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Novel design of piezoelectric ultrasonic transducers and its application on die for die-casting

Mako Nakamura[1‡], Yoshihito Kawamura[1], Kei Nakatsuma[1], Yuma Shimizu[1], Naoki Zaito[1] and Makiko Kobayashi[1*] (Kumamoto Univ.)

1. Introduction

Die-casting is one of the casting methods in which melted metal is filled into a mold at high speed and high pressure to solidify rapidly. It is widely used in various industries, including the aircraft, automobile, and plant industries. However, die-casting process sometimes produces porosity due to oil and moisture on the die surface or volume reduction caused by shrinkage of solidification when the metal gets cool. These porosities have long been a problem because they reduce the mechanical strength and airtightness of the product[1)]. As the method of detecting the porosities, X-ray inspection and ultrasonic testing are widely used. But these sensing systems cannot conduct real-time monitoring because of the matter of safety and heat resistance. Sampling inspection for a fixed quantity of products from a lot, and the products after processing must be re-melted and reprocessed if defective products exist above the standard value. As the carbon-free society has been focused on realizing a sustainable world recently, the research of real-time monitoring systems for the die-casting process should be promoted.

In this study, sol-gel composite piezoelectric sensor was used as an ultrasonic transducer because it has enough heat resistance and thermal shock resistance and its ultrasound has high directivity. As the piezoelectric sensor, sheet-type sensors[2)] and direct-applied sensors[3)] have been the most commonly used. The sheet-type sensors need couplant to improve acoustic bonding and are difficult to fix on the complex mold surfaces. And the couplant should have heat resistance above the mold surface temperature however typical couplant does not have heat resistance. About the direct-applied sensors, it takes time to construct and remove.

So in this paper, we propose sol-gel composite piezoelectric sensor with a novel structure for the real-time monitoring system of die-casting. That is chip-type sensor which is made on the chip and the same substrate as the mold. And it does not need couplant and is easy to exchange when it has reached the end of its life. The chip backside and mold surface was polished and fasten firmly by using chip holder and bolts. The data from the chip sensor was clear as follows.

2. Fabrication

The sol-gel composite piezoelectric sensor was fabricated with the bismuth titanate piezoelectric ceramic powder and the titanium acid sol-gel solution (BiT/TiO_2) because it can be dried out at a lower temperature(200℃)[4)] compared to conventional material such as lead-zirconate-titanate (PZT). So the BiT/TiO_2 is relatively easy to make therefore mass production of the chip sensor made by it is capable. The fabrication method of BiT/TiO_2 sol-gel composite is below.

First, for the chip whose material was the same as the mold, surface modification by ultrasonic cleaning and UV irradiation was performed to improve the wettability. The chip size was circular with a diameter of 15 mm and its thickness was 5mm as shown in **Fig. 1**. After cleaning, BiT/TiO_2 sol-gel composite liquid was sprayed onto the chip by using the automatic spray coating system[5)]. After spray coating, the drying process of 150℃ and the firing process of 200℃ was conducted for 10 minutes and 5 minutes each. These spray coating process and the heating process were repeated until the film thickness reaches the target which is 50μm. After the film on the chip got 50 μm, poling by corona discharge[6)] was carried to the BiT/TiO_2 film. Negative supply voltage for the corona discharge poles the piezoelectric film which is difficult to depolarize under high temperatures. The voltage was about −40 kV. After poling, Ag paste which is about a diameter of 7 mm was attached to the film.

After fabrication of BiT/TiO_2 sensor, The backside of the chip and the surface of the mold which had 20mm deep hole for pouring molten metal was polished as shown in **Fig. 2.** And the chip with BiT/TiO_2 sensor was tightly fixed with torque of over 0.7Nm in each 4 volts. The data was acquired under room temperature.

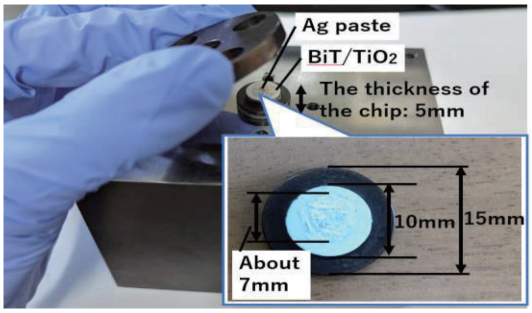

Fig. 1 The structure of the chip-type BiT/TiO_2 sensor

E-mail: ‡226d8515@st.kumamoto-u.ac.jp,
*kobayashi@cs.kumamoto-u.ac.jp

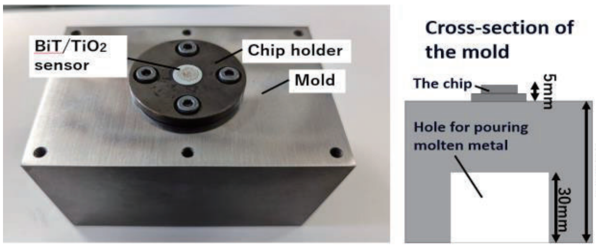

Fig. 2 Fixing with the chip holder and the size of the mold

3. Results and discussion

Ultrasonic waveforms of chip-type BiT/TiO_2 sensor on the mold that is the same material as the chip is shown in **Fig. 3**. The fast Fourier transform (FFT) results in the four sliced waves reflected echoes in **Fig. 3** is shown in **Fig. 5**. **Fig. 4** is ultrasonic response when the chip put on another metal whose material is different from the chip for comparison with **Fig. 3**.

In the **Fig. 4**, the reflected wave from the chip-mold interface was so large that the reflected wave from the mold-air interface are not apparent. In comparison, **Fig. 3** indicates that the reflected wave from the chip-mold interface and that of the mold-air interface were clearly discriminated and the reflected waves at the chip-mold interface were suppressed because the mold material is the same with the chip. The thickness calculated from the time difference between S1 and S4, and the sound speed was 30.9 mm. The error between the calculated value and the theoretical value shown in **Fig. 3** was 3%, which is within the acceptable range. In the **Fig. 5**, tow the reflected waves from the mold-air interface(S1, S4) has the same resonance frequency, which is 15MHz.

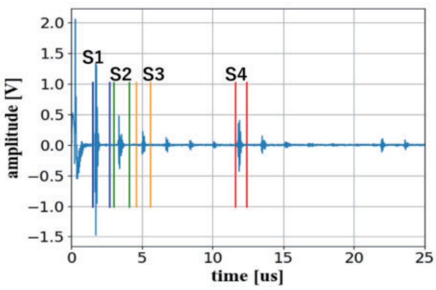

Fig. 3 Ultrasonic response of the mold-air interface with the same mold materials as the chip

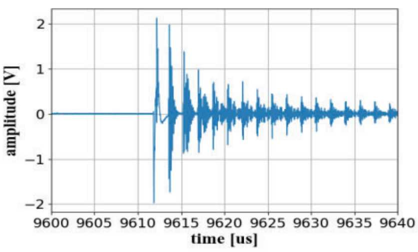

Fig. 4 Ultrasonic response on the different materials from the chip

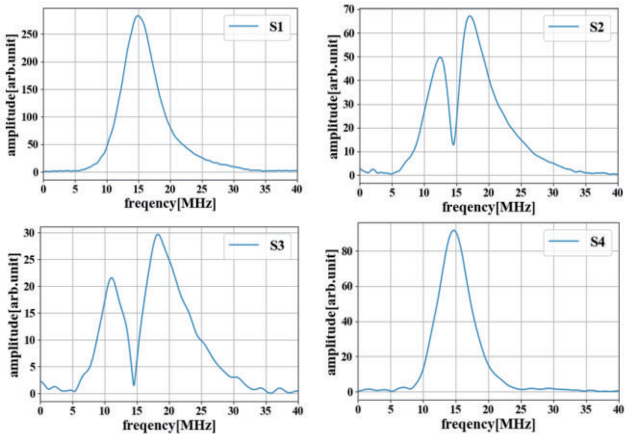

Fig. 5 Frequency Characteristics of S1~S4

4. Conclusions

As a novel structure of the sol-gel composite piezoelectric sensor, chip-type sensor which does not need couplant and can get signals just to fix on the mold was suggested. The reflected wave from mold-air interface was clearly distinguishable from that of chip-mold interface because the material of the chip is the same as that of the mold. And the calculated depths from mold surface to hole were valid. There was no significant difference in the frequency characteristics of the reflected wave from mold-air interface. This measurements using chip-type BiT/TiO_2 sensor were conducted at room temperature, so we plan to conduct and report about high temperature evaluation. And in the future, non-destructive test measurements by the chip-type sensor will be carried while actually pouring melted metal into the hole in the mold.

References

1) H. Guo, Y. Yao and X. Long, in *2018 19th International Conference on Electronic Packaging Technology (ICEPT)* (2018) pp. 472.
2) M. Kobayashi, C.-K. Jen and D. Levesque, IEEE Trans. Ultrason. Ferroelectr. Freq. Control **53** [8], 1478 (2006).
3) M. Nakamura, K. Nakatsuma, M. Kumon and M. Kobayashi, J. Adv. Mech. Des. Syst. Manuf. **17** [4], 1 (2023).
4) A. Hiroaki and M. Kobayashi, in *IEEE International Ultrasonics Symposium, IUS* (IEEE Computer Society, Graduate School of Science and Technology, Kumamoto University, Kumamoto, Japan, 2020) Vol. 2020- Septe.
5) Y. Kiyota, K. Nakatsuma and M. Kobayashi, in *2017 IEEE International Ultrasonics Symposium (IUS)* (2017) pp. 1.
6) H. Xiaofeng, L. Shanghe, W. Ming and W. Lei, in *2007 International Symposium on Electromagnetic Compatibility* (2007) pp. 31.