Evaluation of Ejection Force for Die Castings by FEM Thermal Stress Analysis with Elasto-Plastic-Creep Model*

Shoji Ueda¹, Shinji Sannakanishi¹, Hidetoshi Shiga², Muhammad Khairi Faiz³ and Makoto Yoshida³

¹Ahresty Corporation, Toyohashi 411-3114, Japan

²Nissan Motor Co., Ltd., Yokohama 230-0053, Japan

³Kagami Memorial Research Institute for Material Science and Technology, Waseda University, Tokyo 169-0051, Japan

In the die design of high pressure die casting (HPDC), in order to prevent the casting from the warpage, it is essential to predict ejection force of each ejector pin before locating it. Recently, Shiga *et al.* revealed that their developed elasto-plastic-creep model is more accurate than conventional elasto-plastic models to estimate the thermal stress of casting during cooling with constraint of dies.

In this study, by using the elasto-plastic-creep model, thermal stress analysis was conducted to predict the force generated on each ejector pin in the HPDC process. As a result, the force was estimated within the error of 30% in respect to the measured value. It was also predicted that increasing in the curing time increases the force. [doi:10.2320/matertrans.F-M2021852]

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1. Introduction

In the process of the die-casting, it is necessary for a die-casting to be released smoothly from a die. The improper design of the ejector pin location causes the warpage of the die-casting and productivity deterioration. Therefore, it is essential to predict ejection force and to locate ejector pins properly. For the reasons listed above, the establishment of FEM analysis to estimate ejection force accurately is required. Generally, the ejection force is the sum of release force and sliding resistance of the ejector pin in drive mechanism. The sliding resistance between a die and ejector pins should be an important research subject, but in this study we paid attention to the release force that would occupy most of the ejection force. Conventionally, many expressions to estimate release force have been suggested concerning a cylindrical casting. Oota calculated the release force from pressure and friction.¹⁾ The pressures of inner cylinder and external cylinder were calculated using the shrinkage fit by assuming elastic deformation. Kaneko assumed that the whole casting had plastic deformation and suggested an expression of the release force which was calculated from the tensile or shear strength of the die-casting alloy at the temperature of ejection.²⁾ On the other hand, Aoyama *et al.* evaluated the release force by an elasto-plastic model based on the theory of Hill,³⁾ which treated the cylindrical internal pressure until the whole area became plasticity from elasticity.⁴⁾ Furthermore, they confirmed the validity by an experiment. Recently, Motoyama *et al.* showed the originally developed elasto-plastic-creep model, in which creep recovery was pseudo-considered.⁵⁾ Shiga *et al.* conducted the thermal stress analysis on the I-shaped model, and showed that the prediction of thermal stress was greatly improved. As a result, the difference from the measured value decreased from 50% to 18% by using the elasto-plastic-creep model instead of using the elasto-plastic model.⁶⁾ From these

studies, we assume that thermal stress of the die-casting at the time of ejection greatly affects the release force. Therefore, the prediction accuracy of release force will be improved by using the elasto-plastic-creep model.

In this study, we conducted the release force analysis by FEM with the elasto-plastic-creep model. And we measured the release force and the force generated on each ejector pin for the die-casting in the HPDC process to confirm the validity of release force analysis method and its result. As a criterion of the validity, we assumed less than $\pm 30\%$ of differences with analysis and measurement. Furthermore, evaluation was conducted on the effects of the length of the curing time on the release force and the force generated on each ejector pin. Several experiments were carried out aiming to expand application of developed analysis technique for countermeasures of ejection trouble in future use.

2. Analysis and Experimental Method

In this study, the release force and the force generated on each ejector pin were analyzed and evaluated using an aluminum die-cast product model (BRACKET ENGINE MOUNTING). Also, the actual forces in the die-casting process were measured to confirm the validity of simulation results.

2.1 Material model used for simulation

The material model used for simulation is shown in Table 1. Creep strain input data of ADC12 were used for a die-casting product model. These data were identified from the inelastic strain rate and stress value in the region where the stress is constant.⁶⁾ Those value were obtained by the constant strain rate tensile test. The simplified one-directional elasto-plastic-creep model is given in eq. (1) to (3),

$$\varepsilon_{all} = \varepsilon_E + \varepsilon_{In} + \varepsilon_T \quad (1)$$

$$\varepsilon_{In} = \varepsilon_P + \varepsilon_C \quad (2)$$

$$\dot{\varepsilon}_C = A(T) \cdot \sigma^{n(T)} \quad (3)$$

where ε_{all} is the total strain, ε_E is the elastic strain, ε_{In} is the inelastic strain, ε_P is the plastic strain, ε_C is the creep strain, ε_T

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Table 1 Material model used for simulation.

Material model (Analysis input data) (* temperature dependence available)					Product model (including die)	
					Product	Die
*Young's modulus	contributing to ε_E	Elastic model ($\varepsilon_{all} = \varepsilon_E + \varepsilon_T$)	Elastic-plastic model ($\varepsilon_{all} = \varepsilon_E + \varepsilon_P + \varepsilon_T$)	Elastic-plastic-creep model ($\varepsilon_{all} = \varepsilon_E + \varepsilon_P + \varepsilon_C + \varepsilon_T$)	ADC12 data	2.1×10^5 (MPa)
Poisson's ratio						$\nu = 0.3$
*Coefficient of thermal expansion	contributing to ε_T					
*True stress-logarithmic plastic strain		contributing to ε_P				
*Power law coefficient-power law stress exponent			contributing to ε_C			

is the thermal strain, $\dot{\varepsilon}_C$ is the creep strain rate, $A(T)$ is the power law coefficient, $n(T)$ is the power law stress exponent, and σ is the stress. As the hardening law of the elasto-plastic model, the isotropic strain hardening law was used. In eq. (2), the inelastic strain is separated by the plastic strain and the creep strain, which is determined by the steady state creep. In eq. (1), the elastic, inelastic and thermal strain terms are series ones, respectively.⁷⁾ The elasto-plastic-creep model and the coefficient of thermal expansion have the temperature dependence.

2.2 Analysis and experimental method of die-cast product

2.2.1 Release force and its distribution analysis method

The release force and its distribution analyses of die-cast product (BRACKET ENGINE MOUNTING) were conducted according to the following procedure. Here, release force distribution means the distribution of the force generated on each ejector pin. These analyses were conducted at three levels of 8 s, 10 s and 12 s to investigate the effect of curing time.

① Heat transfer analysis

Heat transfer analysis was conducted using casting analysis software CAPCAST. And its analysis was conducted on the actual casting condition from the curing start to ejection. Table 2 shows the die casting process used for analysis conditions.

② Thermal shrinkage analysis of the product model

As the thermal shrinkage analysis model, the cover cavity insert die, the ejector cavity insert die and the product model (including the gate and the overflow) were prepared. As boundary conditions, the contact condition between the cavity insert die and the product was defined. And the surface where the insert die is in contact with the holding die was constrained. Then, nodal points between each cavity insert die and product defined on the contact surface were adjusted to the same position to maintain the precision of the contact analysis. In addition, for the purpose of reducing the resistance caused by unevenness of contact surface in the ejection, finite elements on contact surface were created smoothly in the direction of the draft. As the temperature histories for the thermal shrinkage analysis, the temperature data obtained by process ① of heat transfer analysis, which were mapped to the product model in each time of curing, die

Table 2 Die casting process used for analysis conditions.

Die casting process	Time (sec)
Curing	10
Die open	2
Ejection	3
Remove a product	3
Spray of cover and ejector	12
Moving time of spray	1
Air blow of cover and ejector	5
Moving time of air blow	2
Die close	3
Ladling	6
Shot	2
Cycle time	49

opening, and ejection, were used. The initial temperature of the product model was 873 K. Because we thought that curing process was important for the shrinkage analysis, we used temperature data by the fine pitch for one second each in curing process. However, the temperature histories of the cavity insert die were not considered because there was a problem in the convergence of the contact calculation.

③ Release force and its distribution analyses

When we analyzed ②, ③ mentioned above, general-purpose structure analysis software ADVENTURECluster 2018-R1.3 was used. Generally, the relation between ejection force, release force and sliding resistance of the ejector pin in drive mechanism is given in eq. (4).

Ejection force = Release force

+ Sliding resistance of extraction mechanism (4)

Here, we define release force as the force required for mold release at the time of ejection against contact force. Due to thermal shrinkage of the product, the contact force is generated on the surface that the product contacts the die. And release force distribution is equivalent to the distribution

of the force generated on each ejection pin. We did not perform the analysis of the sliding resistance between a die and ejector pins in this study. One of the reasons is that its analysis model is complicated and another reason is that an evaluation of the contribution of the release force becomes difficult. Accurate numerical algorithms is challenges of the future. Generally, release force F due to the thermal shrinkage of the die-casting product on the sidewall is estimated as follows. Minute contact force Δf_i is caused by the thermal shrinkage of the die-casting product on the sidewall in micro-area ΔA_i of the contact surface between the die and the product. The eq. (5) shows the minute contact force Δf_i . The subscript shows a node number in the model of FEM.

$$\Delta f_i = \Delta A_i \times P_i \quad (5)$$

In eq. (5), P_i is the contact pressure to generate in the normal direction of the contact surface by the thermal shrinkage of the product. Particularly, in the case of a cylinder casting shape, contact area A is given as follows, $A = 2\pi al$, where a is the cylinder inner radius, l is the cylinder length. The eq. (6) shows the minute release force ΔF_i ,

$$\Delta F_i = \Delta f_i \times (\mu_i \cdot \cos \theta - \sin \theta) \quad (6)$$

Where μ_i is a coefficient of friction of slide force generated on a micro area, θ is a draft angle.²⁾ The release force F in the range of the contact area is the total sum of ΔF_i in eq. (6). The eq. (7) shows the release force F .

$$F = \Sigma(\Delta F_i) \quad (7)$$

It is reported by Aoyama *et al.* that a friction coefficient μ between the die and the product depends on the surface roughness of the die.⁴⁾ The surface roughness of a real die is different for each portion, however, we analyzed the release force using a constant friction coefficient $\mu_i = 0.5$ for an average value in this study. At first the product is released from a cover die and is released by ejection from an ejector die afterward. As an ejection model, 38 ejector pins modeled by rigid body were placed for the product. As velocity boundary condition of ejection, we defined forced speed 2 mm/s and ejection time 1 s on ejector pins so as to obtain the stable peak value of the release force. The force generated on each ejection pin changes by time and shows the peak value. We evaluated the differences of the peak value of the force generated on ejector pin as release force distribution. The total value of the force generated on ejector pin also changes by time and shows the peak value. We evaluated the peak value as release force.

2.2.2 Measurement method of release force and the force generated on each ejection pin

Ejection force and sliding resistance of ejector operation were measured, and release force was evaluated by eq. (4). Furthermore, three different curing time conditions of 8 s, 10 s and 12 s were applied to investigate the effect of the curing time on the release force. The ejection force is obtained from eq. (8).

$$\begin{aligned} \text{Ejection force} &= \text{measured ejection hydraulic pressure} \\ &\times \text{effective sectional area of hydraulic cylinder} \quad (8) \end{aligned}$$

The ejection force was measured ten times of casting. The resistance generated by dry run after actual casting operation

Fig. 1 Shape and size of die-cast product and sites of ejector pin.

was measured ten times. Ejection hydraulic pressure was measured by an oil pressure sensor. On the other hand, the force generated on each ejector pin was measured in six sites shown in Fig. 1, because it is difficult to measure in all 38 sites. The site shown in the following charts is based on Fig. 1. We installed a load sensor (manufactured by FUTABA CORPORATION, SSB16KN12×10H) in the flange of each ejector pin and measured the force generated on each ejector pin using a data logger (manufactured by KEYENCE CORPORATION, NR-500) under condition of sampling rate 1 ms. Ejection force and the force generated on each ejector pin were measured in synchronization with time.

3. Analysis and Measured Results

3.1 Analysis results of release force and the force generated on each ejector pin of die-cast product

Figure 2 shows the analysis result of contact force in ejector cavity insert die. As an example, the analysis results of release force and the force generated on each ejector pin for curing time of 10 s are shown in Fig. 3 and Fig. 4 respectively. From the analysis result of Fig. 2, as curing time increased, the contact force in ejector cavity insert die became larger. Empirically, it is well known that quantity of thermal shrinkage of the product grows larger with increase of curing time. From the analysis result of Fig. 3 and Fig. 4,

Fig. 2 Analysis result of contact force in ejector cavity insert die.

Fig. 3 Analysis result of release force (curing time 10 s).

Fig. 5 Measurement result of ejection force and slide resistance (curing time 10 s).

Fig. 4 Analysis result of force generated on each ejector pin (curing time 10 s).

Fig. 6 Measurement result of force generated on each ejector pin (curing time 10 s). (a) Site ②, ③, and ④; (b) Site ①, ⑤, and ⑥.

the one-peak was observed for release force and the force generated on each ejection pin respectively. Furthermore, the peak value became larger, as curing time increased. The calculated results also agree the insight drawn from experience that contact force in ejector cavity insert die grows larger with increase of curing time.

3.2 Measured results of ejection force, slide resistance and the force generated on each ejector pin of die-cast product

As an example, the measured results of ejection force and the slide resistance generated are shown in Fig. 5 and the force generated on each ejector pin is shown in Fig. 6. The curing time is 10 s for both cases. Slight time difference is shown between the timing of the experiment in Fig. 5, Fig. 6 and those of analysis results in Fig. 3, Fig. 4. The reason is that there was a slight time lag between the actual measurement and the analysis. At the time that seems to be the extruding timing, two peaks were observed. The time corresponding to the second peak is the timing of the ejection. On the other hand, the time corresponding to the first peak was 0.018 seconds earlier on average than that of the second peak. Even if curing time changed, the first peak height did not change significantly. Therefore, we assumed that the first peak was caused by hydraulic surge pressure, which occurred by hydraulic valve switching. For that reason, we evaluated the second peak as ejection force. The slide resistance was evaluated by the force, which generated

by dry run after actual casting operation. The mean value of the slide resistance was 26,702 N. As the measurement results shown in Fig. 6, the force generated on each ejector pin was observed. As curing time increased, the force generated on each ejector pin became larger.

3.3 Comparison of analysis and measured results about release force and the force generated on each ejector pin

The difference rate, % between the value of the analysis result and that of the measurement result was defined by the following eq. (9).

$$\begin{aligned} \text{Difference rate, \%} &= (\text{analysis value} \\ &\quad - \text{average measured value}) \\ &\quad \times 100 / \text{average measured value} \end{aligned} \quad (9)$$

Fig. 7 Comparison of release force between analysis and measurement.

Table 3-1 Difference rate, % of release force and force generated on each ejector pin between analysis value and average measurement value.

Curing time(s)	Difference between analysis and average measurement(%)						
	Release force	Force generated on each ejector pin					
		Site①	Site②	Site③	Site④	Site⑤	Site⑥
8	+28	+3380	-16	-68	+46	+130	+8
10	+48	+3070	-14	-15	+45	+127	+5
12	+65	+3034	-1	+39	+52	+124	+5

Table 3-2 Difference rate, % of release force and force generated on each ejector pin between analysis value and measured value obtained by adding 3σ to the average.

Curing time(s)	Difference between analysis value and measured value obtained by adding 3σ to the average (%)						
	Release force	Force generated on each ejector pin					
		Site①	Site②	Site③	Site④	Site⑤	Site⑥
8	-10	+1674	-30	-72	+18	+107	-7
10	-5	+1469	-27	-24	+26	+113	-3
12	+8	+1787	-13	+24	+29	+99	-3

※ σ : Standard deviation

Figure 7 shows the comparison of release force between analysis and measurement. The variation of the measured values is shown by $\pm 3\sigma$. Here, σ is standard deviation. Table 3-1 shows the difference rate, % of the release force and the force generated on ejector pin between analysis and average measurement value. Table 3-2 shows the difference rate, % of the release force and the force generated on each ejector pin between analysis value and measured value obtained by adding 3σ to the average. The reason in comparison with average $+3\sigma$ value is that we assume a design in consideration of the upper limit of dispersion in practical use. As for the release force, from the comparison results, the difference rate, % between the analysis and the

Fig. 8 Comparison of force generated on each ejector pin between analysis and measurement.

Fig. 9 Correlation of force generated on each ejector pin between analysis and measurement.

measurement average value was within $+28$ – $+65\%$. The difference rate, % between the analysis and average $+3\sigma$ value was within -10 – $+8\%$. As the reason that analysis value became larger than that of measurement, the following two reasons will be considered. The first reason will be that it is difficult to remove a surge pressure at the time of measurement, and measurement accuracy decreases by it. Another reason will be that the analysis input value of the coefficient of friction μ includes a problem because the coefficient of friction between mold and die-cast product at the time of ejection is not still clear enough. Concerning the effect of curing time to the release force, it was confirmed that release force became larger with the increase of curing time in both analysis and measurement results. Figure 8 shows the comparison of the force generated on each ejector pin between the analysis and measurement results. Here, we showed the dispersion of the measured value in $\pm 3\sigma$. Figure 9 shows the correlation of ejector pin force between the analysis and measurement results. From the results of Fig. 8, Table 3-1 and Table 3-2, it was found that the force generated on each ejector pin could be predicted by analysis except for the site ① and the site ⑤. The analysis value tended to be larger than the measured one in site ⑤. Similar to the effect of curing time on the release force, it was confirmed that the force generated on each ejector pin

Fig. 10 Positional image of ejector pin and die-casting just before ejection (only ejector pins 1 to 6 are displayed).

became larger with the increase of curing time both analysis and measurement results, too. However, the measured value in site ① was about 100 N, and very small compared with the analysis value. The reason for this is as follows. The measurement was carried out repeatedly, and the tendency did not change. We judged that the load sensor installed in site ① did not have the abnormality, because the casting pressure generated on ejector pin was measured correctly from an injection start of the casting to just before ejection. Therefore, we assume the difference is caused by the analysis model. Figure 10 shows the image diagram showing the positional relationship of ejector pins and die-casting just before ejection. In the casting process until just before ejection, thermal deformation is caused by thermal shrinkage of die-casting product after the solidification. Due to the deformation, it was confirmed by analysis that the dent of ejector pin in die-casting was separated from ejector pins just before ejection. The analysis result of the product deformation with respect to ejection direction just before ejection shows that the value of the product deformation at site ① was 0.35 mm. On the other hand, the values of the product deformation at the sites ②–⑥ were within 0.18–0.32 mm. It was confirmed that the deformation value at site ① was the largest of the six sites. Therefore, in analysis, the time that the ① ejector pin starts touching the product is the latest in six sites at the time of ejection. Furthermore, in the real phenomena, the friction transits from static friction to dynamic friction in ejection process, and the friction coefficient decreases.⁸⁾ However, the value of the dynamic friction coefficient in die-casting has not been enough investigated and reported. Therefore, in this analysis model, a static friction coefficient is used, and the effect of dynamic friction is not taken into account. However, in the real phenomena, it is estimated that release force decreases by transiting from static friction to dynamic friction in ejection process. For these reasons, we assume that release force had already decreased in the die-casting when the ejector pin ① began to touch the product. In addition, the temperature histories of the cavity insert die and its effect on the die thermal strain in curing time are not considered in this analysis model. We assume this is the one of the causes of the difference. In both release force and the force

generated on each ejector pin, the differences were observed for force history, when we compared Fig. 5 with Fig. 3, or Fig. 6 with Fig. 4. About this difference, we assume that the reason is ejector operation involves a dynamic phenomenon of hydraulic pressure, whereas this analysis solves a static balance, and is a static model. This is the problem that we should improve in the analysis model in future. From the result of Fig. 9, the correlation factor r was +0.77. And it was confirmed to be correlative from the result of the scatter chart. It was confirmed that the analytical model is a model that can evaluate the effect of curing. In this study, as a result, the analysis results could be almost estimated within the error of $\pm 30\%$ compared with measurement average $+3\sigma$ values in the evaluation of release force and the force generated on each ejector pin. Therefore, in evaluation of ejection force for die-castings by FEM thermal stress analysis with elasto-plastic-creep model, we successfully confirmed the validity of the analytical model and the analytical method in practical use. We believe that this analysis is the level that can apply in a die-casting ejection design. In future, we will improve the analysis model of friction and/or the measurement accuracy for prediction precision.

4. Conclusions

- (1) Release force and the force generated on each ejector pin were analyzed by FEM thermal stress analysis with elasto-plastic-creep model, and the validity was evaluated by the measurement using aluminum die-cast products: BRACKET ENGINE MOUNTING. As a result, the difference rate, % between the analysis and the measurement average value was within $+28$ – $+65\%$. The difference rate, % between the analysis value and the measured value obtained by adding 3σ to the average was within -10 – $+8\%$.
- (2) As for the force generated on each ejector pin, the correlation factor r between the analysis and measured values was +0.77, and it was confirmed to be correlative from the result of the scatter chart. However, the measured value in site ① was very small compared with the analysis value. We assume this difference is caused by the product deformation just before ejection. And as the cause of this difference, we assume that the dynamic friction, the temperature histories of the cavity insert die, and its effect on the die thermal strain in curing time are not considered in analysis model.
- (3) Effects of curing time on release force and the force generated on each ejector pin were evaluated by comparison and validation between the analysis and measured results. As a result, we confirmed that it could be evaluated by the analytical model that release force and the force generated on each ejector pin become larger with the increase of curing time.
- (4) For a die-casting design, the analyses with elasto-plastic-creep model were almost estimated within the error of $\pm 30\%$ compared with the measurement average $+3\sigma$ values. And we successfully confirmed the validity of the analysis model.

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