中國機械工程學刊第四十一卷第六期第 799~806 頁(民國一百零九年)
Journal of the Chinese Society of Mechanical Engineers, Vol.41, No.6, pp.799~806 (2020)

Condition Monitoring Technique for Injection Molding Process by Waveform-Analysis Method

Yoshio Fukushima*, Zhao Zongyang**, Akiko Sakamoto*** and Naoki Kawada****

Keywords： injection molding process, condition monitoring, waveform analysis, failure discrimination

ABSTRACT

IoT technology has spread rapidly all over the world in recent years. Many companies and engineers are paying attention to introduce IoT technology to a practical production process. To avoid some defects of injection molding easily and efficiently, the production process implemented by IoT technology can be useful. Most modern injection machines include the function that can measure some process information, such as pressure, temperature, clamping force, etc. This process information helps us to achieve a stable production system. In this study, in addition to the process information, the data of the acceleration sensor mounted to the mold has also been measured. By utilizing this information, process information and acceleration data, the waveform analysis has been carried out. Also, by using pattern recognition technology called MT-system, the method of discriminating defects has come to be realized. The important value called MD, Mahalanobis Distance, in MT-system was applied. In conclusion, it has been clarified that the change of the waveform and the quality of the molded parts have a relation to each other (e.g., acceleration, clamping force of the mold). From these things, it is found that the condition monitoring that can detect the injection process failure and the molded parts defects is possible by using MT-System.

Paper Received June, 2020. Revised Sepfember, 2020. Accepted November, 2020. Author for Correspondence: Yoshio Fukushima.

* *Professor, Department of Mechanical Engineering, Saitama Institute of Engineering, Fukaya Saitama, Japan.*

** *Graduate School Student, Saitama Institute of Engineering, Fukaya Saitama, Japan.*

*** *Researcher, Advanced Science Lab., Saitama Institute of Engineering, Fukaya Saitama, Japan.*

**** *Associate Professor, Department of Mechanical Engineering, Saitama Institute of Engineering, Fukaya Saitama, Japan.*

INTRODUCTION

With the introduction of IoT technology, a new technology, called the smart manufacturing process, has been improved and expanded. Recently, there are factories equipped with modern machineries, e.g. machining center, pressing machine and injection molding machine, which have many kinds of sensors, such as temperature sensors, pressure sensors, load cells, acceleration sensors and so on. The information provided by these sensors will speedily help the process for the prevention of technical problems. Since sensing technology and data analysis technology are indispensable for smart manufacturing, it is necessary to perform the study concerning these technologies. Also, the advantages of smart manufacturing help cost reduction and performance optimization. Therefore, various researches on condition monitoring (Kawada et al., 2009; Tsuchiya et al., 2015) have been studied for many years. Also, the recent research of IoT implementation (Otobe et al., 2019) for the small and medium enterprises, SME, is a good example. These studies include data analysis as well as condition monitoring of major processes such as laser welding, press working, injection molding (Fukushima et al., 2009). In addition, we investigated data analysis and a pattern-matching technology (Fukushima et al., 2009; Zhao et al., 2018). This study focused on an issue such as the technology for monitoring a manufacturing process of the test/practical mold. And we carried out the waveform analysis, MT system, as data analysis for the development of the stable manufacturing process in injection molding. Also, by using the important value called MD, Mahalanobis Distance, in MT-system, we investigated the failure discrimination method for the discriminating between Quality-molded-goods and Inferior-molded-goods. Finally, we examined the effectiveness of MT-system waveform-analysis.

CONDITION MONITORING

General Process of Injection Molding

Generally, the three-phases shown in Fig.1 are typical fractionation processes for injection molding.

In pre-process, the optimized molding condition should be determined by CAE and some optimization techniques. It goes without saying that the experiences of engineers are also important. These findings are the keys to find out the best or better conditions. In this study, the suitable injection molding condition was obtained by CAE. In-process and post-process are the main issues of this study, which need the monitoring technology of manufacturing by sensors and the failure discrimination method by waveform analysis, respectively.

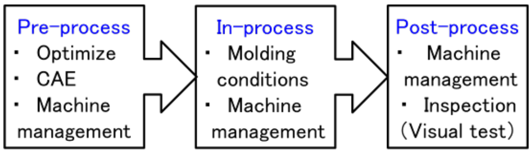


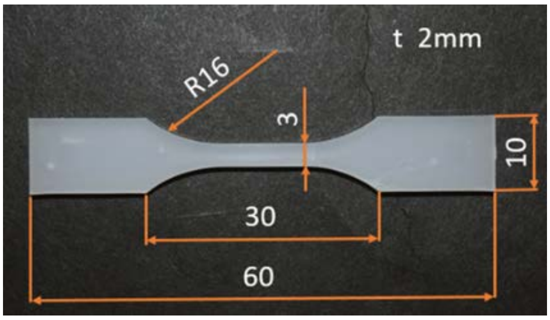
Fig. 1. The fractionated process diagram of injection molding.

Models for the CAE Analysis and the Condition Monitoring Experiment

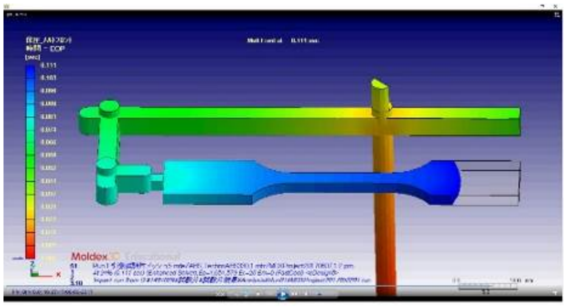
In this study, as shown in Fig. 2(a)-(d), the dumbbell-like test piece model(a) (b) and practical model(c) (d) were used as the CAE analysis model to estimate the suitable molding condition and the condition monitoring experiment. CAE analysis was performed by using Moldex3D developed by CoreTechSystem Co., Ltd. The practical model is called Fukka-chan, a mascot character in Fukaya-city, Saitama-prefecture, Japan.

The Information Obtainable from Injection Molding Machine and Sensor Attached to the Mold

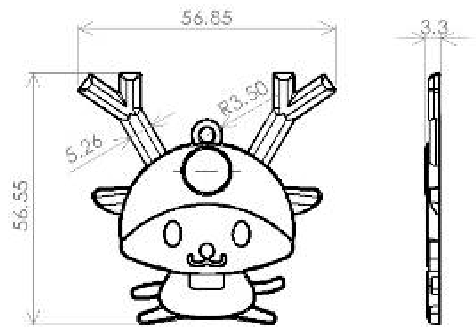
There are two kinds of information obtainable from the injection molding machine. One is information called process information which is acquired from the injection machine itself, second is the information which is acquired from the retrofitted acceleration sensor. The injection molding machine, Sumitomo Heavy Industries, Ltd SE75EV-A, which has a function to acquire many manufacturing information, process-information, clamping force[kN], injection speed[mm/s], holding pressure[MPa] and resin temperature[℃], etc. was used. Also, it provides online information and outputs of the waveform using the machine-mounted monitor. And the uniaxial acceleration sensor, ONOSOKKI NP-3211, and triaxial acceleration sensor, ONOSOKKI NP-3574, were used for the acquisition of mold vibration.



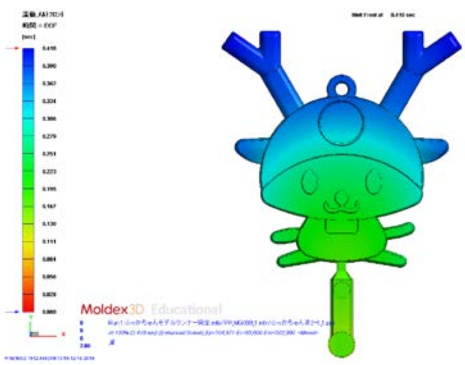
(a) Dumbbell-like test piece.



(b) CAE analysis of dumbbell-like test piece.



(c) Practical model, Mascot character.



(d) CAE analysis of practical model.

Fig. 2. Schematic of the model and CAE analysis for the condition monitoring.

Technology about the Abnormality Detection and the State Change Detection by Waveform Analysis

In the beginning, the basic concept for abnormality detection and the state change detection are described. To monitor the state of injection molding machine, and mold which had the retrofitted sensor, acceleration sensor, it is necessary to clarify the normal state of the machine condition. That is, our biggest goal is to develop the method that can evaluate the difference between a normal state waveform and some subsequent waveform. Therefore, the core technology to achieve the goal mentioned above is the development of the method that can detect the change of state of the manufacturing process using obtainable time-series waveform. And so here, for the reasons mentioned below, the data obtained by one-injection-cycle, approximately 10 seconds in this experiment, is to be set as "one waveform data-set" for processing. (1) The molding time is relatively short in comparison with other manufacturing. (2) To revise a molding condition in the middle of the molding process is difficult. For instance, in case of the cutting process, even if you stop the process during cutting, you can make a restart relatively easy. Meanwhile, once you stop the process during injection molding, it takes a long time to make a restart. This is because it is necessary to relieve the residual resin out from the mold and plasticizing apparatus.

In this study, the pattern recognition technology called MT-system, Mahalanobis-Taguchi-System, was applied. The MT-system is Taguchi's design of a systematic method for using the Mahalanobis Distance. The objective of the MT-system is to develop and optimize a diagnostic system with a measurement scale of abnormality. MT-system is also very useful in monitoring a manufacturing process. In that case, the normal condition group would be defined as the group existing when the process is producing perfect products which mean quality-goods. The MT-system provides a measurement system to assess abnormality. To define a measurement system, we need two parameters defined the origin and a unit scale. For an MT-system, the origin, zero, and one unit are defined by the normal condition group. The average of Mahalanobis Distances for samples from the normal condition group is typically 1.0. The Mahalanobis Distance for an abnormal sample should become much larger than 4.0. Here, the discrimination processing of molded part's quality by using the MT-system was carried out subject to the following rules, (1) The normal data was the condition which was optimized for the quality-goods (2) The abnormal data was the condition which was intentionally changed for the inferior-goods. Fig. 3 shows the basic concepts of the MT-system. The followings are the procedure of the discrimination processing of molded part's quality by using MD, MT-system. Firstly, to determine the space called "Unit-space" which is derived from plural normal condition data, and secondly, to calculate MD, Mahalanobis Distance which is represented by Eq. (1) -(2), between unit-space and condition data. Assuming the data consists of k variables; i is the variable (i = 1, 2, …, k); n represents the number of samples in the data; and j is the sample number (j = 1, 2, …, n), the variables are standardized as defined in Eq. (1).

$$U_{ij} = (x_{ij} - m_i) / S_i \qquad (1)$$

where, m_i and S_i represent the mean and standard deviation of the ith variable, respectively, and U_{ij} is the standardized vector obtained from the standardized values of x_{ij}. MD values are calculated as defined in Eq. (2).

$$MD_j = \frac{1}{k} U_{ij} R^{-1} U_{ij}^T \qquad (2)$$

where, k: Number of data for detection target, $\boldsymbol{U_{ij}}$: Data matrix for detection target, $\boldsymbol{R}^{-1}$: Inverse matrix of correlation matrix for measuring data, $\boldsymbol{U_{ij}}^T$: Transposed matrix of "$\boldsymbol{U_{ij}}$".

In this study, the unit-space was formed from 10 normal conditions. If "a condition data" is the condition of quality-goods, the calculated MD becomes closer to 1.0. Meanwhile, if "a condition data" is the condition of inferior-goods, the calculated MD becomes larger. However, the threshold of "quality-goods/inferior-goods" must be set in each case. Therefore, the pre-process for determining the optimal molding condition, shown in Fig. 1, is an important phase to establish stable production.

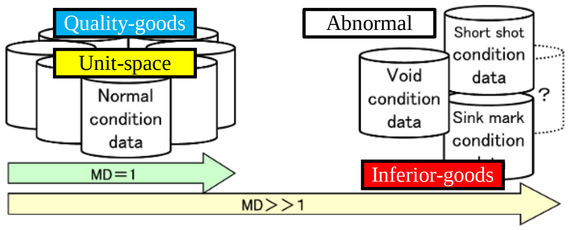


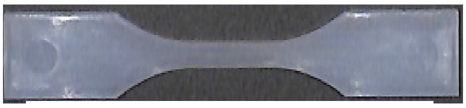
Fig. 3. Basic concepts of MT-system.

RESULTS AND DISCUSSIONS

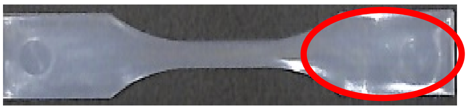
Defective Samples

Fig.4(a)-(d) show the photographs of dumbbell-like test pieces. Fig.4(a) shows the photographs of the quality-goods. Fig.4(c)-(d) show the intentionally manufactured inferior-goods/ defective samples, abnormal condition, called the sink-mark, the void in the molded part and the short-shot. The sink-mark defective sample has the recess on the surface, the void in the molded part includes the air/gas and the short-shot is the non-filling state in the mold cavity as indicated by the circle, respectively.

Fig.4(e)-(h) show the photographs of practical model pieces. Fig.4(e) shows the photographs of the quality-goods. Fig.4(f)-(h) show the intentionally manufactured inferior-goods, mild-level short-shot, moderate-level short-shot and severe-level short-shot, respectively. The portions surrounded by the red circles in Fig.4(f)-(h) are the defective molding, short-shot.



(a) Quality-goods for dumbbell-like test piece.

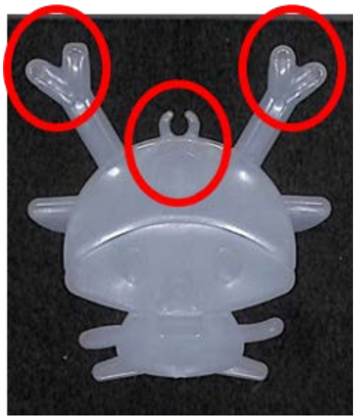


(b) Sink mark.

(c) Void.

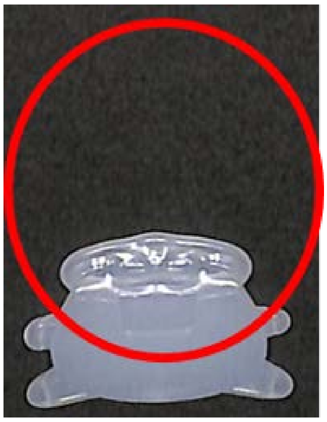
(d) Short shot.

(e) Quality-goods for practical model.



(f) Mild-level, short-shot.

(g) Moderate-level, short-shot.

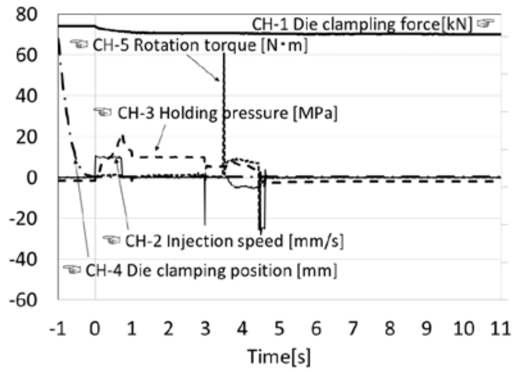


(h) Severe-level, short-shot.

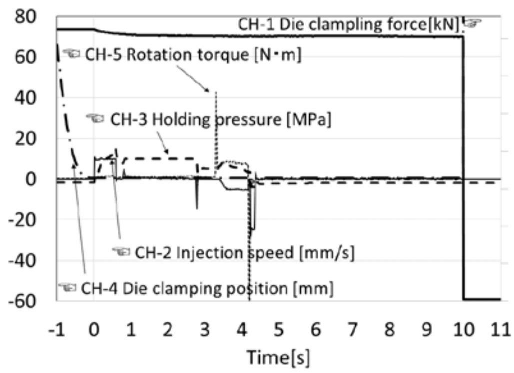
Fig. 4. Molded samples, quality or inferior-goods.

Waveform Acquisition Result

The experiment for each abnormal condition was conducted 5 times, and the experiment for the normal condition was conducted 10 times. As noted above, we put the data of the normal condition data to determine unit-space as shown in Fig. 3. Fig.5(a) and (b) show the waveforms of quality-goods and inferior-goods, short-shot, for the manufacturing information obtained from an injection molding machine : CH-1: clamping force[kN], CH-2:injection speed[mm/s], CH-3: holding pressure[MPa], CH-4: die clamping position[mm] and CH-5: rotating torque[N・m]. The difference of the holding pressure, CH-3, the dotted line in these figures, between quality-goods and inferior-goods was worthy of special mention in Fig.5 (a), (b). Generally speaking, since the holding pressure has a large effect on the short-shot defect, this difference is rational even if this experiment was intentionally performed.



(a) Quality-goods.

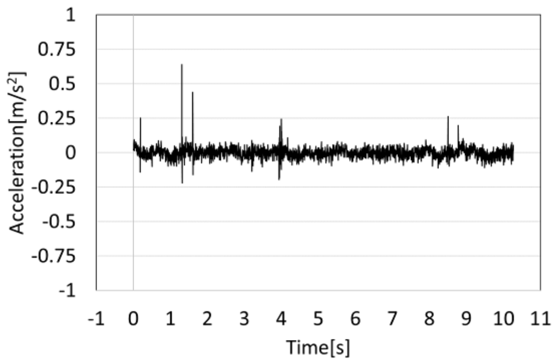


(b) Inferior-goods, short-shot.

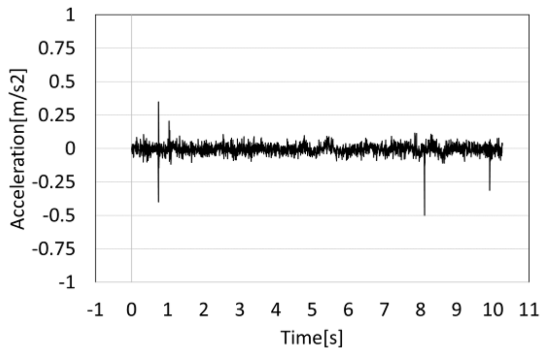
Fig. 5. Collected waveform by monitoring for dumbbell-like test piece.

Also, Fig.6 (a) and (b) show the waveforms of quality-goods and inferior-goods, short-shot, for an acceleration sensor. From these figures, it is slightly difficult to recognize the differences. Here, the pattern recognition analysis by MT-system was carried out by using all waveform data, acceleration, and CH-1~5, process information.

Likewise, the obtained results of waveform data and acceleration for the practical model had a similar tendency to dumbbell-like test pieces.



(a) Quality-goods.



(b) Inferior-goods, short-shot.

Fig. 6. Collected acceleration data for dumbbell-like test piece by monitoring.

Result of Pattern Recognition Analysis by MT-system

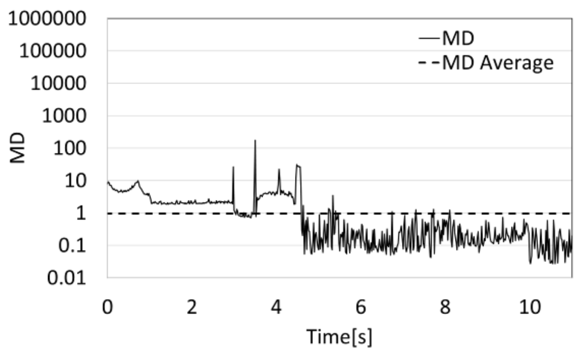
As noted above, when the MD value is closer to 1.0, a quality-goods can be manufactured. On the other hand, if the MD value is sufficiently larger than 1.0, it is a molding condition for an inferior-goods. Fig.7(a)-(d) show the relationship between MD and time for each condition of dumbbell-like test pieces. Fig.7(a) indicates the relationship between MD and the time for the normal condition with one another. At the initial stage, MD value exceeds "100" due to the variation phenomenon of waveform. But throughout the one-process which is approximately 10 seconds in this experiment, the MD average value, the dotted line in the figure, is close to 1.0. That means a normal condition that can manufacture the quality-goods.

Meanwhile, Fig.7 (b), (c) and (d) indicate the relationship between the quality-goods and short-shot, void, sink-mark, respectively. At a later stage of processing, the rapid increase of the MD value was observed. Throughout the one-process of these cases, the dotted MD average value in the figure, is over 100000. That means an abnormal condition where quality-goods cannot be manufactured.

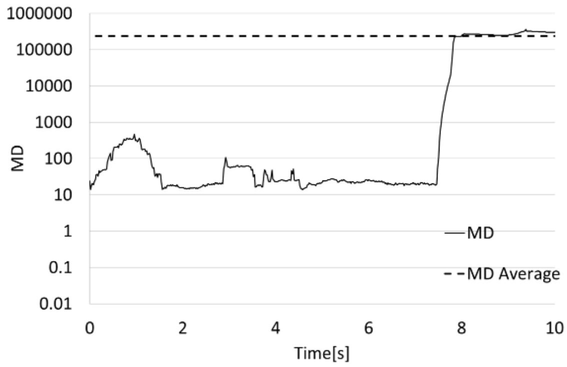
Likewise, Fig.7(e)-(h) show the relationship between MD and time for each condition of a practical model. Fig.7(e) indicates the relationship between MD and time for the normal condition with one another. The MD average value as shown in the dotted line is 0.93. As mentioned above, this value is close to 1.0. That means a normal condition where quality-goods can be manufactured. And the MD average values for mild-level short-shot, Fig.7(f), moderate-level short-shot, Fig.7(g), and severe-level short-shot, Fig.7(h), are 9.30, 26.77 and 53.66, respectively. We can see that the MD average value is gradually getting bigger with an increase of the defective level.

In this study, a temporary threshold value 4.0 shown in the dashed line in Fig.7(e)-(h) is set. Here, we focus on the time-series changes of MD. Even if the Fig.7(e) is normal, the time-series changes of the MD sometimes exceed the threshold. Assuming that the time-series of the MD value is only set as a monitoring target when the MD value exceeds the set threshold, the manufacturing process is stopped by the system. As noted above, in the injection molding process, since restart operation is time-consuming, inadvertent interruption should be avoided. The operation time needed to take out the residual resin from the mold and plasticizing apparatus is extremely inefficient. However, in this study, the data obtained by one-injection-cycle is to be set as one waveform data-set for processing. Then, the MD average value derived from one waveform data-set MD value was used for the failure discrimination. This means that production efficiency can be achieved because the process is not interrupted.

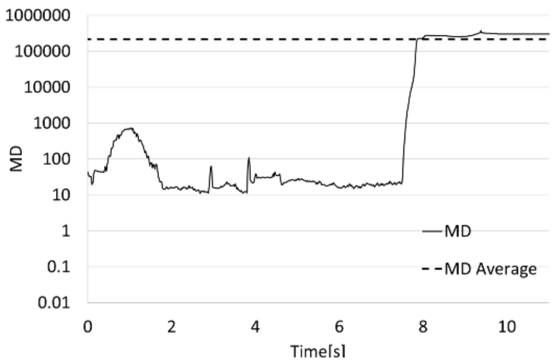
In this experiment, since the intentional condition for the inferior-goods was set, the differences between the waveform in Fig.5 (a) and (b) are easy to be recognized. However, since each waveform is strongly fluctuating, the threshold setting to distinguish between quality-goods and inferior-goods is difficult. Therefore, the pattern matching method utilizing MT-system, MD, by using all waveform data make it possible to achieve failure discrimination.



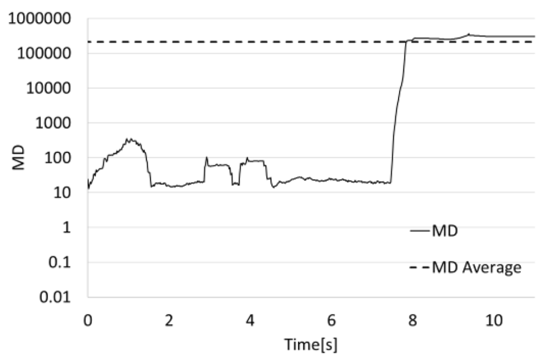
(a) Normal condition, Quality-goods, for dumbbell-like test piece.



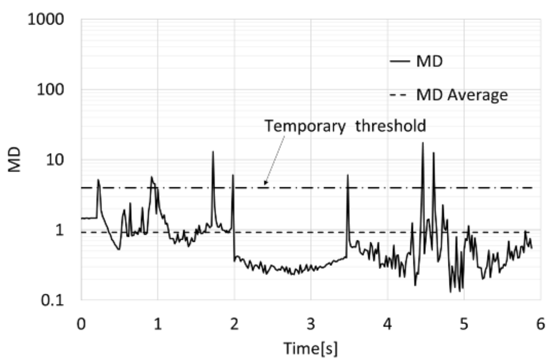
(b) Failure Condition, Inferior-goods, short-shot, for dumbbell-like test piece.



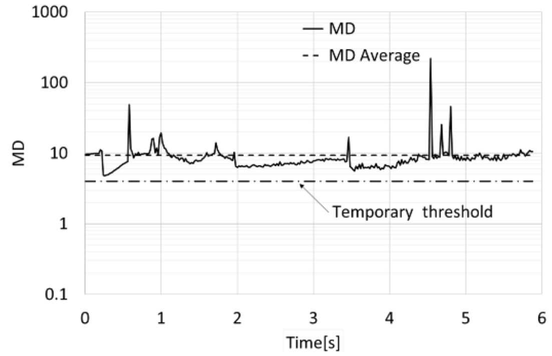
(c) Failure Condition, Inferior-goods, Void, for dumbbell-like test piece.



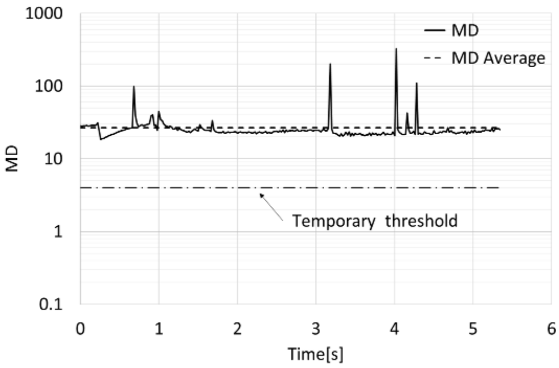
(d) Failure Condition, Inferior-goods, Sink-Mark, for dumbbell-like test piece.



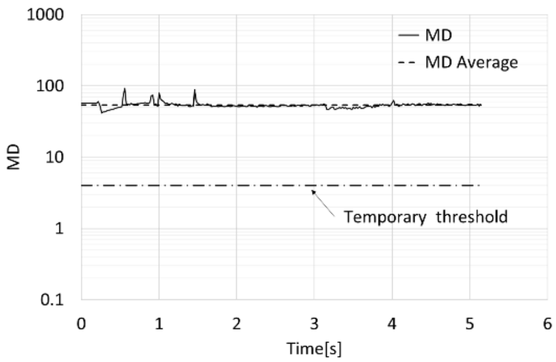
(e) Normal condition, Quality-goods, for practical model.



(f) Failure Condition, Inferior-goods, mild-level short-shot, for practical model.



(g) Failure Condition, Inferior-goods, moderate-level short-shot, for practical model.



(h) Failure Condition, Inferior-goods, severe-level short-shot, for practical model.

Fig. 7. The results of Mahalanobis Distance for normal condition and each failure condition.

The Effectiveness of Acceleration Data for the Improvement of Failure Discrimination

Fig.8 shows the relationship between the level of inferior-goods and MD average whether to use the acceleration. As shown in Fig.8, it is obvious that the tendency of “the higher the inferior level, the larger the MD average” could be seen clearly under the utilization of acceleration data in the MD calculation. Basically, there is no function in the process-information to detect a phenomenon that occurred in the mold. So, the acceleration data which is obtained from the retrofitted acceleration sensor in the mold is very useful for the improvement of the failure discrimination. Although the acceleration sensor/data is very useful in this experiment, the key to success in each experiment is to find out the effective sensing method.

Fig. 8. The relationship between the level of inferior-goods and MD average.

CONCLUSIONS

In this study, we focused on issues such as technology to monitor the manufacturing process for injection molding and carried out the waveform analysis by Mahalanobis Distance, MD. We conclude the followings:

(1) The failure discrimination is possible using manufacturing information from the injection molding machines and retrofitted sensors such as acceleration sensors.

(2) In the case of injection molding, data, obtained in one-injection-cycle and set as the one waveform data-set for processing, is useful for the failure discrimination.

(3) The MD average value obtained in one-injection-cycle is suitable for failure discrimination. Because, if the time-series MD value is only set as a monitoring target, there is a possibility that the manufacturing process is stopped by the system carelessly.

(4) The retrofitted sensor, such as an acceleration sensor in this study, which can detect the objective to be monitored is important to improve the performance of failure discrimination.

The investigations by using “continuous manufacturing data” and “accidental failure data” are to be considered in the next step.

Furthermore, since the operation for factors, such as temperature, holding pressure, etc.., can be possible by CAE analysis, the investigation for the low-cost manufacturing and the development of discrimination methods that have a high-precision performance is very important for the effective use of CAE.

ACKNOWLEDGMENT

We would like to thank Fukaya-city, Saitama-prefecture, Japan for the cooperation of the use of mascot character, Fukka-chan**.**

REFERENCES

Fukushima, Y., Kurose, M., and Kumehara, H., "Monitoring system to minimize deformation of die-casting by orthogonal analysis and SOM," Journal of the Society of Materials Science, Vol. 58, No. 5, pp. 430-436 (2009)

Fukushima, Y., Saito, K., Chiba, R. and H. Kumehara, "A study on monitoring system for near-net-shape casting by mahalanobis distance," Journal of the Robust Quality Engineering, Vol. 17, No. 2, pp. 92-98 (2009)

Kawada, N., Oikawa, M., Ootsuka, Y., Iwaki, I., and Kumehara, H., "Development of Condition Monitoring System for Laser Welding System of Stainless Steel Sheets," Journal of the Japan Society for Precision Engineering, Vol. 75 No.5, pp. 629-633 (2009)

Otobe, S., Urano, M., Oizumi, K., Hayashi, T., Ishigami, A., Natthapong, C., and Ito, H, "Development of "Experiment AI" and "Iot-Based Mold" in Mold Manufacturing SME," Journal of the Japan Society of Polymer Processing, Vol.31 No.12, pp.452-455 (2019)

Tsuchiya, K., Lu, Y., kato, M. and Tomono, Y. , "Process monitoring for a new product management system using small production machines," SEISAN-KENKYU, Vol. 67 No.6 , pp. 641-645 (2015)

Zhao, Z., Hamakawa, S., Nakayama, Y., Kawada, N., Fukushima, Y., and Nemoto, Y., "Research on state monitoring technology in injection molding," pp.5-6, Preprints of Seikei-Kakou Autum meeting(2018)

NOMENCLATURE

i variable (i = 1, 2, …, k)

j sample number (j = 1, 2, …, n)

k variables

MDj mahalanobis distznce

mi mean of the ith variable

n number of samples

$\boldsymbol{R}^{-1}$ inverse matrix of correlation matrix for measuring data

S*i* standard deviation of the ith variable

U*ij* the standardized vector obtained from the standardized values of *xij*

Uij Data matrix for detection target

$\boldsymbol{U}_{ij}^{T}$ transposed matrix of "***Uij***"

基於波形分析法狀態監測技術在塑膠射出成型過程中的使用

福島祥夫　趙宗陽　坂本明子 河田直樹
琦玉工業大學機械工學科

摘 要

近年來，物聯網技術在全球迅速普及。許多公司和工程師開始注重將物聯網技術引入實際生產過程。利用物聯網技術來實現生產可以有效地避免塑膠射出成型過程中一些缺陷的產生。大多數現代的塑膠射出成型機都具有測量壓力、溫度、鎖模力等工藝數據的功能，進而幫助我們獲得穩定的生產系統。在本研究中，除了上述的工藝數據外，還測量了安裝在模具上加速度傳感器的數據。利用機台數據和加速度傳感器數據來進行波形分析。MT 系統模式識別技術實現了對於缺陷的識別。實際上，在 MT 系統中應用了一個重要的數值 MD，也就是馬哈蘭距離。綜合上述所言，波形的變化與模具零件的質量有關（例如模具的加速度、鎖模力）。在此基礎上，利用 MT 系統實現了對塑膠射出成型製程缺陷及模具狀況的監測。