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Development of In-process Surface Roughness Evaluation System for Cast Nylon 6 Turning Operation

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Abstract

This paper aims to develop in-process surface roughness evaluation system for cast nylon 6 turning operation. Construction of the developed system composes of data acquisition system and fuzzy logic system. The data acquisition system includes a miniature load cell inserted in a tool holder, signal conditions and a signal interface card in order to detect cutting force signal and transmit signal to the data analysis module constructed by LabVIEW program. The mamdani-type fuzzy inference system was utilized and twenty fuzzy rules were determined based on relationship of cutting speed, feed rate and cutting force for prediction both of surface roughness value (Rz) and symbolic representation. The results indicated that prediction by the developed system had 87% of accuracy with an average absolute error of 4.8 µm. The method validation results exhibited that precision and surface roughness value obtained from conventional measuring method and the developed prediction system was not significant different.

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Keywords: Surface roughness, Fuzzy logic system, Method validation, Cast Nylon material, In-process prediction system

1. Introduction

An index of machined part quality is evaluated by surface roughness which is determined in a shop floor drawing. In practical, the surface roughness is evaluated during operation process by decision of an experience-skilled worker and inspection of the finished surface by surface roughness tester in quality control process. A large number of errors from operators’ surface roughness decision making were frequency obtained in machining operation resulting in increase of production time and operation costs. In

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recent year, several researchers have been proposed the surface roughness prediction methods using cutting parameters for example a linear regression in statistical method and artificial intelligent methods as reviewed by P.G. Benardos and G.-C. Vosniakos (2003) [1]. The statistical method using linear regression reported by Hun-Keun Chang et al.,(2007) [2] has been used for in-process surface roughness prediction with a mean accuracy of 95%. Artificial intelligent techniques, such as artificial neural networks and fuzzy logic were successfully applied to surface roughness prediction through recent year. For example, Wen-Tung Chien and Chung-Yi Chou (2001) [3] introduced artificial neural network (ANN) for surface roughness prediction model creation with an error of the prediction at 4.4%. Sivarao (2009) [4] and Sivarao et al.,(2009) [5] studied surface roughness prediction by fuzzy logic including mamdani-type and sugeno-type fuzzy inference system. The comparative predicted surface roughness and observed values clearly indicated that these two outputs were acceptable. F. Dweiri et al.,(2003) [6] designed a knowledge-based system for surface roughness modeling in milling process by adaptive neuro fuzzy inference system (ANFIS). N.R. Abburi and U.S. Dixit (2006) [7] developed a knowledge-based system using neural network and fuzzy logic for prediction of surface roughness in turning process. The developed knowledge-based system was also used for making prediction of the process conditions. R.A. Mahdavinejad and H. Sharifi Bidgoli (2009) [8] applied fuzzy-neural network model for prediction of surface roughness in dry turning process with an average prediction error of 20.188%, the minimum and the maximum error was 0.3% and 63.7%, respectively.

However, all developed systems and prediction models focused on ferrous materials such as carbon steel, stainless steel and cast iron steel. But the surface roughness prediction system for polymer material has not been reported yet. The cast nylon 6 is a special polymer material thus its properties is different from steel materials especially in dimensional properties including available shapes, sizes and surface texture. The surface texture, color and refractive index of cast nylon 6 affects on difficulty of machined surface roughness evaluation by workers’ decision during the process. The suitable surface roughness prediction model and in-process surface roughness prediction system in polymer material turning operation have not been proposed. Therefore, a real-time surface roughness evaluation system for cast nylon 6 during turning operation is required for productivity improvement and operation costs reduction. This paper focus on the development of in-process surface roughness evaluation of cast nylon 6 turning operation using fuzzy logic system in order to simplify and correctly indicate machined finishing surface. The method validation [9] is also applied to analyze precision of the developed surface roughness evaluation method and conventional surface roughness measuring method.

2. Development of In-process Surface Roughness Evaluation System

2.1. System Construction

The system structure consists of data acquisition system and fuzzy logic system. The data acquisition system comprises of hardware module, signal conditioning module and data analysis module. A miniature load cell Kyowa type LM Class N is selected as a hardware module and it is installed on a cutting tool holder in order to detect cutting force signal. The signal condition module consists of amplifier circuit and NI DAQ 6008 interface card where the detected signal is transmitted and transformed to analogue signal into digital signal. The digital signals from signal condition module are sent to a computer as the data analysis module created by LabVIEW programming. A block diagram of data analysis program is shown in Fig.1. A linear calibration equation of load cell and a change of revolution to cutting speed equation are included in this module for computing cutting force and cutting speed, respectively. Cutting force, cutting speed and feed rate were determined as input variables of fuzzy logic system. The fuzzy logic system was structured by using PID and Fuzzy Tool-kit in LabVIEW program. An output from the fuzzy system is a
surface roughness value $R_z$ and the formula node was created in order to change the numerical surface roughness value into a symbolic representation following the JIS B-0601 standard.

2.2. Fuzzy Logic Model

The designed fuzzy logic model consists of three input variables as a cutting force (N), a cutting speed (m/min) and a feed rate (mm/rev) and output variable is a surface roughness value $R_z$ ($\mu$m). The mamdani-type fuzzy inference system was used in this study. The input-output data sets are fuzzified as presented in Fig.2 - Fig.5. Each variable comprises of three interval membership functions consisting of small or Negative, N; medium or Zero, Z; and large or Positive, P. The data of previous study in cutting conditions influence on surface roughness in cast nylon [10] were also analyzed and considered for construction of fuzzy rules in this study. Twenty linguistic rules and values of linguistic variable in the premises were interpreted as shown in Fig.6. The centroid or center of area method was used for defuzzification of output membership functions.
Fig.4. Membership functions of feed rate

Fig.5. Membership functions of fuzzy out (Rz)

1. IF (Cutting Force = N) AND (Cutting Speed = N) AND (Feed Rate = N) THEN (Fuzzy Out = Z)
2. IF (Cutting Force = N) AND (Cutting Speed = N) AND (Feed Rate = P) THEN (Fuzzy Out = Z)
3. IF (Cutting Force = N) AND (Cutting Speed = Z) AND (Feed Rate = N) THEN (Fuzzy Out = Z)
4. IF (Cutting Force = N) AND (Cutting Speed = P) AND (Feed Rate = P) THEN (Fuzzy Out = N)
5. IF (Cutting Force = Z) AND (Cutting Speed = N) AND (Feed Rate = Z) THEN (Fuzzy Out = Z)
6. IF (Cutting Force = Z) AND (Cutting Speed = P) AND (Feed Rate = N) THEN (Fuzzy Out = Z)
7. IF (Cutting Force = Z) AND (Cutting Speed = P) AND (Feed Rate = Z) THEN (Fuzzy Out = P)
8. IF (Cutting Force = Z) AND (Cutting Speed = N) AND (Feed Rate = N) THEN (Fuzzy Out = Z)
9. IF (Cutting Force = Z) AND (Cutting Speed = N) AND (Feed Rate = Z) THEN (Fuzzy Out = Z)
10. IF (Cutting Force = Z) AND (Cutting Speed = P) AND (Feed Rate = P) THEN (Fuzzy Out = P)
11. IF (Cutting Force = Z) AND (Cutting Speed = P) AND (Feed Rate = N) THEN (Fuzzy Out = N)
12. IF (Cutting Force = Z) AND (Cutting Speed = Z) AND (Feed Rate = N) THEN (Fuzzy Out = Z)
13. IF (Cutting Force = P) AND (Cutting Speed = N) AND (Feed Rate = N) THEN (Fuzzy Out = N)
14. IF (Cutting Force = P) AND (Cutting Speed = N) AND (Feed Rate = P) THEN (Fuzzy Out = P)
15. IF (Cutting Force = P) AND (Cutting Speed = Z) AND (Feed Rate = N) THEN (Fuzzy Out = N)
16. IF (Cutting Force = P) AND (Cutting Speed = Z) AND (Feed Rate = P) THEN (Fuzzy Out = N)
17. IF (Cutting Force = P) AND (Cutting Speed = P) AND (Feed Rate = N) THEN (Fuzzy Out = N)
18. IF (Cutting Force = Z) AND (Cutting Speed = Z) AND (Feed Rate = Z) THEN (Fuzzy Out = Z)
19. IF (Cutting Force = N) AND (Cutting Speed = Z) AND (Feed Rate = N) THEN (Fuzzy Out = Z)
20. IF (Cutting Force = P) AND (Cutting Speed = Z) AND (Feed Rate = P) THEN (Fuzzy Out = P)

Fig.6. A set of fuzzy rules

3. Materials and Methods

All experiments have been carried out in dry machining on TUG-40 Nr-1275 lathe. Fifteen workpieces used in this study were made from cast nylon 6 with 25.4 mm in diameter and 120 mm in length. The square 9.5 mm single-point high-speed steel cutting tool (Molybdenum type model Super Extra 1900 SWENDE) was used in turning operation. The cutting tool geometry was 66° for wedge angle and 12° for side angle, rake angle and clearance angle. The cutting conditions are cutting speed, feed rate and depth of cut. Each operation was performed by a certain combination of the parameters including cutting speed which is randomly operated by various diameters of workpieces by fixing turning revolution (rpm), feed rate (mm/rev) and depth of cut (mm). In this study, turning revolutions at 1,060 and 1,500 rpm were used, feed rate were randomly operated in range of 0.04 - 0.2 mm/rev and cutting depth were 1.25 - 4.5 mm. The cutting force during machining was measured by a miniature load cell Kyowa type LM Class N with sensitivity of ± 1% which was inserted inside a specific tool holder. The detected signal was transmitted to the fuzzy logic module via the signal conditioning and the interface card. The system predicted the surface roughness value as Rs (µm) and symbolized the Rs value. In order to compare an accuracy of the
developed system, the surface roughness of machined workpieces were measured by AltiSurf500 surface roughness and profile meter with ± 3µm of accuracy. The percentage error of each experiment was computed to determine effectiveness of the developed system. In this study, the method validation was applied for analysis of the measured and predicted data set using a two-tailed paired t-test. Furthermore, both data sets were evaluated by F-test for method precision [9].

4. Experimental Results

The cutting conditions consisting of cutting speed in rage of 57.28-109.33 m/min, feed rate at 0.05- 0.20 mm/rev and cutting depth at 1.25-4.25 mm were randomly operated in the experiments. The cutting force and surface roughness obtained from the experiment was 6.60-55.45 N and 22.7-59.60 µm, respectively (Table 1). The average absolute errors between the measured and predicted values were 4.87 µm with standard deviation at 5.15µm and percentage errors was 13.00% with standard deviation of 18.35% as presented in Table 1. The missing of symbolic representation of surface roughness was 13.33 %. The method validation results, the analysis of measured and predicted data set exhibits that statistical t-value of - 0.4778 was below the critical t-value of 2.145 and p-value 0.640 > 0.05 as shown in Table 2.

Therefore, the null hypothesis that the developed surface roughness prediction method does not significantly differ from the conventional measuring method with 95% confidence. The analyzed precision of prediction system exceeds that statistical F-value of 0.070 < critical F-value of 4.196; therefore, null hypothesis is accepted as presented in Table 3. Thus it can be concluded with 95% confidence that there is no significant difference in precision between the prediction surface roughness method and convectional surface roughness measuring method.

Table 1. Experimental and error evaluation results

| Cutting Speed (m/min) | Cutting Force (N) | Feed Rate (mm/rev) | Cutting Depth (mm) | Measured Rz Value (µm) | Predicted Rz Value (µm) | Absolute Error (µm) | Percent Error (%) | Measured Symbol | Predicted Symbol | Verified Result |
|----------------------|------------------|--------------------|--------------------|------------------------|-------------------------|---------------------|--------------------|----------------|----------------|----------------|
| 57.277               | 11.042           | 0.045              | 4.25               | 22.70                  | 39.43                   | 16.73               | 73.70              | #3             | #2             | Incorrect       |
| 92.834               | 11.867           | 0.045              | 3.00               | 38.00                  | 39.43                   | 1.43                | 03.76              | #2             | #2             | Correct         |
| 65.602               | 10.732           | 0.068              | 3.00               | 41.90                  | 39.43                   | 0.24                | 05.89              | #2             | #2             | Correct         |
| 97.546               | 24.860           | 0.120              | 2.50               | 40.50                  | 39.43                   | 0.01                | 02.64              | #2             | #2             | Correct         |
| 102.258              | 14.742           | 0.068              | 2.00               | 39.30                  | 39.44                   | 0.14                | 03.66              | #2             | #2             | Correct         |
| 65.602               | 17.368           | 0.075              | 3.00               | 44.40                  | 39.44                   | 0.96                | 11.17              | #2             | #2             | Correct         |
| 75.593               | 06.000           | 0.082              | 1.50               | 43.10                  | 39.44                   | 0.66                | 08.49              | #2             | #2             | Correct         |
| 57.277               | 26.791           | 0.105              | 4.25               | 36.40                  | 39.44                   | 0.04                | 08.35              | #2             | #2             | Correct         |
| 97.546               | 17.187           | 0.075              | 2.50               | 42.80                  | 39.45                   | 0.35                | 07.83              | #2             | #2             | Correct         |
| 109.327              | 23.560           | 0.150              | 1.25               | 36.10                  | 39.45                   | 0.35                | 09.28              | #2             | #2             | Correct         |
| 75.593               | 07.721           | 0.090              | 1.50               | 37.60                  | 39.49                   | 0.89                | 05.03              | #2             | #2             | Correct         |
| 85.765               | 20.964           | 0.090              | 3.75               | 53.30                  | 39.49                   | 13.81               | 25.91              | #3             | #3             | Incorrect       |
| 81.053               | 55.454           | 0.195              | 4.25               | 59.60                  | 59.00                   | 0.60                | 01.01              | #3             | #3             | Correct         |
| 58.942               | 54.972           | 0.195              | 4.00               | 55.90                  | 59.91                   | 0.01                | 07.17              | #3             | #3             | Correct         |
| 68.932               | 22.141           | 0.165              | 2.50               | 51.40                  | 63.96                   | 12.56               | 24.44              | #3             | #3             | Correct         |

Average  04.87  13.00  Missing  13.33%
SD  05.15  18.35
Table 2. The paired T-test results for investigation of different data set of measured and predicted surface roughness value

| Detail                | Measured Rz Value | Predicted Rz Value | t Stat | t Critical two-tail | P(T<=t) two-tail |
|-----------------------|-------------------|--------------------|--------|---------------------|-----------------|
| Mean                  | 42.867            | 43.749             | -0.4778| 2.145               | 0.640           |
| Variance              | 85.638            | 80.313             |        |                     |                 |
| Observations          | 15                | 15                 |        |                     |                 |
| Pearson Correlation   | 0.692             |                    |        |                     |                 |

Table 3. The ANOVA results for evaluation predicted system precision comparing with measuring method

| Source of Variation | SS      | df | MS    | F Stat | F Critical | P-value |
|---------------------|---------|----|-------|--------|------------|---------|
| Between Groups      | 5.834   | 1  | 5.834 | 0.070  | 4.196      | 0.793   |
| Within Groups       | 2323.315| 28 | 82.976|        |            |         |
| Total               | 2329.149| 29 |       |        |            |         |

5. Conclusions

The developed system construction comprises of data acquisition system and fuzzy logic system. The load cell was used for the cutting force values detection and the value was transmitted to the data acquisition system and fuzzy logic system created by LabVIEW program. The cutting conditions consisting of cutting speed, feed rate and cutting force were used to establish a set of fuzzy rules. From the experiment, the developed system performed prediction accuracy of 87% approximately and the average absolute error was 4.87 \( \mu \)m. The method validation was employed to analyze difference of data set and precision between measured and predicted surface roughness values. The analysis results exhibited that the predicted surface roughness values are precise and are not significant different from the conventional surface roughness measuring value with 95% of confidence. Therefore, it can be concluded that the developed in-process surface roughness evaluation system can predict the surface roughness in cast nylon 6 turning operation accurately and reliably on the shop floor level of the enterprises.

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