Effect on Mold Releasability on EDM Finished Surface using Powder Mixed Working Fluid

Ryoji Kitada*, Keita Fujii**, Ruixiang Wang**, Akira Okada**
(Received on January 10, 2018)

* Sojo University, 4-22-1, Ikeda, Nishi-ku, Kumamoto, 860-0082, Japan
** Okaya University, 3-1-1, Tsushimanaka, Kita-ku, Okayama, 700-8530, Japan

Abstract

In this study, separation forces between molded epoxy resin and EDM finished surfaces were measured by using a tensile tester in order to quantitatively evaluate mold releasability. Based on the releasability test results, factors affecting the releasability of molded resin were discussed. Experimental results clarified that the separation force of molded epoxy resin from the EDM finished surface with kerosene type working fluid decreased with an increase of the surface roughness. The separation forces from the EDM finished surfaces with silicon powder mixed fluid and aluminum power one were higher than that with kerosene type working fluid. Furthermore, EDM finishing using nickel powder mixed fluid was tried to form thin surface layer containing nickel which would have high releasability. By using nickel powder mixed fluid, nickel could be included into the EDM finished surface, which led to lower separation force of molded resin.

Key words: EDM finished surface, Mold releasability, Separation force, Surface roughness, Surface component

1. INTRODUCTION

In recent years, high precision technology has increasingly become important for the manufacturing industries. For example, electrical discharge machining (EDM) is necessary to produce the precision metal molds. Accordingly, EDM finishing technology has been rapidly developed and widely used in the manufacturing industries 1), 2). Particularly, EDM finished surface has been directly used as a final metal mold surface for semiconductor packaging with epoxy resin 3). In such a case, surface characteristics of the EDMed surface affect the life time of metal mold and the molding performances. In the plastic molding process, one of the important factors for long life and high molding performances of metal mold is a mold releasability which means degree of detachment of molded resin from metal mold surface 3), 4). Low releasability could cause problems with producing products.

Based on the background, the mold releasability of molded resin from EDMed surface has been investigated in order to improve the releasability when the EDMed surfaces will be directly applied as metal mold surfaces. Then, our previous studies clarified that an average inclination angle of EDMed surface profile influences the releasability of molded epoxy resin in the case of EDM under middle-finish conditions 5). Moreover, improvement of the mold releasability was obtained by EDM using chromium powder mixed working fluid 6). Therefore, fundamental investigation of the mold releasability regarding EDM conditions and powder mixed working fluids is significant.

In this paper, the releasability of molded resin from EDM finished surface using the small discharge energy, silicon powder mixed working fluid, or aluminum one is experimentally investigated. Moreover, EDM finished surface using nickel powder mixed fluid is tried in order to form the thin surface layer containing nickel for improving the mold releasability. The factors affecting the releasability, such as the micro-scale geometry and chemical component of the EDMed surface using each working fluid are discussed.

2. EXPERIMENTAL PROCEDURE

2.1 EDM Conditions

EDM finishing equipment in this study is shown in Fig. 1. A die-sinker electrical discharge machine with linear motor drive (Sodick API1) formed EDMed surfaces. An electrode was a cylindrical copper of 25 mm in diameter. Alloy tool steel SKD11 in JIS specifications was used as a workpiece.
material because it is popular as a metal mold material for plastic molding. Four types of working fluid, normal kerosene type working fluid, silicon powder mixed fluid (SPMF), aluminum powder mixed fluid (APMF) and nickel powder mixed fluid (NPMF) were used. The finished EDM surface using normal kerosene type working fluid was made for the comparison with those using SPMF, APMF and NPMF.

Silicon powder, aluminum powder and normal kerosene are widely used as the working fluid in finishing EDM. Concentrations of mixed silicon powder and aluminum one were 10 g/L and 0.2 g/L respectively, since the EDM maker recommended these concentrations for better surface finish. The particle sizes of silicon powder and aluminum one were 1-8 µm and 1-5 µm respectively. The working fluid with the powder was stirred with a rotating screw during EDM in order to prevent the powder precipitation in the fluid.

In the production sites, metal mold surfaces are coated by various kinds of thin films in order to improve the surface characteristics, including the mold releasability. In these coatings, nickel series material is often selected as a coating material 7). In this study, the formation of surface containing nickel component was tried by EDM using NPMF, and the possibility to improve the releasability was investigated 8). The density of mixed nickel powder into the working fluid was set to 1.0 g/L, in which the powder was easily dispersed in the fluid. The average particle size of nickel powder was 2 µm.

The EDM conditions are listed in Table 1. EDMed surfaces with various types of surface profiles were prepared by varying the pulse duration \( t_e \), the discharge current \( i_e \) and the electrode polarity under the constant duty factor \( \tau = 20\% \).

| Table 1 EDM conditions |
|------------------------|
| **Discharge current** \( i_e \) | 0.4 - 3.0 A |
| **Discharge duration** \( t_e \) | 1 - 12 µs |
| **Electrode polarity** (\(+\), \(-\)) | |

2.2 Releasability Test

The method to evaluate the releasability of molded resin from EDMed surface in this study is based on “Testing methods for tensile strength of adhesive bonds, JIS K 6849 (1994)”. The releasability testing equipment is shown in Fig. 2. The equipment which is a vertical tensile tester is modified for thermosetting resin. The releasability test conditions are shown in Table 2. The tensile force during the releasability test using the equipment is shown in Fig. 3 as an example. The maximum force in Fig. 3 is defined as a separation force in this study. Remaining force after the separation force is tare weight which consists of the jig, the weight and the cured resin because the value of the force gauge is set to zero before the test. The releasability of resin from EDMed surface is investigated by comparing these separation forces.

3. EDM Finished Surfaces

Fig. 4 shows the SEM images of EDMed surfaces using kerosene type working fluid, SPMF, and APMF. The discharge conditions were \( i_e = 0.4 \) A, \( t_e = 1 \) μs in any EDMed surfaces. When the electrode polarity is negative, it can be observed that there are
many flat regions on EDM finished surfaces using SPMF and APMF, compared with that using kerosene type working fluid. Also, there are few dark concave regions on EDMed surfaces using SPMF and APMF [10]. On the other hand, discharge craters with smaller diameter are formed densely and the EDMed surface with high frequent irregularity is formed when the electrode polarity is positive. However, significant differences with type of working fluid cannot be confirmed.

Fig. 5 shows the roughness curves of EDMed surface using different types of working fluid. When the electrode polarity is negative, the spacing between the peaks on the EDMed surface roughness curves is relatively long and the frequencies of surface undulation are low in the cases using SPMF and APMF, compared with those using kerosene type working fluid. Also the tips of convex parts are rounded. On the other hand, in the case of positive electrode polarity, the spacing between the peaks is shorter than that in the case of negative electrode polarity. Then, the surface roughness in the cases of SPMF and APMF are slightly smaller than that in the case of negative electrode polarity. Furthermore, there is no large difference in roughness curve with the type of working fluids.

There was large visual difference in the gloss of EDMed surface. Therefore, the surface glossiness was quantitatively measured using a glossiness tester (JIS Z 8741). The results are shown in Fig. 6. The surface glossiness values of EDM finished surface in the case of negative electrode polarity are higher than those in the case of positive electrode polarity in any working fluids. The glossiness of EDMed surface using powder mixed working fluids is higher than that using kerosene type working fluid. In particular, the surface glossiness is the highest in the case of SPMF. On the basis of the results in Fig. 5 and Fig. 6, it is considered that the directionality of optical reflection on the surfaces using powder mixed working fluids becomes high due to their smooth and rounded peak shapes on the surface profiles without color change.

4. Effect of Surface Roughness on Mold Releasability

The influence of EDMed surface roughness on the mold releasability was discussed. Fig. 7 shows the relationship between separation forces and surface roughness (maximum height roughness $R_z$) on EDMed surface under small discharge pulse energy conditions.

It is obvious that the separation forces tend to decrease as the surface roughness increases under
the finishing condition with small discharge pulse energy in the cases of kerosene type working fluid on the electrode (+) and (-). Kitada et al. reported that there was a good correlation between the separation force of molded epoxy resin and the surface roughness of EDMed surface under middle-finishing conditions using kerosene type working fluid, and the separation force decreased with the surface roughness, since the average inclination angle of the EDMed surface profiles increases with surface roughness, which leads to smaller force needed for the separation. Also under finishing conditions, it is considered that the average inclination angle of the EDMed surface profiles increases in the case of kerosene type working fluid, and the epoxy molded resin can be easily separated from the EDMed surface with small force.

On the other hand, clear correlation between the separation forces and the surface roughness cannot be found out in the cases of powder mixed working fluid. Small separation forces were expected in the cases of powder mixed working fluid. However, the separation forces of SPMF and APMF are actually higher than those in the case of kerosene type working fluid, as shown in the graph. In some cases, the separation forces are almost twice larger than those of kerosene type working fluid. When the separation forces between SPMF and APMF are compared, they can be regarded approximately the same level, although they greatly varies.

Next, the relationship between the surface roughness of EDMed surface using NPMF and the separation forces of molded resin was discussed. In the EDMed surface using NPMF, there are not any clear correlations between the surface roughness and the separation forces. However, the separation forces in the case of EDMed surface using NPMF are significantly low, compared with those in the case of SPMF or APMF, and they are lower than those using kerosene type working fluid under some conditions.

Since the smoothed convex shapes of the profile were obtained on the EDMed surface using NPMF as well as those using SPMF and APMF, high separation forces of molded resin were expected in the case of NPMF. However, the separation forces in the case of NPMF are actually low. In fact, the separation force of mirror surface on the workpiece is 137 N which is higher than that of NPMF. On the basis of these results, it is considered that the dominant factor causing the low separation force is the chemical bonding force between EDMed surface and molded resin.

5. Factors on Mold Releasability

5.1 Factors Affecting Separation Force

The reasons of the high separation forces in the cases of SPMF and APMF are discussed here. The separation force \( F \) in this study can be expressed with the following equation (1):

\[
F \propto f \cdot S
\]

where, \( f \) is the adhesive force per unit area, \( S \) is the real contact area between molded resin and EDM finished surface. The adhesive force per unit area \( f \) is related to the chemical bonding force between EDMed surface and molded resin because the chemical components of EDMed surface greatly affects the bonding strength on the adhesive interface. The real contact area \( S \) is the factor pertaining to the profiles on EDMed surface. Meanwhile, the separation forces in Fig. 7 tend to decrease as the surface roughness increases. This is because the average inclination angle of the EDMed surface profiles increases with surface roughness as previously explained. Therefore, the separation forces of EDMed surfaces are basically lower than that of smooth surface, and they are affected by the real contact area \( S \) and the average inclination angle of the EDMed surface profiles.

5.2 Shape Factor

The effect of the real contact area \( S \) on the separation force was first investigated. Since the real contact area is very difficult to be directly measured, it was evaluated by the real length of profile curve on EDMed surface and the replicating ratio of molded epoxy resin to EDMed surface. The real length of the surface profile curve \( L \) must reflect the real surface area of EDM finished surface rather than average length \( R_{sa} \) on the surface. Also, the replicating ratio of molded resin to EDMed surface \( R \) was evaluated by the ratio of the surface roughness value of molded resin surface to that of EDMed surface after the releasability test.

Fig. 8 shows the real length \( L \) on the measured
horizontal length of 10 mm on the profile curve on EDM finished surface. As shown in the figure, the real length is almost the same regardless of the type of working fluid. Under other EDM conditions, it was confirmed that the real length was almost constant regardless of the discharge conditions.

Fig. 9 shows the replication ratio of molded epoxy resin to the EDM finished surface calculated by the surface roughness of EDMed surface and that of molded resin surface after the releasability test. As shown in the figure, the replication ratio of molded resin is nearly 100% in any types of working fluid. Also, the replication ratio was nearly 100% under other discharge conditions. From these results, it can be concluded that the real contact area between molded epoxy resin and EDM finished surface is almost the same regardless of type of working fluid and discharge conditions in finishing EDM. Therefore, it is considered that the real contact area doesn’t affect the separation forces in the cases of kerosene type working fluid, SPMF and APMF.

5.3 Chemical Factor
Next, in order to investigate the effect of the chemical component change of the EDMed surface, component analyses on EDM finished surface in kerosene type working fluid and SPMF were carried out by energy dispersive X-ray spectroscopic analysis (EDS). The results are shown in Fig. 10 and Fig. 11 respectively. The EDM conditions are shown in order of \( i_e \cdot A \cdot t_e \) µs on the horizontal axis in the bottom of figures. In the case of EDM finished surface using kerosene type working fluid, the silicon content rate is under 0.4%, which corresponds to the original amount of silicon in the workpiece SKD11. The ratio of other components also corresponds to the components of the base material.

In contrast, the EDM finished surface using SPMF includes more silicon than that in the base material. Therefore, it is considered that silicon from the SPMF was included into the surface during the machining by using SPMF. Also, the silicon content increases as the discharge pulse energy conditions become lower. In general, the adhesion force between epoxy resin and silicon is high \(^{12},^{13}\). Therefore, epoxy resin has been used as the material for packaging of silicon IC chips. Accordingly, inclusion of much silicon on EDMed surface would lead to the increase in separation force of molded epoxy resin.

The cross-sections of EDMed surfaces were observed by a field-emission transmission electron microscopy (JEOL Ltd., JEM-2010F) in order to investigate the difference in material structure with type of working fluid. Fig. 12 shows the TEM images. The white parts observed on the upper part in the images are coating films, and the EDMed surface is beneath the white parts.

As can be seen from the figure, the resolidified layer of about 1-2 µm in thickness could be observed on the EDM finished surface in kerosene type
working fluid. In the layer, the crystal grain size is relatively small, as compared with that in the base matrix observed below the layer. That is, the different surface structure from the base matrix is formed due to the melting and resolidification of surface material by EDM. On the other hand, in the case of SPMF, a thin surface layer of about 1 µm in thickness can be observed, in which the material microstructure cannot be observed at this magnification ratio, while the base matrix structure is obviously observed and the border between them can be clearly confirmed.

Fig. 13 shows the electron diffraction patterns at the points in the resolidified layer and in the base matrix in the case of EDM using SPMF. In the resolidified layer, any diffraction pattern doesn’t appeared, which means that the layer has an amorphous structure. Additionally, Fig. 14 shows the componental analysis results by EDS (Noran, Vantage) on the line marked in the TEM images of the EDMed surface using SPMF. It can be understood from the figure that not only carbon but also a large amount of silicon are present in the resolidified layer within 0.5 µm from the surface.

From these results, it was made clear that a large amount of silicon was present on the EDMed surface using SPMF, compared with that using kerosene type working fluid, and amorphous structured thin layer containing silicon was formed. Therefore, it can be concluded that the amorphous surface layer including a large amount of silicon influences the releasability with molded epoxy resin and increases the separation force $F$, regardless of EDM conditions in the case of SPMF. However, even when the amount of silicon in the layer is relatively low, for example $i_c=1.5$ A, $i_t=7$ µs, the separation force is sometimes high. So, the amorphous surface layer including a large amount of silicon may not be only a dominant factor for the high separation force.

Fig. 15 shows the component analyses results of EDMed surface using APMF. The aluminum content into EDMed surface is less than 0.3 % in each EDM condition because of the low concentration of mixed aluminum powder into the working fluid. Consequently, it is considered that the adhesion force per unit area $f$ is almost constant in the case of EDMed surface using APMF, regardless of the EDM conditions. Moreover, since the component of EDMed surface using APMF is not different from that using kerosene type working fluid, it is considered the component of aluminum powder in the working fluid hardly influences the releasability of molded epoxy resin. Nevertheless, high
separation forces were measured in the case of APMF. Hence, it is considered that the cause for the high separation forces is the smoothed convex shapes of the profile of EDMed surfaces using APMF and SPMF as shown above.

The separation force is divided into vertical force and shear force along the interface of the profile between EDMed surface and molded resin surface. The shear force needed for separation of two surfaces is generally smaller than the vertical stress for the separation. Thus, the separation force becomes smaller with the average inclination angle of the profile \(^5\). During the separation test, the shear component of tensile force acting on the interface would be small in the cases of EDM using powder mixed working fluids because of their smoothed convex shapes of the profile. Consequently, it is considered that the separation force would become high in the cases of EDMed surfaces using powder mixed fluids.

5.4 Factors of Low Releasability

Lastly, the reasons of the low separation forces in the case of NPMF are discussed. Fig. 16 shows the SEM images of EDMed surface using NPMF. Since the surface roughness becomes relatively high when the electrode polarity is positive, EDMed surface with negative electrode polarity was shown in Fig. 16. The rounded convex shapes on EDMed surface profile were observed, similarly in the cases using SPMF or APMF as mentioned above. Fig. 17 shows the component analyses results of EDMed surface using NPMF. As shown in the figure, nickel is included in the EDMed surface using NPMF. Also, the amount of nickel contained in the EDMed surface increases with the decrease of the discharge pulse energy on the discharge condition, similarly to in the case of SPMF. Then, up to around 20% nickel can be contained in the EDMed surface. Furthermore, the relationship between the separation force and the nickel content in EDMed surface using NPMF is shown in Fig. 18 \(^9\). It is obviously confirmed from the figure that the separation force decreases with the increase of nickel content in EDMed surface. Therefore, the releasability of molded epoxy resin strongly depends on the nickel content in the EDMed surface.

From these results, the releasability of molded resin from the EDMed surface can be improved by EDM using NPMF. Moreover, the separation force would be further decreased if the EDMed surface with less smoothed convex shapes on the surface profile could be formed.

6. CONCLUSIONS

In this study, mold releasability on EDM finished surface using powder mixed working fluid was experimentally investigated. Main conclusions are as follows;

1. In EDM finished surface using kerosene type working fluid, the separation force linearly decreases with the surface roughness. On the other hand, there is no clear correlation between the separation force and the surface roughness in the cases of powder mixed working fluids.
2. Silicon can be contained on EDM finished surface by using silicon powder mixed fluid and the amount of silicon on the surface increases as

---

Fig. 16 SEM images of EDMed surface using NPMF

Fig. 17 Element ratio of EDMed surface using NPMF

Fig. 18 Relationship between separation force and nickel content in EDMed surface
the pulse energy in EDM conditions is lower.

(3) The separation forces between epoxy resin and EDM finished surface using silicon powder mixed fluid or aluminum powder mixed fluid become higher than those using kerosene type working fluid, regardless of discharge conditions.

(4) Nickel can be contained on EDM finished surface by using nickel powder mixed fluid, and the separation forces of molded epoxy resin from the EDMed surface are smaller than those using silicon powder mixed fluid or aluminum powder mixed fluid.

(5) In the case of EDMed finished surface using nickel powder mixed fluid, the separation force decreases with the increase of nickel content on EDMed surface.

Overall, this study clarified relationship between the mold releasability and the EDMed surface characteristics using powder mixed working fluids. Based on the research findings, control of the EDMed surface profiles and components is required in order to improve the mold releasability. Then, the mold releasability could be controlled by the EDM conditions and the types of powders. Therefore, the EDMed surface using powder mixed working fluids definitely has possibilities of high mold releasability.

ACKNOWLEDGEMENTS

The authors would like to express their thanks to Sodick Co., Ltd. and Mitsubishi Electric Corporation for their help throughout this study, and to TOWA Corporation for their cooperation to evaluate the releasability. This research was partially funded by Japan Science and Technology Agency in Okayama prefecture.

REFERENCES

1) N. Mohri, N. Saito, M. Higashi, A New Process of Finish Machining on Free Surface by EDM Methods, Ann. CIRP 40 (1) (1991) 207-210.

2) Y. S. Wong, L. C. Lim, I. Rahuman, W. M. Tee, Near-mirror-finish Phenomenon in EDM Using Powder-mixed Dielectric, J. Mater. Process. Technol. 79 (1-3) (1998) 30-40.

3) M. Yoshii, N. Suzuki, Investigation into the Release Behavior and Releasability Evaluation of the Encapsulation of Semiconductor Packages, IEEE T. Electron. Pa. M. 30 (3) (2007) 228-235.

4) T. Sasaki, N. Koga, K. Shirai, Y. Kobayashi, A. Toyoshima, An Experimental Study on Ejection Forces of Injection Molding, Precis. Eng. 24 (3) (2000) 270-273.

5) R. Kitada, A. Okada, Y. Uno, Y. Yang, H. Hioki, Fundamental Study on Releasability of Resin from EDMed Surface, Proc. 9th Int. Conf. Euspen 1 (2009) 117-121.

6) R. Wang, R. Kitada, R. Toshimitsu, A. Okada, Improvement of Surface Characteristics for Long Life of Metal Mold by EDM in Chromium Powder Mixed Working Fluid, Int. J. Elec. Mach. (22) (2017) 26-30.

7) K. A. Gross, A. Kovalevskis, Mold Manufacture with Plasma Spraying. J. Therm. Spray Techn. 5 (4) (1996) 469-475.

8) L. Liu, Q. Lu, Y. Wang, W. Dai, X. Zhang, Y. Li, X. Wu, Effect of PIII on the Adhesion Behavior of Epoxy Molding Compound-Nickel Interface, Proc. Int. Conf. Electron. Packag. Technol. High Density Packag. (ICEPT-HDP), (2009) 945-948.

9) S. Iwasaki, R. Kitada, A. Okada, Y. Okamoto, Study on Surface Characteristics of EDMed Surface with Nickel Powder Mixed Fluid, Key Eng. Mater. 656-657 (2015) 375-380.

10) Y. Uno, A. Okada, Surface Generation Mechanism in Electrical Discharge Machining with Silicon Powder Mixed Fluid, Int. J. Elec. Mach. (2) (1997) 13-18.

11) F. Awaja, M. Gilbert, G. Kelly, B. Fox, P. J. Pigram, Adhesion of polymers, Prog. Polym. Sci. 34 (9) (2009) 948-968.

12) K. Iko, Y. Nakamura, M. Yamaguchi, N. Imamura, Encapsulating Resins for Semiconductors, IEEE Electr. Insul. M. 6 (4) (1990) 25-32.

13) N. Kawamura, K. Hirohata, T. Kawakami, K. Sawajia, T. Mino, A. Kurosu, E. Takano, H. Y. Yoo, Adhesion Integrity Evaluation of Plastic Encapsulated Semiconductor Package, Proc. 48th IEEE Electron. Comp. Technol. Conf. (1998) 1132-1139.

14) N. Sumi, A. Goto, H. Teramoto, Y. Yasunaga, Y. Nakano, Study of Si-containing Amorphous Layer by Electrical Discharge Coating, Int. J. Elec. Mach. (16) (2011) 27-32.