# Modeling of Variation on Oil Quenching with Iterative Quenching Using Cellular Automaton

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The vapor film collapse that occurs in the quenching process is complicated and unstable, these affects the heat treatment quality and its distortion. In order to incorporate it into the MBD technology required these days, it is necessary to predict the quality of heat treatment by CAE, shorten the product development period. However, in the past day, in order to formulate the vapor film collapse on a simulation, it was necessary to perform an exceptionally large amount of computational calculation (CFD), because of a problem in computer resources and the model of vapor film collapse. In addition, this phenomenon has a complexity behavior of the phenomenon in iterative processing in mass production, which also complicates the calculation. The vapor film collapse phenomenon was visualized by using cellular automaton simulation it includes the phenomena of "Vapor film thickness", "Flow disturbance", "Surface step of workpiece". In this study, the Markovian property of vapor film surface vibration was clarified, and the heat treatment deformation instability of ring-shaped parts due to it was predicted.

***Keywords:*** *quenching distortion, CFD, vapor film collapse, cellular automaton*

## 1. Introduction

To improve the strength and fatigue life of metal parts such as gears, carburized quenching using a liquid quenchant such as oil/water is performed to improve the bending or wear strength. While carburized quenching shows a significant improvement in strength compared to non-treatment parts, poor shape accuracy due to deformation, etc., causing noise during operation. Such deformation is called as heat treatment deformation. Post-processing such as finish grinding is performed to correct heat treatment deformation, but post-processing costs hundreds of billions of yen in Japan [1]. In order to reduce this cost, it is beneficial to predict the tendency and amount of heat treatment deformation in advance and feed it back to the pre-machining shape, and to set the optimum heat treatment deformation through the process[2].

Because of longer heat treatment time, it is often carried out in a mass parts processing and variations in heat treatment deformation occur within the processing lot and between processing lots, which is a process that appropriately considers the heat treatment deformation. It makes process design difficult. In response to the growing expectations for model-based development technology in recent years[3, 4], heat treatment simulation technology has also developed. In this study, in order to carry out a simulation that reproduces heat treatment deformation and its variation within an economically beneficial time, we develop a cellular automaton simulation include vapor film collapse phenomena that simulates a low-dimensional space as film and verify its effectiveness.

## 2. Theory

The vapor film collapse phenomenon and the change in heat transfer coefficient during quenching were described in the cellular automaton according to the contents of the above-mentioned investigation of the mode. Cellular automaton describe the phase of the film covering the surface and the temperature of the surface of the component. With reference to the research results on coagulation by Oono et al.[5], described a similar phenomenon by Wolfram[6] and Paul, G., et.al.[7] , the phase change is in the vicinity of Neumann, which is affected by the cells of interest, up, down, left, and right, and the temperature is up, down, left, and right, as well as the upper right, upper left, and lower right, the vicinity of Moore, which is also affected by the lower left, was adopted. As a result, it is possible to reproduce the state of the gently covered vapor film in which the state of the vapor film changes in a staggered arrangement for the phase.

For the phase, the vapor film stage, boiling stage, and convection stage are set to 0, 1, 2 respectively, and the actual temperature of the surface is described for the temperature. Fig. 5 shows the heat transfer coefficient curve when there are no factors that change the state of the vapor film such as disturbance. It is available from each oil manufacturer and public database. In Japan, it is published on the website of the Japan Society of Heat Treatment Association [8]. $T_b$, which transitions from the vapor blanket stage to the boiling stage, and $T_c$, which transitions from the boiling stage, are defined from the heat transfer coefficient curve, and the transitions are shown in equations (1) and (2). The transition from the vapor film stage to the boiling stage shows the ease of transition. $b$ is shown in (i), (ii) and (iii).

For temperature changes, in addition to heat transfer in the direction parallel to the surface, a Newton cooling term that controls the heat transfer coefficient and quenchant temperature from the surface was added.

Phase Change：

Transition to the boiling stage:

$$S_0^t = 0 \text{ and } \sum_{i=1-4} S_i^t \geq b \text{ and } T_0^t \leq T_b \text{ then } S_0^{t+1} = 1,\ T_0^{t+1} = T_0^t - \alpha \quad (1)$$

Transition to the convection stage:

$$S_0^t = 1 \text{ and } T_0^t \leq T_c \text{ then } S_0^{t+1} = 2,\ T_0^{t+1} = T_0^t - \beta \quad (2)$$

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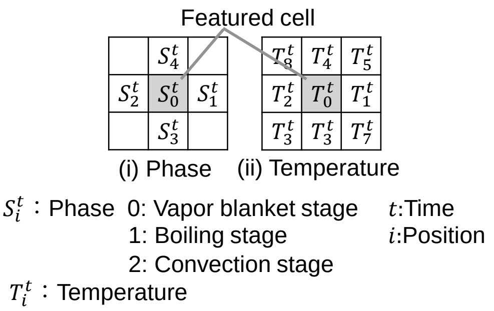


**Fig. 4 Cell automaton of phase and temperature**

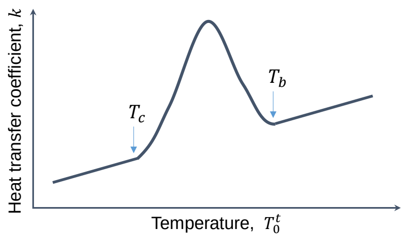


**Fig. 5 Heat transfer coefficient and its parameter in still quenching condition**

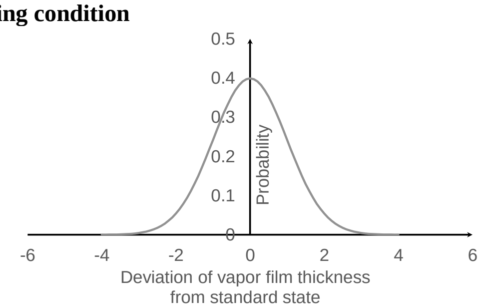


**Fig. 6 Deviation of vapor film thickness from standard stat**

Temperature Change:

$$T_0^{t+1} = T_0^t + \left\{\frac{1}{6}(T_1^t + T_2^t + T_3^t + T_4^t) + \frac{1}{12}(T_5^t + T_6^t + T_7^t + T_8^t) - k \cdot T_e\right\} \quad (3)$$

$\alpha, \beta$ :Latent Heat

$b$ :Factors for vapor blanket corraps

$T_e$ :Quenchant temperature

$T_b, T_c, k$:Shown in Fig.5,

$k$ is heat transfer coefficient

Vibration of vapor film surface:

The Equation (4) was created by incorporating the fluctuation of the vapor film thickness due to the vibration caused by the surface tension [] and the disturbance of the flow. $\gamma$ is a factor that vibrates the vapor film, which is determined by the aspect of the flow. A normal distribution is shown as shown in Fig. 6. N has a probability distribution with Markov property with previous all time steps and also has continuity with Moore neighborhood cells.

$$b = b_0 + \sum_t \gamma N(\mu, \sigma^2) \quad (4)$$

$\gamma, \mu, \sigma$ : Control parameter for vapor film vibration

Reduction of vapor film thickness due to edge shape:

At the edge, the vapor film thickness becomes thinner due to the influence of surface tension at the gas-liquid interface of the vapor film, and the vapor film collapse is promoted [10]. This is described by Equation (5).

$$b = b_0 + \delta \quad (5)$$

$\delta$: Vapor film collapse due to edge

Effect of surface tilt:

Equation (6) describes that the air remaining in the vapor film and the hardened oil stays on the lower surface and the cooling is hindered.

$$b = b_0 - \varepsilon\cos(\theta)\,|_{\theta \le 0} \quad (6)$$

$\theta$ :Tilt of surface (Horizontal:0, downward is minus)

## 3. Experimental Procedure

We verified whether the cooling state could be reproduced using a cellular automaton whose constitutive equation was examined. Using Microsoft Excel 365 and Visual Basic for Applications, the state transition from $t$-1 step to $t$ step over a unit time is described in Equation (1) to (6). When the calculation in all one step is completed, the result in $t$ step is transferred to the worksheet in $t$-1 step, and the calculation of the next unit time is executed again. The calculation of the number of steps up to the predetermined finish time was completed, and when the end time was reached, the calculation was completed.

Since the calculated cooling curve shows the heat flux per unit area, it can be treated as the heat transfer coefficient as it is by correcting the curvature of the surface and differentiating it with time. Therefore, the heat transfer coefficient of each part was calculated from the calculated cooling curve.

In order to compare with the calculation results, the cooling state was calculated with various coolants and test pieces, and the heat treatment deformation was calculated especially under the asymmetrical boundary conditions where the surroundings were disturbed.

In order to verify the validity of the method, we observed the quenching state of the ring part with reference to the state of the collapse of the vapor film on the gear part and simulated the same situation by the cellular automaton method of this research. Using the results, heat treatment deformation was calculated.


**Fig. 7 Comparison of cooling curve with experimental**

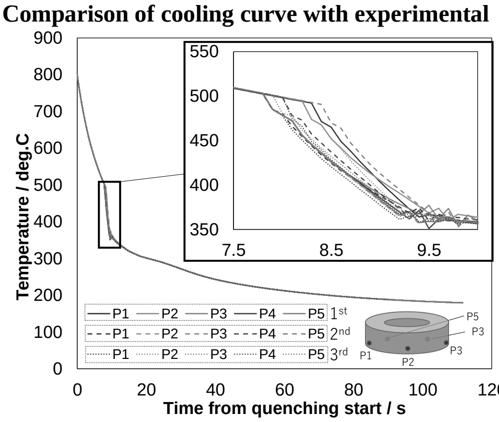


**Fig. 8 Comparison of cooling curve in three times calculation**

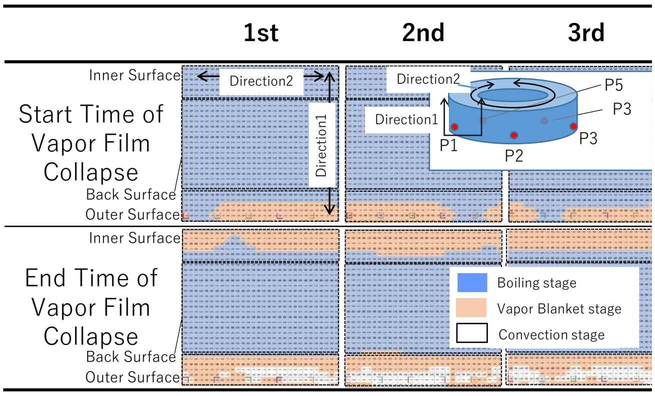


**Fig. 9 Vapor film collapse mode in three times quenching**

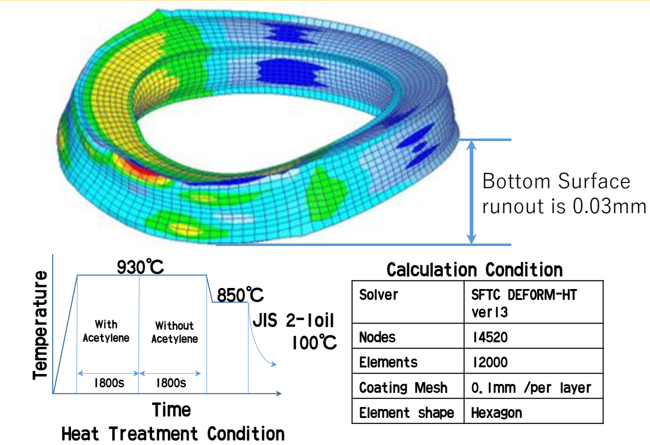


**Fig. 10 Vapor film collapse mode in three times quenching**

## 4. Result

Fig. 7 shows the collapse of the vapor film when a ring-shaped gear is quenched. A vapor film collapse has started from a part of the side surface, and the collapse is spreading to both sides. At the inner diameter and the back surface, vapor film collapse progressed at a later stage. The starting point of collapse was not constant in repeated quenching.

Three times calculations were performed, and the cooling curve at the lower part of the outer periphery of each ring are indicated by P1-P5 in Fig. 8. The cooling curves were almost the same for quenching at 15 curves (5 points × 3 times). However, there were 15 differences in the start timing of vapor film collapse, the cooling curve at the boiling stage, and the subsequent cooling curve. In particular, the range of variation in the cooling time of P1-P5 was almost the same in the three quenching cycles, but the cooling order varied among the three quenching cycles.

Fig. 9 shows the state of the vapor film collapse on the surface around the ring shape obtained by three cooling calculations. At the beginning of the collapse of the vapor film. The location of the collapse of the vapor film at the beginning of the collapse varied with three quenching cycles, but the collapse shape around the beginning of the collapse became similar. The vapor film collapse occurred first on the outer surface, and then on the inner surface. This is thought to be due to the fact that the outer circumference is convex outward, so cooling occurs first.

Fig. 10 shows the results of heat treatment deformation calculations for the 1st specimen based on these results. The amount of deflection of the ring-shaped part was 30 µm, and the part with large deformation was the part where the first vapor film collapse occurred.

## 5. Conclusion

By using a cellular automaton using simple parameters, it was possible to obtain the heat transfer coefficient, vapor film collapse mode distribution during quenching and quenching deformation. This may allow us to describe various phenomena related to heat treatment variations in a wider variety of ways. In the future, we would like to improve this cellular automaton so that it can directly correspond to the actual heat treatment conditions, and also make it possible to calculate fluctuations in the quality of repeated heat treatments and the quality distribution in the packaging.

## References

[1] Kinki Bureau of Economy, Trade and Industry, By simulation utilization technology Development of advanced heat treatment method, https://www.chusho.meti.go.jp/keiei//sapoin/portal/seika/2006/18-40-16-5.pdf : May, 2022

[2] Brinksmeier, E., Lübben, T., Fritsching, U., Cui, C., Rentsch, R., Sölter, J., Distortion minimization of disks for gear manufacture, *International Journal of Machine Tools and Manufacture*, 51(4), 331-338, 2011

[3] Fujikawa, S., Model Based Development in Mazda, *Mazda Technical Review*, 31, 2013, 44-47

[4] Xingui He, Ertian Hua, Yun Lin and Xiaozhu Liu, MBD Based Automotive Products Process Planning Technology, *Applied Mechanics and Materials*, 88-89, 570-575, 2011

[5] Oono, Y. and Puri, S., Computationally efficient modeling of ordering of quenched phases. *Phys. Rev. Lett.*, 58(8), 836-839, 1987.

[6] Wolfram, S., *A New Kind of Science*, Wolfram Store, 2007

[7] Paul G., Seybold A B E, Matthew J. O'Malley A, Lemont B., Kier C and Chao-Kun Cheng, Cellular Automata Simulations of Vapor–Liquid Equilibria, *Australian Journal of Chemistry*, 59(12) 865-868, 2006

[8] Japan Society of Heat Treatment, Quenchant Database for Heat Treatment Simulation, https://jsht.or.jp/study/ : May, 2022

[9] Kanatani, K., Interfacial instability induced by lateral vapor pressure fluctuation in bounded thin liquid-vapor layers, *Physics of Fluids*, 22, 1-38, 2009

[10] Abe, Y., Matsukuma, Y.; Tochio, D., N Numerical Simulation of Vapor Film Collapse Behavior on High-Temperature Droplet Surface with Three-Dimensional Lattice Gas Cellular Automata, *Transactions of the Atomic Energy Society of Japan*, 7(4), 321-327, 2008