Invited Paper

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Shape Optimization of Plunger Tip Based on Linear Cumulative Damage Law

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Abstract

Die casting is suitable for mass production and has the advantage of being able to yield complicated shapes accurately. One disadvantage of die casting for high-speed injection molding is the occurrence of blow holes. To avoid the occurrence of blow holes, the shape of a plunger tip with the curved surface is very effective in actual manufacturing facilities. However, this shape is very weak to wear-out. Therefore, this plunger tip is highly breakable. In this paper, an optimum shape of the plunger tip is calculated by utilizing the real – coded genetic algorithm incorporating a FEA and a CFD simulator with stress analysis and a linear cumulative damage law. Then, the fatigue strength of the plunger tip is evaluated, and it is clarified that the optimum shape is superior in strength for reducing the amount of entrained air and preventing the occurrence of blow holes in die-cast products.

Keywords: Die casting, Process control, Optimization, Fatigue analysis, CFD simulator

1. Introduction

Recently, die casting is used for the manufacture of various products such as automobiles and mechanical parts. Die casting is a kind of the cast method which a large amount of castings of high accuracy with smooth surface are produced by press fitting the melting metal to a precise metal mold. The metal mold of die casting is made by mainly hot work tool steel, it is installed in the die cast machine, and castings is casted by press fitting the metal of melting aluminum alloy, zinc alloy, magnesium alloy, and copper alloy. This process is partially automated, and the cast method appears appropriate for high productivity mass production. Die casting has better dimensional accuracy than other castings and its strength is high, the cast surface is smooth and beautiful, requiring a little further machine work. Die casting cause an entrained air in the sleeve because a melting hot water is filled by the high speed and the high pressure. Therefore, there is the disadvantage of causing the decrease in product strength because of the occurrence of the defect such as blow holes.

It is thought that it is necessary to change the plunger tip shape as a method of reducing defects in die casting. The plunger tip is located at the end point of the plunger. There is a problem of obtaining a shape which an initial billow can suppress because immediately after the injection the billow influences the entrainment of air in the sleeve of the die casting.

The proposed tips capable of suppressing initial billow are the linear type tip with inclined plane and the quadratic function tip with curved surface as shown in Fig. 1. [1, 2].

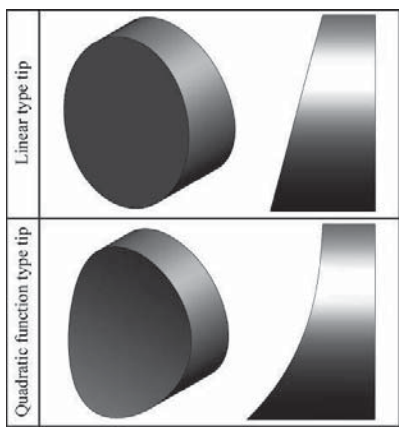

Fig. 1. Linear type tip and quadratic function type tip.

These tips have structural defect that makes them easily damaged by galling with the sleeve and the pressure caused by the injection. As a result, the fatigue life shortens.

The strength of the structures and shapes are evaluated by considering the distortion and stress obtained by analysis using Finite Element Method (FEM). The evaluation measures often used are the peak stress of the maximum Mises stress, the maximum shearing stress, and the mean stress. However the strong shape can be derived for an excessive load when these stresses are used as an evaluation, but it is not necessarily a superior shape in terms of strength from the viewpoint of using it in a medium/long term. Therefore, the method that estimates the damage caused by the use of the repetition in the object is necessary.

In this study, the damage estimation algorithm that estimates the damage caused by the use of the repetition of an object is proposed. Then, this proposed method is applied to die-cast plunger tip. Finally, the die-cast plunger tip that can keep constant strength and reduce the entrained air is designed because the shape to satisfy evaluation criteria of the damage value and the entrained air is calculated by using the real-coded genetic algorithm.

2. Damage Estimation Algorithm

2.1 Damage evaluation using linear cumulative damage law

The linear cumulative damage law assumes that the stress of various amplitudes occurs at random as the sums of the stress of different amplitudes like $\sigma_1, \sigma_2, \dots, \sigma_i$ are individually repeated, the fatigue life is estimated. This method has the advantage that favorable estimate is possible because it is based on the result of fatigue testing of the material. In order to make it a concrete procedure, it is assumed that the occurrence of the stress amplitude is $\sigma_1, \sigma_2, \dots, \sigma_i$ in the structure, and the repeated number of time like $N_1, N_2, \dots, N_i$ from the S-N curve to the rupture is obtained. Then, the damage values when these stress amplitudes are repeated respectively in number of time of $n_1, n_2, \dots, n_i$ are $\frac{n_1}{N_1}, \frac{n_2}{N_2}, \dots, \frac{n_i}{N_i}$. The damage value is obtained by calculating those damage sums of two values. Finally, the damage value is given by Equation (1).

$$D = \frac{n_1}{N_1} + \frac{n_2}{N_2} + \cdots + \frac{n_i}{N_i} = \sum_{i=1}^{k} \frac{n_1}{N_i} \tag{1}$$

If the damage value is 1.0 or more, the fatigue failure is caused. This method is enhanced by the use of the finite element model for structural analysis. The stress value of each node σ_{node} corresponding to the constant load p is necessary for the linear cumulative damage law. Therefore the stress value is calculated by structural analysis. Then, the repeated number of time N_{node} to the rupture corresponding to the stress value in each node σ_{node} is obtained from the S-N curve. The damage value of each node on the finite element model d_{node} is calculated by Equation (2) as the repeated number of time under those loads is *n*.

$$d_{node} = \frac{n}{N_{node}} \tag{2}$$

When the loading condition is changed, the structural analysis is executed again, and the damage value in each node is calculated. The damage value of each node D_{node} is given by Equation (3).

$$D_{node} = \frac{n_1}{N_{1,node}} + \cdots + \frac{n_i}{N_{i,node}} = \sum_{i=1}^{k} \frac{n_i}{N_{i,node}} \tag{3}$$

where *k* is number of stress amplitudes on the linear cumulative damage law.

2.2 Quantitative evaluation of fatigue damage

The damage of the object is evaluated by using the damage value of each node on the finite element model. According to the linear cumulative damage law, the more the damage value closer to 1.0, the more likely the fatigue failure is to occur. Then, it is considered that the node that has the damage value more than the definite value is dangerous, and the total number of those nodes is an evaluation value. Moreover, the damage is evaluated by using the level function like Equation (5) because the change in the number of its total nodes caused by the shape change is considered.

$$D_{eval} = \sum_{i=1}^{j} X_A\left(D_{node}(i)\right) \quad (4)$$

$$X_A(x) = \begin{cases} 0 & (0 \le x < 0.7) \\ 1 & (0.7 \le x < 0.8) \\ 2 & (0.8 \le x < 0.9) \\ 3 & (0.9 \le x < 1.0) \\ 100 & (x \ge 1.0) \end{cases} \quad (5)$$

where j is the total number of nodes on the finite element model.

3. Damage Estimation of Die-cast Plunger Tip

3.1 FEM simulator and simulation condition

The damage estimation algorithm of this proposed method applies to die-cast plunger tip, and damage evaluation has also been carried out.

In the study, the structural analysis software, Solidworks Simulation (Dassault Systèmes SolidWorks Inc.) is used. The schematic diagram of the constraint and loading condition that is the boundary condition of the analysis is shown in Fig .2. The surface of the plunger side becomes a full restraint without degree of freedom because the plunger tip is fixed to the plunger. The surface of the sleeve side becomes a full restraint as well as the plunger side because the frictional influence is disregarded. Moreover, the perpendicular pressure is exerted on the tip by the setting of the load condition so that the pressure and galling on the tip are reproduced.

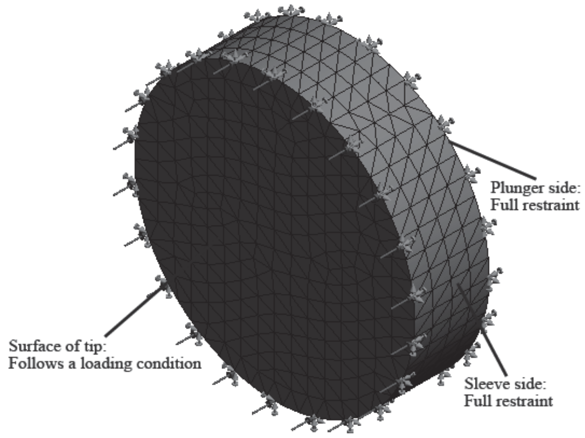

Fig. 2. Boundary condition of plunger tip for FEM simulation.

As a target material of the die-cast plunger tip, hot work tool (SKD61) was assumed. Table 1 shows physical properties used for the simulation.

Table 1. Physical properties of SKD61.

Elastic Modulus $[N \cdot mm^{-3}]$	216000
Poisson's Ratio	0.284
Shear Modulus $[N \cdot mm^{-3}]$	84320
Temperature Coefficient	0.000013
Specific Heat $[J \cdot kg^{-1} \cdot K^{-1}]$	444
Thermal Conductivity $[W \cdot m^{-1} \cdot K^{-1}]$	30.7
Density $[g \cdot mm^{-3}]$	0.007736
Tensile Strength $[W \cdot m^{-2} \cdot K^{-1}]$	1340
Yield Strength $[W \cdot m^{-2} \cdot K^{-1}]$	1147

The S-N curve of SKD61 material used for the damage estimating uses the one open to the public in general [3]. The approximation formula of this S-N curve is given by Equation (6).

$$N = \exp\left(\frac{1267.9 - \sigma}{30.87}\right) \quad (6)$$

where N is number of repeating time until rupture, σ is stress.

An initial pressure value of the loading condition is 60 MPa, and the stress value is increased in step of 60 MPa, the calculation is repeated until becoming 600 MPa that is about half of the value of yield strength. The number of repeating time *n* under each loading condition is 25000 that is the frequency for which the plunger tip made from SKD61 material is generally used. The kind of the stress used is Mises stress.

3.2 Result of damage estimation

The result of the damage estimation algorithm applied to flat tip and linear tip and quadratic function tip is shown in Table 2.

Table 2. Damage estimation of conventional tips.

Tip type	D_{eval}
Flat	8000
Linear	12907
Quadratic function	20318

From the result, flat tip is strongest against the pressure and the galling compared with conventional tips, and it is guessed that linear tip and quadratic function tip are easily damaged. In addition, this proposed method is effective because the superiority or inferiority of strength is correctly evaluated.

4. Optimization of Die-cast Plunger Tip Shape Based on Damage Estimation

4.1 Formulation of the optimization problem

The die-cast plunger shape is optimized based on the damage estimation by an algorithm proposed in Chapter 2. The quantity of air entrainment is calculated by CFD simulator and the damage value is obtained by the damage estimation algorithm, and thus the shape satisfying these evaluation criteria is derived. In this study, the CFD simulator, FLOW-3D (FlowScience Inc.), is used.

The plunger tip shapes of interest in this study are flat type, linear type and quadratic function type with spline curve. This spline curve is controlled by 7 variables shown in Fig. 3.

The constitution of the die and sleeve and the mesh setting depicting the simulation field are shown in Fig. 4, and the mesh parameters are listed in Table 3. The range of the mesh analysis is reduced by half due to shape symmetry. This is helpful in terms of computational time saving, because the shape and movement in the analysis are symmetrical against the YZ plane.

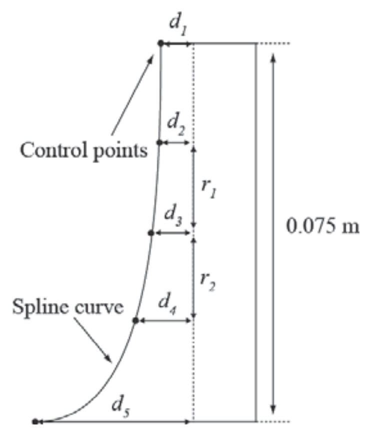

Fig. 3. Concept of optimum tip design: a two-dimensional diagram.

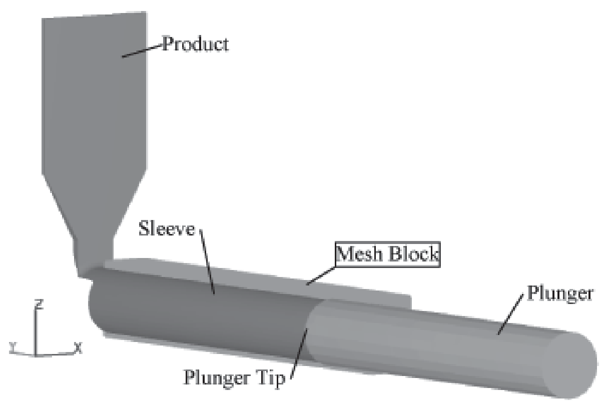

Fig. 4. Mesh setting for CFD simulation.

Table 3. Mesh parameters.

	X	Y	Z
Number of cells	35	350	55
Cell size [m]	0.016	0.016	0.016
Total number of cells	673750		

The air entrainment is quantified by using Equation (7).

$$A = \sum_{k=1}^{n}(V_{ak}F_{fk}V_{fk}V_{ck}) \quad (7)$$

where A is the quantity of air entrained, V_a is the volume of air entrained per unit time, F_f is the fluid fraction, V_f is the volume fraction, V_c is the volume of the mesh cell, and n is the aggregate number of mesh cells. Therefore, the optimization problem is defined by the following equation.

$$\begin{aligned} &Minimize && A(d_1, \dots, d_5, r_1, r_2) \\ &Subject\ to && D_{eval}(d_1, \dots, d_5, r_1, r_2) \le \varepsilon_d \\ & && 1 \le d_1, \dots, d_5, r_1, r_2 \le 30 \end{aligned} \quad (8)$$

where A is the quantity of air entrainment, D_{eval} is the damage evaluation of the plunger tip, ε_d is an upper limit in the damage value. The damage value is adjusted to become a scale almost equal to the quantity of air entrainment because D_{eval} becomes a high value against A. That is, D_{eval} multiplies 10^{-5}. The upper limit is assumed to be a damage value of linear tip ε_d = 0.1291 obtained by analyzing it beforehand.

The real-coded genetic algorithm is applied as a means of obtaining a desired solution of this problem. The optimized calculation is discontinued when the improvement of a solution was not seen and 15th generation passed. The parameter used for the optimized calculation is shown in Table 4.

Table 4. Parameters of Real-coded genetic algorithm.

Number of variable	7
Number of population	20
Number of elite preservation	2
Selection method	Roulette Selection
Crossover method	BLX-α (α = 0.2)
Mutation method	Uniform (0)

4.2 Verification of optimization and simulation results

The plunger tip shape calculated by optimization is shown in Fig. 5.

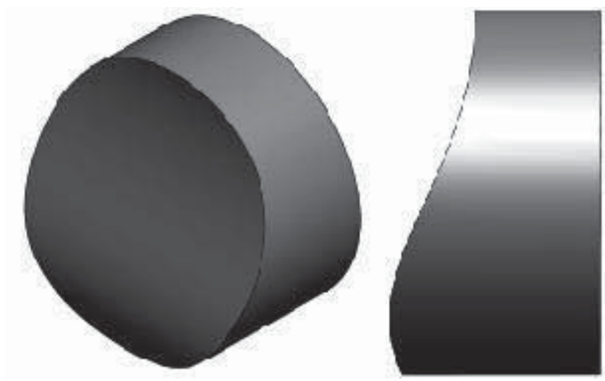

Fig. 5. Optimum shape of plunger tip.

The time required for optimization by the CFD simulator with 2 parallel-ins, was about 143 hours using a PC with an Intel Core2 Quad 2.66 GHz processor. The solution converged after the 38th generation. The values of each variable were d_1 = 6.4, d_2 = 9.9, d_3 = 15.7, d_4 = 21.9, d_5 = 21.3, r_1 = 15.1 and r_2 = 14.9; the quantity of air entrainment was A = 1.7049 x 10^{-8}, and the damage value was D_{eval} = 0.1152.

The simulation results of the optimum shape and flat tip are shown in Fig. 6 and Fig. 7. From these results, it can be confirmed, concerning the optimum tip, that the occurrence of the entrained air is suppressed but for the flat tip, the entrained air occurs sideward on the sleeve.

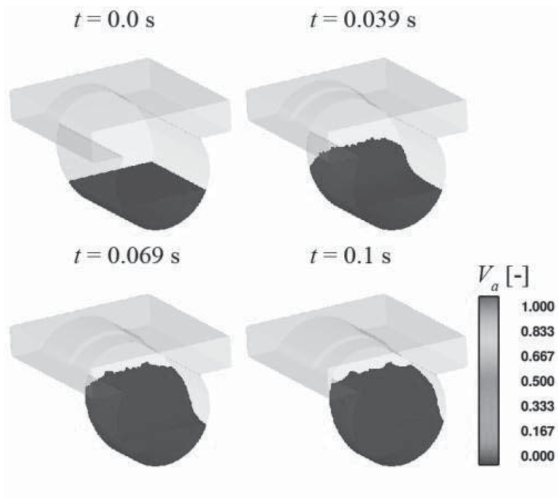

Fig. 6. Simulation result using the optimum tip shape.

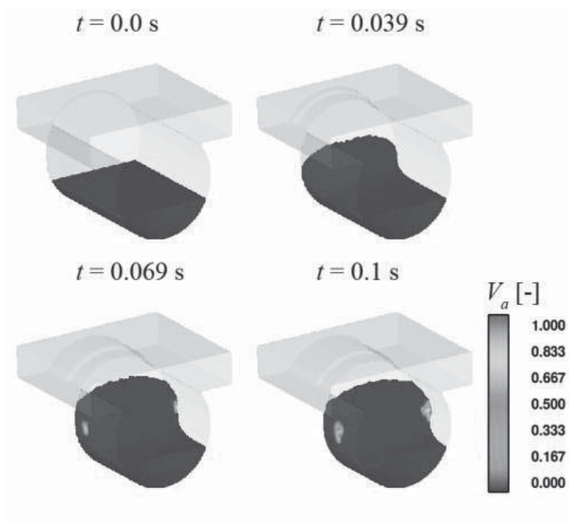

Fig. 7. Simulation result with flat tip.

The values of each evaluation of the optimum shape, the flat type, and the quadratic function type are listed in Table 5 for comparison. As a result, the derived optimum shape can reduce the quantity of air entrainment the most, and this shape's strength is superior because the likelihood of damage is improved from the linear type tip. Finally, the derived optimum shape of the end point of the linear tip becomes round without any local contact with the sleeve.

Table 5. Quantity of air entrainment and damage evaluation.

Tip type	A	D_{eval}
Optimum	1.7049×10^{-8}	0.1152
Flat	0.0805	0.0800
Linear	0.0210	0.1291
Quadratic function	0.0060	0.2032

5. Conclusion

In the present study, the damage estimation algorithm to which the damage caused because an object is repeatedly used is estimated by structural analysis and the linear cumulative damage law was constructed. This proposed method was applied to the die-cast plunger tip, the damage evaluation was done, and the effectiveness was evident. The die-cast plunger tip that can keep constant strength and reduce the entrained air was derived with the shape satisfying evaluation criteria of the damage value. The entrained air was calculated by using the real-coded genetic algorithm. It is evident that the defect of the product in the die-cast can be decreased.

References

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Biography

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