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A Framework of Accuracy Assured Machining for Smart Manufacturing

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Abstract

This paper presents a framework of accuracy assured machining which enables information driven manufacturing. As a framework of accuracy assured machining, a closed loop machining operation is proposed based on four fundamental functions. They are physics conscious operation planning, intelligent monitoring, on-machine shape measurement and error source estimation and determination of re-machining strategy. Last three functions are essential in accuracy assured machining. As a preliminary development of the accuracy assured machining, a method to achieve a rapid and accurate on-machine shape measurement is also explained.

Keywords: Accuracy assurance, line laser displacement sensor, process monitoring

1 INTRODUCTION

From the MAP (Manufacturing Automation Protocol) project proposed by General Motors in 1980's, network connectivity of manufacturing facilities has been an important issue. Recently, network connected and information driven manufacturing based on modern information technologies such as IoT (Internet of Things), Cloud computing technology and CPS (Cyber-Physical System) becomes a realistic solution(1). In such an emergent manufacturing system, agile and smart adaptation to changeable demands must be accomplished (2). Functional modularity of each facility is an essential characteristic of the system. Accuracy assured part machining guarantees the modularity of machining stations. In the conventional manufacturing system, accuracy inspections are separated from machining station. Furthermore, accuracy improvements are often based on an empirical human know-how.

It is reported that a closed loop machining using on-machine shape measurement can achieve an accuracy assured machining (3)(4). Furthermore, contactless measurement using a laser displacement sensor is also reported as a promising method for on-machine shape measurement. From the previous research related to the closed loop machining, the following problems have not been overcome.

- Efficiency and accuracy of measurement are not enough to utilize actual machining situation.
- There is no systematic re-machining principle.
- Monitoring of machining process is not integrated to the closed loop machining.

The objective of this research is to construct a systematic accuracy assurance procedure and to design a prototype of the accuracy assured machining station based on an intelligent monitoring method (5) and rapid on-machine shape measurement. A framework of the accuracy assured machining and developed fundamental methods are explained in this paper.

2 FRAMEWORK OF ACCURACY ASSURED MACHINING

In order to overcome the problems of conventional machining process, on-machine shape measurement and error source estimation based on intelligent monitoring are introduced. Figure 1 illustrates a framework of an accuracy assured machining. The framework contains four topics: 1) physics conscious operation planning, 2) intelligent monitoring, 3) on-machine shape measurement and 4) Error source estimation and determination of re-machining strategy.

Before the machining, operation planning is generated based on a machining process simulation. The method is called model-based operation planning. Furthermore, predicted machining situations are recorded as a systematic representation scheme which is called machining scenario (6)(7). During the machining, an accurate and workpiece wide state estimation method is applied. The method is based on a combination of

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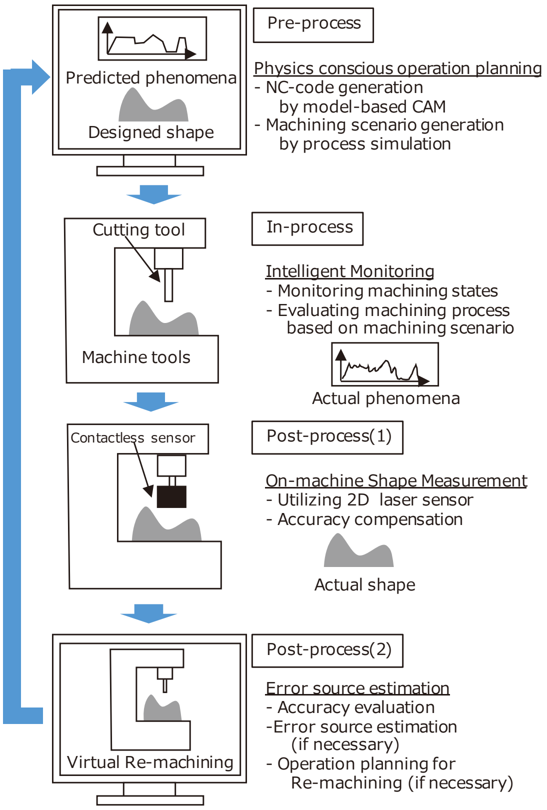


Fig.1 Framework of accuracy assured machining

locally measured values (temperatures and strains) and the process simulation technique (5). After the machining, workpiece shape is measured by using a 2D laser displacement sensor. The 2D displacement sensor enables rapid measurement of the workpiece shape. A method to improve an accuracy of the 2D displacement sensor will present a next section. Furthermore, the measured shape is compared with designed workpiece shape. If the accuracy is not sufficient, error sources must be estimated. Development of a method to estimate the error source is a future work of this research. Decomposition of machining error into possible error source based on a compositional machining model (7) is a possible approach to estimate the error source. Conventional approach to re-machining is only based on geometrical information. By using the estimated error source, a determination of a re-machining strategy will become more rational and reasonable. Based on the strategy, operation planning for re-machining can be carried out. The re-machining is executed same as the original procedure. This systematic and rational re-machining process is expected to reduce a number of trials. From the following sections, methods to implement the proposed framework are presented.

3 ON-MACHINE SHAPE MEASUREMENT

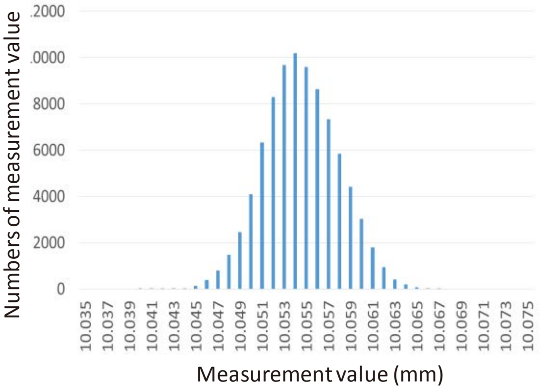


Fig.2 Measured data for 10mm gauge block

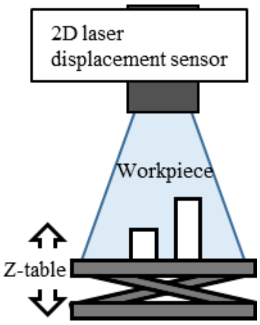


Fig.3 Experimental setup

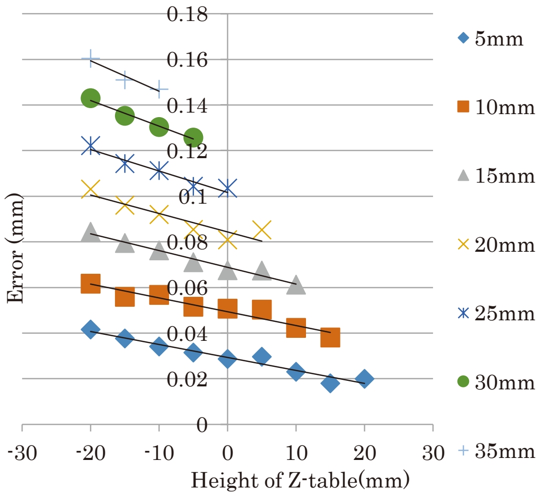


Fig.4 Measured error at different conditions

Contactless on-machine measuring systems have been attracted attention for accuracy assurance of products. 2D laser displacement sensors are expected as promising devices because of their efficiency. However, their accuracies are not enough to utilize on-machine shape measurement (8)(9). An accuracy improvement method is necessary to utilize the 2D laser sensor to the on-machine shape measurement.

In order to improve the accuracy of the 2D laser sensor, a geometrical feature-based compensation method is evaluated. In this method, local workpiece shape is categorized into pre-determined shapes such as

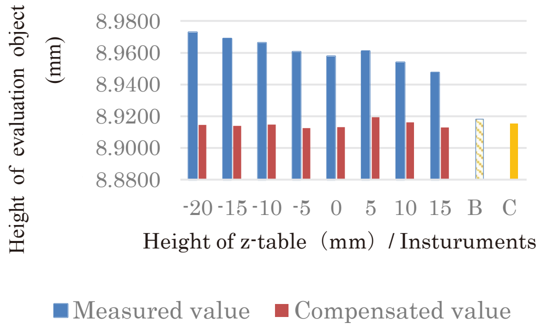


Fig.5 Evaluation of compensated values

flat plane, cylindrical surface, sphere and so on. Output values of sensor for each shape category are calibrated in advance. In this paper, compensation for flat plane is evaluated.

As a reference flat surface, gauge blocks (Mitsutoyo Rectangular Gauge Block grade 0) which have accurate dimensions are employed for calibration. Based on measurements of gauge blocks surface with 2D laser sensor (Keyence LJ-V7080, measurement range ±23mm, linearity 0.1% of measurement range), the characteristics of the sensor are obtained. The dispersion of measured values follows the normal distribution as shown in Fig. 2. Therefore, compensation of measured values by averaging is considered effective. Differences between the average value and real displacement come from the measurement range. It is expected that measured values can be compensated as a function of the distance between a sensor head and a workpiece surface. In order to verify this assumption, seven workpieces which have 5-35 mm height are set on a z-table and measured by moving z-table shown in Fig. 3. The result is shown in Fig. 4.

A compensation model based on a multiple regression model is derived from the measured data. The suitability of the compensation is evaluated by comparing the compensated values and the result of precise measurement. Different workpiece is prepared as an evaluation object. A 3D-CMM and an accurate digital micrometer are employed as the precise measurement instruments. Figure 5 shows comparison of these values. The compensated values show good agreement with the results of precise measurements.

This result shows a feasibility of efficient and accurate contactless measurement. However, the proposed compensation method is to be applied for a workpiece which have a flat top. Compensation for measurement of 3-dimensional shape including cylindrical surface, sphere and curved surface is a future works of this research.

4 INTELLIGENT MONITORING

Modern machine processes are separated from the operators to secure the safety. This separation will be enlarged in the digital and networked production situations. Therefore, monitoring technologies become more important than the conventional operator controlled machining environment. A framework for accurate and simple setup monitoring method has been proposed. The framework is based on combining locally measured information and FEM (Finite Element Method)-based process simulation (5).

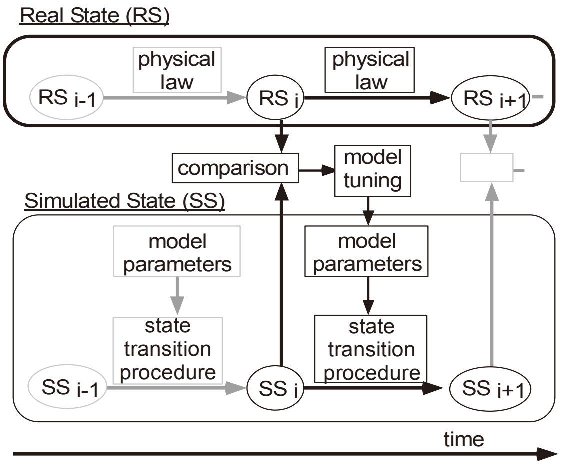


Fig.6 Adaptive estimation procedure

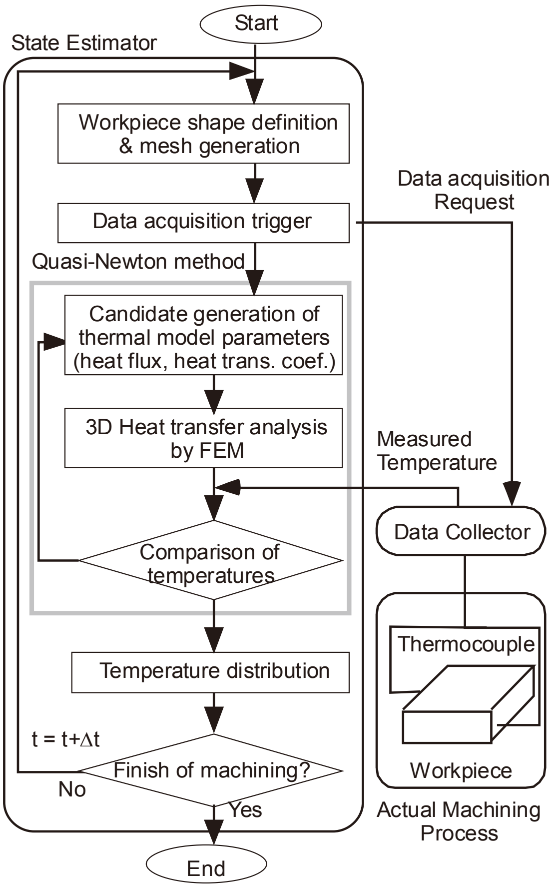
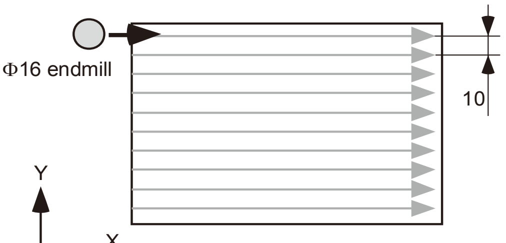


Fig.7 Configuration of thermal state estimation system (5)

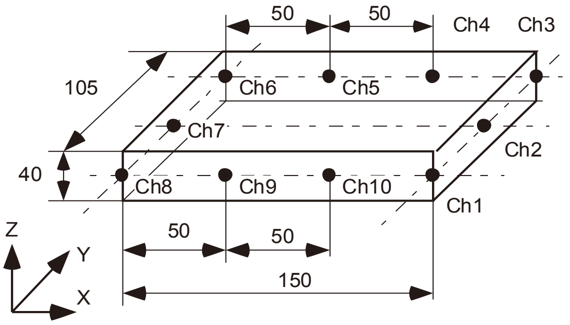
Because transient heat conduction problem is formalized based on FDM (Finite Differential Method) formulation in time domain, the problem is solved step by step. Simulation results are obtained as the time series of thermal states. As shown in Figure 6, we introduce a model tuning procedure into the every state transition. Concerning the thermal state estimation, parameter tuning of heat transfer coefficient and heat flux is enough to realize the model tuning. A procedure of thermal estimation is as follows:

1. Measured state of predetermined region (RS_i) and simulated state at present step (SS_i) are compared.
2. Model parameters are estimated based on the results of comparison.
3. Simulated state at next step (SS_{i+1}) is calculated by using the estimated parameters.

By tuning the model parameters at every state transition, the procedure is expected to achieve an adaptively of situational variation.



(a) Tool path of experiment



(b) Workpiece shape and location of thermocouples

Fig.8 Experimental setup and tool path

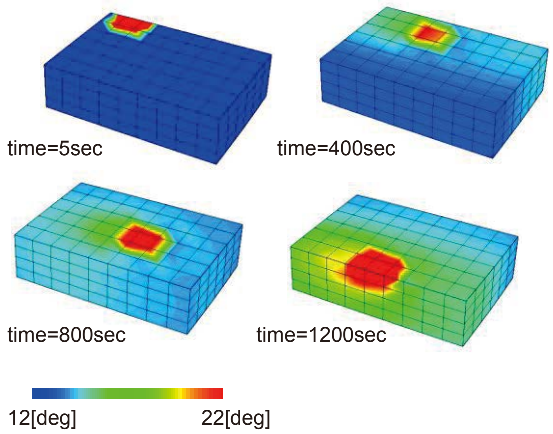


Fig.9 Temperature distribution of workpiece

Figure 7 illustrates a configuration of the prototype system developed for the thermal state estimation. The prototype system consists of two major modules. They are a data collector and a state estimator. The system acquires temperatures of predetermined points by using thermocouples when a data acquisition request message is sent to the data collector. A minimum interval of data collection is one second. A state estimator is developed based on an optimization method which searches parameters. The Quasi-Newton method is employed as an optimization method. FEM analysis provides to evaluate the optimization candidates. After iterating the optimization procedures, appropriate parameters to fit the measured data are selected so as to reduce the difference between measured data and corresponding analysis results. After determining the parameters, the estimation step is incremented to a next time step. Communication between state estimator and data collector is implemented based on RS-232C protocol. All software are coded by C++ language.

Figure 8 shows an example problem for an evaluation of the procedures of thermal state estimation. Workpiece material is S45C steal. Axial depth of cut is 1mm and tool path is shown in Fig 8(a). Measurement points of temperature for the estimation are also illustrated in Fig. 8(b). By using these measured temperatures (Ch1, Ch3, Ch6), temperature distribution in transient heat conduction is estimated. In this case, a heat flux of the heat source and a heat transfer coefficient of the surface are estimated as variable parameters. From the comparison between the measured temperature and estimated temperature at Ch2 and Ch 7, mean square errors of both points are less than 3°C (5). Figure 9 shows the estimated temperatures distribution at different time. By using the limited surface information, a whole temperature distribution of workpiece can be estimated accurately. Converging this information into the machining error information obtained by post-process measurement is an important future work.

5 CONCLUTIONS

As a basic component for the smart manufacturing, a concept and framework of accuracy assured machining are proposed. As the topics regarding fundamental technologies to implement the proposed concept, outline of on-machine shape measurement and intelligent monitoring are explained. Although the results are only from small-scale evaluation, these technologies can be employed to implement the accuracy assured machining. By integrating these technologies, the changeable manufacturing, which enables product personalization, becomes a common production style in near future.

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