-finish grinding process.

The control limits of power signal by selecting the maximum and minimum power signals for each 5 ms is created to be the references of control limits as shown in Figure 9. The upper and lower control limits are generated based on the actual data under various nozzle injectors. It is understood that the upper and lower control limits can be used to monitor and control the in-process surface finish, which are obtained from the experimental results as the surface roughness and power signals are consistent.

4. Monitoring of surface finish

The new super-finish grinding experiments are performed to validate the in-process monitoring of the surface finish and control limits of power signals as shown in Figure 10. The experimentally obtained power signals fell in the control limits, which are proposed to control the in-process surface finish referring to the acceptable surface roughness less than 0.6 µm. The experimentally obtained surface roughness is monitored referring to the references of control limits in super-finish grinding process as shown in Figure 9. The number of super-finish grinding tests, which are 105 tests, have been run and confirmed the references of control limits. It has been proved that the experimentally obtained control limits can be used to monitor the surface finish. Since the experimentally obtained power signals are fallen in the control limits and +10% of maximum control limit with –10% of minimum control limit. The ±10% of control limits can be interpreted that the surface roughness is approximately from 0.3854 µm to 0.1765 µm, which are still less than the acceptable surface roughness of 0.6 µm, referring to the measured surface roughness on the nozzle body seats as shown in Figure 8.

The algorithm is developed to check the in-process surface finish in super-finish grinding process referring to the previously determined control limits, which are maximum and minimum power signals as shown in Figure 11. The proposed algorithm has been installed in the controller of the CNC machine which connects directly to the WattPilote. Hence, the dynamic power signals are detected and monitored real time during in-process super-finish grinding. The testing conditions to prove the proposed algorithm have been set as the major conditions due to the fixed and constant parameters for super-finish grinding process of nozzle body seat as shown in Table 1.

It is understood that the proposed algorithm offers the advantage to detect and evaluate the surface finish in real time, reduce the defects, and enhance overall process capability. This research has developed an intelligent monitoring system using in-process power signal from WattPilote to control the in-process surface finish. The power-based monitoring technique is implemented in real super-finish grinding process on CNC grinding machine to control and maintain the desired surface quality effectively. In addition, the proposed system provides a practical method to reduce the production costs by promptly detecting and preventing defects arising from inadequate surface quality. However, the limitation of this work needs to monitor and collect more data since it may cause false alarms or missed signals. Hence, the in-process prediction of surface finish will be modelled and developed in future research to ensure that the surface finish is still in the control limits, which can estimate the surface roughness of nozzle injector during high-precision grinding.

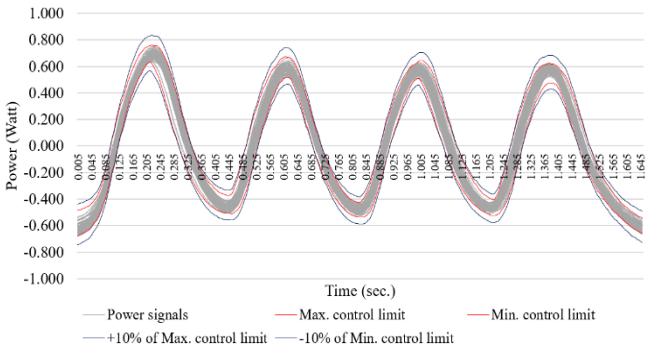


Figure 10. Illustration of experimentally obtained power signals fell in control limits during in-process super-finish grinding.

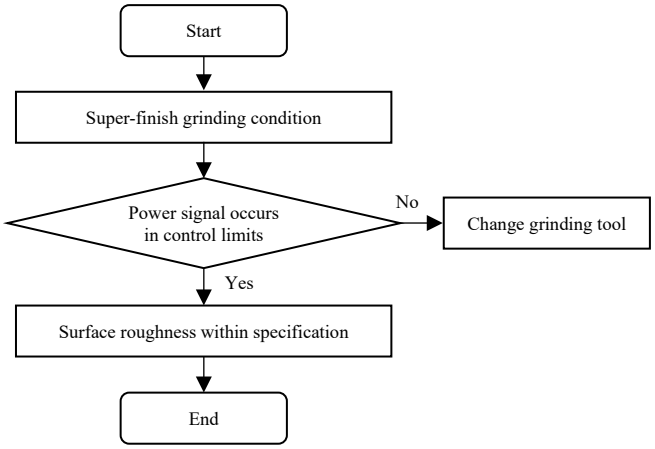


Figure 11. Illustration of developed algorithm to monitor the in-process surface finish in super-finish grinding process.

5. Conclusions

As the intelligent grinding machine is expected to be realized in the future, the in-process monitoring of surface finish is required by utilizing WattPilote to obtain the power signals during the super-finish grinding process. The experimentally obtained results showed that the power signals can be used to monitor the in-process surface finish. A new algorithm to obtain maximum and minimum power signals is proposed and developed to control the surface finish during in-process super-finish grinding. It has been proved that the in-process monitoring of surface finish runs satisfactorily refers to upper and lower control limits, which are determined from the real experimental data.

Data availability statement

The authors confirm that the data supporting the findings of this study are available within the article and its supplementary materials.

Conflicts of interest

The authors declare no competing interests.

Acknowledgement

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