NADCA DIE CASTING CONGRESS & EXPOSITION, (2018), Transaction No. T18-012



# Evaluation of Heat Checking of Molds through Flow and Solidification Simulation

N. Umemori, M. Kawano, T. Masuda (Daido Steel Co., Ltd.)

## ABSTRACT

Generally, the major failure modes of die casting molds are heat checking, soldering and gross cracking. Our steel manufacturer conducts researches into the influencing factors of each failure mode by performing die casting tests and numerical analyses. In addition, the appropriate steels[1), 2)], heat treatment, surface treatment and repair materials[3)] for die casting are developed to suppress the occurrence of initial damage on molds. This study shows thoughts of influential factors and numerical analyses of heat checking through flow and solidification simulation. Moreover, versatile simulation of initial crack prediction was derived by evaluating the area and the occurrence of heat checking during die casting tests.

1) Main material characteristics which make an effect on heat checking resistance are proof stress and thermal conductivity of mold steel.
2) Proof stress at maximum temperature can be higher by raising hardness of mold steel at room temperature.
3) Thermal stress becomes lower by increasing thermal conductivity of mold steel.
4) The lower ratio of thermal stress divided by proof stress can extend the occurrence of heat checking.

## INTRODUCTION

With the expanding demand of high fuel economy to meet emission regulation, automakers are pursuing light weight vehicles. To achieve the weight reduction of vehicles, it is projected increasing number of aluminum die castings will be applied[4)]. Generally, heat checking is the major failure mode of die casting molds. When we look at the failure mode of die casting molds as shown in Fig. 1, heat checking counts almost 78 %[5)]. The heat checking causes water leak or the patterns of heat checking are transferred to the die casting parts. Therefore, to maintain the surface quality of the parts, molds are repaired by welding or replacing to a new one. Initial crack prediction is important on the plan of maintenance and order of molds. However, conventional prediction precision is not high because it does not consider flow and solidification damage of mold surface. Moreover, it is not necessarily clear that the relation between the material properties and damages of molds. In these circumstances, we have conducted the die casting tests on systematically changed material properties by using an actual die casting machine. In this paper, it shows thoughts of influential factors to heat checking. And it evaluated versatile simulation of initial crack prediction derived through flow and solidification analysis.

 

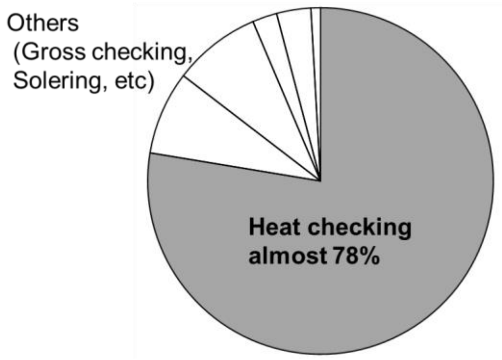


Fig. 1 Failure modes in die casting molds.

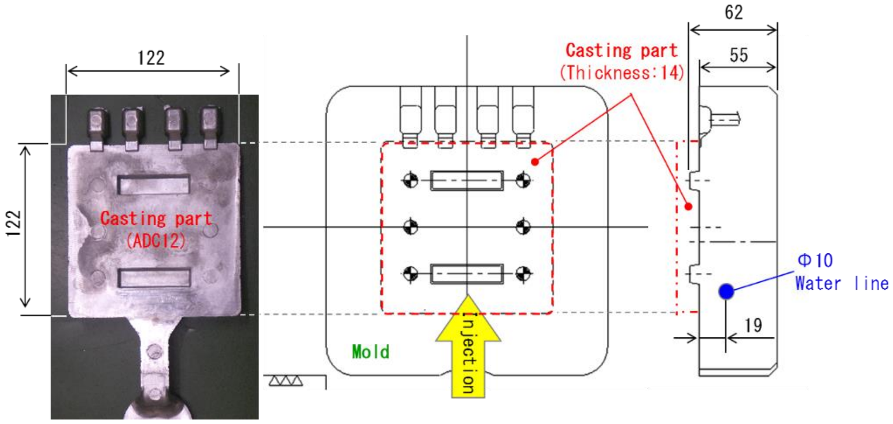


Fig. 2 Shape of test mold.

## DIE CASTING TESTS

### TESTS PROCEDURE

The chemical composition of mold steels used in the tests is shown in Table 1. Steel A is H13. High temperature strength of steel B is same as steel A but hardenability and thermal conductivity is higher than steel A. High temperature strength and thermal conductivity of steel C is much higher than steel A and B.

The test block of these mold steels sized 210 x 205 x 65 mm were quenched from 1030 ° C (1886 ° F) by rapid cooling rate and then tempered to 38, 43 and 48 HRC. The steel A of 43 HRC only was quenched by both rapid cooling rate and slow one. After tempering, the mold of Fig. 2 was made from the block. The test was carried out by using 135 ton actual die casting machine: TOSHIBA DC-135JT. Test mold weighted 18 kg. It has two projections sized 50 mm width and 7 mm height for easy crack initiation. The aluminum cast was 122 mm square and 12 mm thick weighted 600 g. The conditions using on die casting test are shown in Table 2. Molten aluminum alloy, ADC12, was injected to the mold through gate with 54 m/sec and the cycle time was 28 sec including 3 sec spray time[2]. The surface temperatures of depth 1 mm of molds were measured at 6 places by sheathed thermocouple of diameter 1.6mm.

In this test, heating and cooling to mold were promoted in order to be easy to occur heat checking due to higher thermal stress[6]. The temperature of molten aluminum is higher from 30 to 60 ° F than general temperature to strengthen compressive stress on the surface of mold. Moreover, the area and thickness of aluminum cast created larger than general one in terms of thermal capacity. On the other hand, the spray time was lengthened 3 second to increase tensile stress on the surface of mold. After casting, heat checking was observed by dye penetrant testing.

Table 1 Chemical composition of steel A, B, and C (mass%).

| | C | Si | Mn | Cr | Mo | V | Comments |
|---|---|---|---|---|---|---|---|
| Steel A | 0.39 | 1.0 | 0.4 | 5.2 | 1.2 | 0.9 | H13 |
| Steel B | 0.36 | 0.5 | 0.7 | 5.5 | 1.2 | 0.6 | |
| Steel C | 0.33 | 0.1 | 0.6 | 5.5 | 3.0 | 0.9 | High quality steel |

Table 2 Conditions of die casting test.

| Items | | Conditions |
|---|---|---|
| Al alloy | | ADC12 |
| Molten alloy temperature | | 973 K (1292 °F) |
| Cast | Weight | 600 g |
| | Size | 122 mm×122 mm×14 mm |
| Injection velocity | Low | 200 mm/s |
| | High | 1600 mm/s |
| Pressure | | 65 MPa |
| 1 cycle | Whole time | 28 s |
| | Solidification | 8 s |
| | Air blow | 0.5 s |
| | Spray | 3 s |
| | Air blow | 1.5 s |
| Water cooling | Temperature | 298 K (77 °F) |
| | Volume flux | $1.83\times10^{-4}$ $m^3/s$ |

MICROSTRUCTURE OF MOLDS

Microstructures of steel A, B and C are shown in Fig. 3. These hardness are 43 HRC. The grain size of austenite in steel B was only larger than others because steel B had lower V and also had lower VC precipitate of stopping grain boundaries during quenching. The microstructure of rapid cooling rate in the quenching of all steels was martensite. However, the microstructure of slow cooling rate of steel A was martensite and bainite.

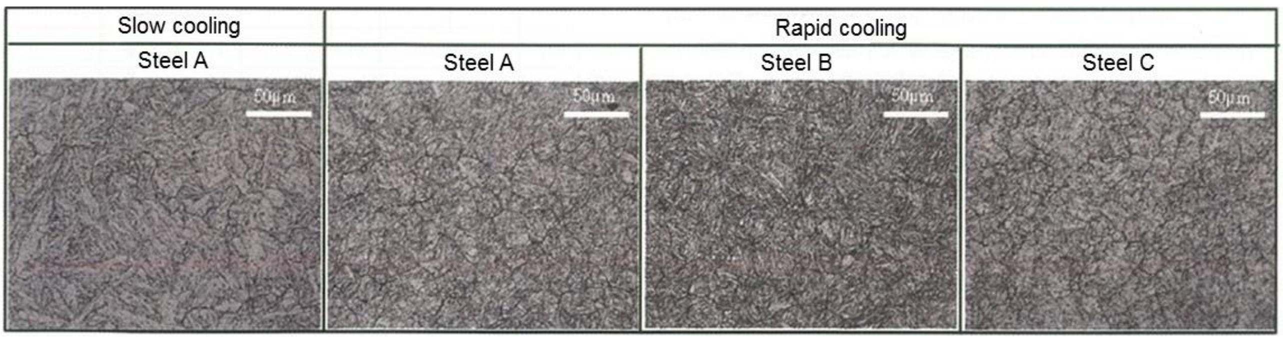


Fig. 3 Microstructure after quenching and tempering of 43 HRC.

HEAT CHECKING

The molds of steel A, B, and C after 10000 shot casting are shown in Fig.4-6. In all of the steels, heat checking was occurred in the vicinity of the gate of the mold. However, in high quality steel C at high hardness 48 HRC, there was less heat checking and no crack near the center of the designing surface.

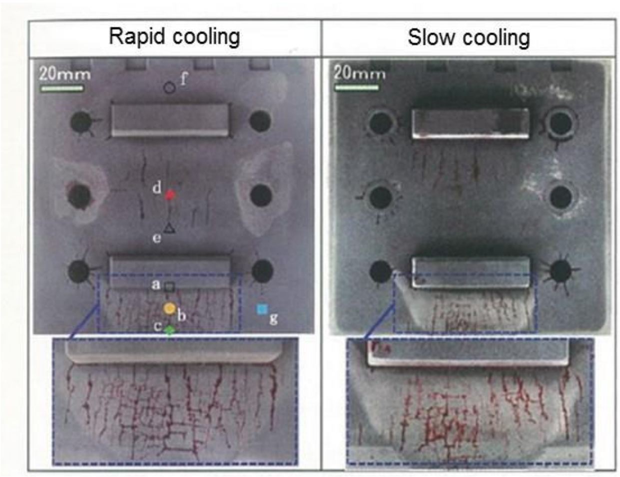


Fig. 4 Heat checking test result (Steel A, 43 HRC).

Table. 3 Material properties (Steel A, 43 HRC).

| | ***Rapid cooling*** | ***Slower cooling*** |
|---|---|---|
| *Level of damaging of mold* | *4* | *4* |
| *Impact value (2mm U notch)* | *52 J・cm$^{-2}$* | *21 J・cm$^{-2}$* |

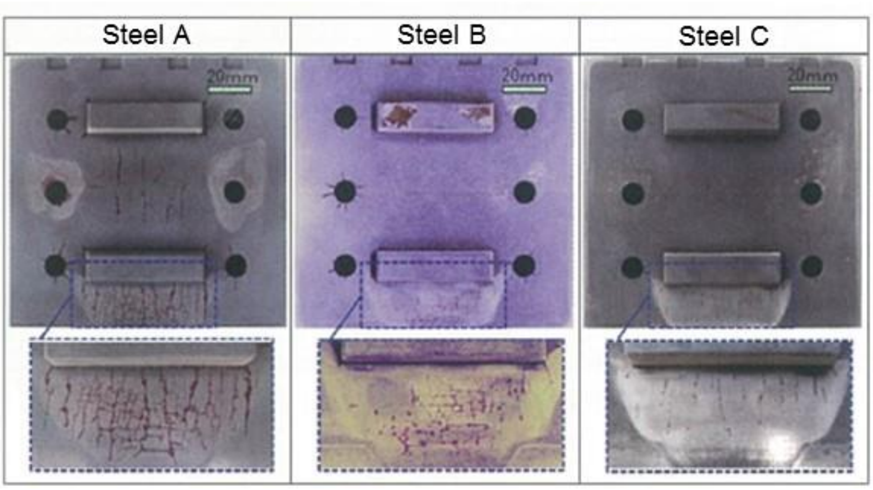


Fig. 5 Heat checking test result (43 HRC).

Table 4 Material properties (Rapid cooling, 43 HRC).

| | ***Steel A*** | ***Steel B*** | ***Steel C*** |
|---|---|---|---|
| *Level of damaging of mold* | *4* | *3* | *2* |
| *Impact value (2mm U notch)* | *52 J・cm$^{-2}$* | *56 J・cm$^{-2}$* | *51 J・cm$^{-2}$* |
| *Fracture toughness* | *96 MPa・√m* | *90 MPa・√m* | *56 MPa・√m* |
| *Reduction of area at 500 °C (932 °F)* | *74 %* | *73 %* | *62 %* |
| *0.2 % proof stress at 500 °C (932 °F)* | *826 MPa* | *827 MPa* | *891 MPa* |
| *Thermal conductivity* | *26 W・(m・K)$^{-1}$* | *29 W・(m・K)$^{-1}$* | *31 W・(m・K)$^{-1}$* |
| *Thermal expansion rate* | *12.0×10$^{-6}$ ℃$^{-1}$* | *12.0×10$^{-6}$ ℃$^{-1}$* | *11.9×10$^{-6}$ ℃$^{-1}$* |

 

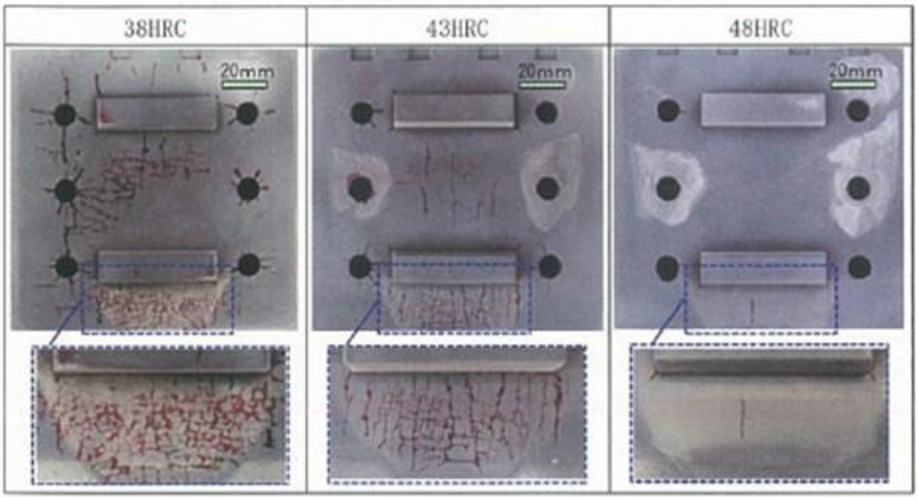


Fig. 6 Heat checking test result (Steel A).

Table 5 Material properties (Steel A, Rapid cooling).

| | *38 HRC* | *43 HRC* | *48 HRC* |
|---|---|---|---|
| *Level of damaging of mold* | *5* | *4* | *1* |
| *Impact value (2 mm U notch)* | *72 J・cm$^{-2}$* | *52 J・cm$^{-2}$* | *27 J・cm$^{-2}$* |
| *0.2 % proof stress* | *696 MPa* | *826 MPa* | *991 MPa* |

## MATERIAL PROPERTIES EFFECT ON HEAT CHECKING

### TOUGHNESS, DUCTILITY

The heat checking resistance and Charpy impact value of steel A with different cooling rate of quenching are shown in Table 3. According to Fig. 4 and Table 3, even if microstructure and Charpy impact value were very different, crack appearance was almost same. Furthermore, the depth of cracking was not also shown a marked difference. Therefore, Charpy impact value was not able to explain an effect on heat checking[7)].

The heat checking resistance and material properties at 43 HRC of steel A, B, and C are shown in Table 4. The value in this table explains a damage level of molds. The lower the value is, the lower the damage is to molds. Steel C had the lowest fracture toughness, but it showed superior performance to other steels. As a result, fracture toughness did not show the relation to heat checking.

Ductility was unable to indicate an effect on heat checking because the reduction of area after fracture of tensile test of steel C which had superior was the lowest in the 3 steels.

### THERMAL CONDUCTIVITY, THERMAL EXPANSION RATE

Table 4 showed that the higher the thermal conductivity of molds was, the lower the occurrence of heat checking was. Because higher thermal conductivity of mold caused to lower thermal stress from contact with molten aluminum and from a spray cooling[7)].

In general, the thermal stress $\sigma$ which works on the surface of an object having a difference temperature in the cross-section surface is calculated by Equation 1 to 3. The $\lambda$ increasing lets $\Delta T$ and $\sigma$ decrease.

The gap of E, $\alpha$ and $\nu$ between each mold steel is narrow. These values are shown in Table 4.

$$\sigma = C \times E \times \alpha \times \Delta T \cdots \text{Eq.1}$$

$$\Delta T = f(\lambda) \cdots \text{Eq.2}$$

$$C = f(\nu) \cdots \text{Eq.3}$$

E: Young's modulus

$\alpha$ : Thermal expansion rate

$\Delta T$: Temperature difference from internal and surface

$\lambda$ : Thermal conductivity

$\nu$ : Poisson's ratio.

## PROOF STRESS AT HIGH TEMPERATURE, MECHANICAL FATIGUE STRENGTH

The heat checking resistance and 0.2 % proof stress at 500 °C(932 °F) of steel A with different hardness are shown in Table.5. Hardness, which is proof stress at high temperature indicated huge effect on heat checking. The reason is that steel C had superior heat checking resistance. It could be explained by high thermal conductivity and high proof stress at high temperature.

The mechanical fatigue strength of steel A and C at room temperature are shown in Fig. 7. These steels had different heat checking resistance, but the rotating bending fatigue strength was same. Therefore, mechanical fatigue strength at room temperature only could not explain relation to heat checking resistance.

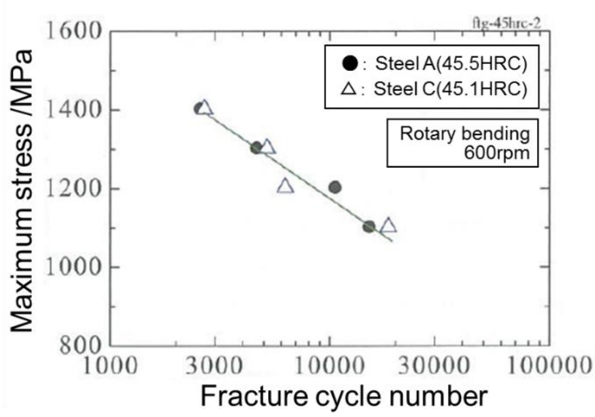


Fig. 7 Mechanical fatigue strength.

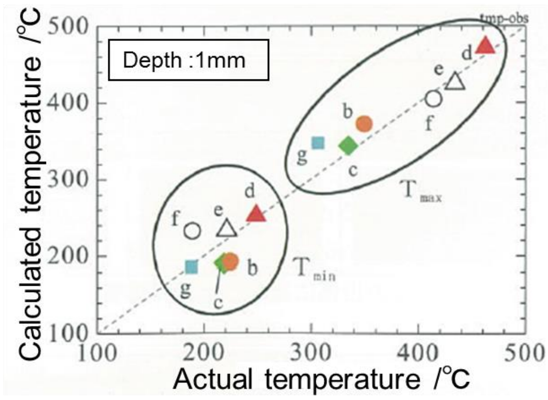


Fig. 8 Actual temperature and calculated temperature.

By these knowledge, main attention properties of mold steels in heat checking during die casting were thermal conductivity and proof stress at high temperature. The difference between each steel of young's modulus, thermal expansion rate and Poisson's ratio which effect on thermal stress were low. That of mechanical fatigue strength was also low. And that of impact value, fracture toughness and ductility seemed directly not to have a correlation to heat checking resistance. Furthermore, softening resistance had little effect on heat checking resistance because the temperature of molds during die casting was not so much high as to be softened hardness of molds[7].

 

## CASTING FACTOR EFFECT ON HEAT CHECKING

Temperature, thermal stress and flow speed were estimated by flow and solidification software MAGMASOFT®. The actual temperature and calculated value on the surface of mold of steel A were shown in Fig. 8. Maximum temperature $T_{max}$ and T minimum temperature $T_{min}$ at 1mm depth from surface were evaluated. Parts b - g in Fig. 8 were correspond to Fig. 4. Maximum error of calculated temperature to actual one was about 20 ° F and the accuracy of estimate temperature was better.

## TEMPERATURE DIFFERENCE FROM INTERNAL AND SURFACE

The load and damage level of parts a - f in Fig. 4 are shown in Table 6. It means the lower of damage level is better. On the damage level 1 of part f, heat checking did not occur. $\Delta T$ did not seem the relation to damage of mold.

$\Delta T$: Temperature difference from maximum and minimum on the surface of mold

## THERMAL STRESS

$\sigma_3^{min}$ which was minimum of minimum principal stress indicated the most relation to damage of mold. $\sigma_3^{min}$ is maximum compressive stress which occurs when it contacts with molten aluminum. This result was corresponding with equation 4[8]. This denominator is equivalent to compressive stress at injection.

$$\text{Mold life} \propto (\sigma_B / (E \times \alpha \times \Delta T)) \cdots \text{Eq.4}$$

$\sigma_B$: Tensile strength at high temperature

$\Delta T$: Temperature difference of molten aluminum and mold

$\Delta P_S$ is $\sigma_1^{max}$ - $\sigma_3^{min}$, $\sigma_1^{max}$ is maximum of maximum principal stress during spray cooling. $\Delta P_S$ was consistent with tendency of the level of damage. In this study, we linked $\Delta P_S / \sigma_y$ to $N_C$. $\sigma_y$ is 0.2 % proof stress at maximum temperature $T_{max}$, and $N_C$ is a shot number of initial crack occurrence. The relation of $\Delta P_S / \sigma_y$ and $N_C$ is shown in Fig. 9. $N_C$ was the results of die casting test, and $\Delta P_S / \sigma_y$ was calculated by flow and solidification software. Moreover, it evaluated the influence of time integration $I_{vf}$ of flow speed when flow speed was changing (v1 > v2 > v3). When $\Delta P_S$ against $\sigma_y$ was higher, initial crack occurred earlier, and the initial crack occurrence became earlier by increasing $I_{vf}$. The change of surface roughness of casting part when steel A is shown in Fig. 10. It is shown part b in front of pouring gate. At 1 shot of casting, the smooth grinding surface of mold was transferred to casting part. At 1000 shot, the surface roughness of mold became about 1.5 times, but did not show heat checking occurrence. At 2000 shot, the roughness became about 4 times, and heat checking occurred.

According to these results, it is confirmed that flow and solidification effect on heat checking occurrence. It is also supposed that heat checking is thermal stress phenomenon accompanied with erosion.

Table 6 Level of damage and load (Steel A, 43 HRC).

| | | a | b | c | d | e | F |
|---|---|---|---|---|---|---|---|
| *Level of damaging of mold* | | 6 | 5 | 4 | 3 | 2 | 1 |
| $\varDelta T = T_{max} - T_{min}$ | | 1 | 3 | 2 | 6 | 5 | 4 |
| *Principal stress* | $\sigma_3^{min}$ | 6 | 5 | 4 | 3 | 2 | 1 |
| | $\sigma_1^{max}$ | 1 | 2 | 3 | 6 | 4 | 5 |
| | $\varDelta Ps = \sigma_1^{max} - \sigma_3^{min}$ | 6 | 5 | 4 | 3 | 1 | 2 |
| *Flow and solidification* | $I_{vf}$ | 4 | 5 | 6 | 3 | 2 | 1 |

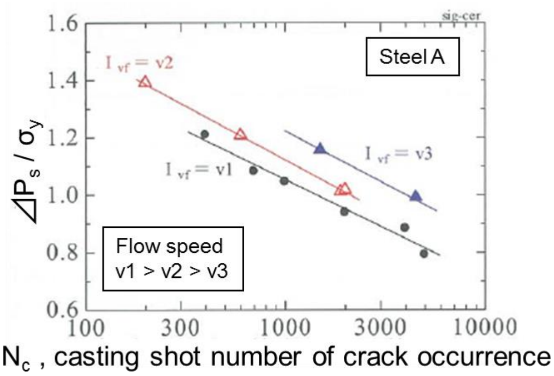


Fig. 9 Influence to crack occurrence on $\varDelta P_S / \sigma_y$ and $I_{vf}$.

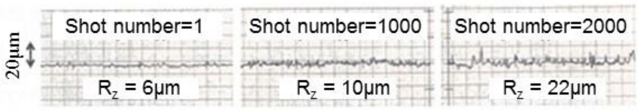


Fig. 10 Change of surface roughness of mold.

VALIDATION OF DAMAGE PREDICTION MODEL

By using these results of this study, $N_C$ was formulated. $\lambda$, $\alpha$, E and $\nu$ also are functions of steel grade and temperature. The damage prediction was confirmed by calculating $N_C$ when steel grade, hardness and mold shape were changed through MAGMASOFT®.

$N_C = f(\sigma_y, \varDelta P_S, I_{vf})$ …Eq. 5

$\sigma_y = f(\text{steel grade, hardness(HRC), temperature})$ …Eq. 6

$\varDelta P_S = f(\lambda, \alpha, E, \nu)$ …Eq. 7

The $N_C$ distribution of steel A, B and C at 43 HRC are shown in Fig. 11. In this figure, the left half is the result of die casting test, and the right half is the result of $N_C$ prediction by flow and solidification software. The results were confirmed that the reproducibility of the difference of steel grade about heat checking resistance. For example, the analysis results which steel C had the lower damage was same tendency as the die casting test. And it was shown that the lower $N_C$ was, the more the damage degree is actually. The $N_C$ distribution of steel A of 38, 43 and 48 HRC are shown in Fig. 12. The analysis results were also reproducible to the hardness difference of mold about heat checking resistance, and higher hardness of mold had lower damage. In Fig. 11 and 12, the maximum difference from actual and calculated value of $N_C$ at the part b which had more damages was up to nearly 25 %, and the prediction precision was better. Even if steel grade and hardness change, it can predict how times die life becomes.

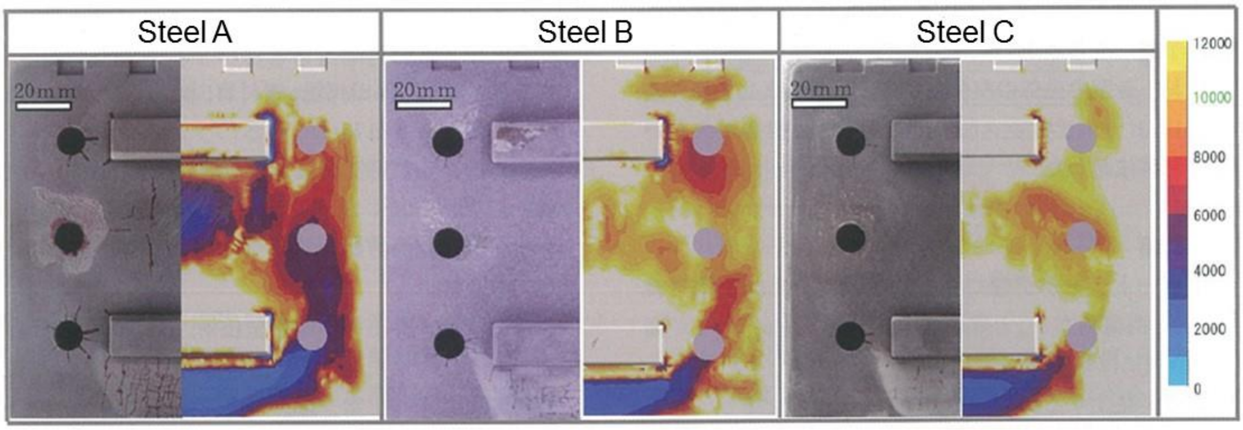


Fig. 11. Influence to $N_C$ distribution on steel grade.

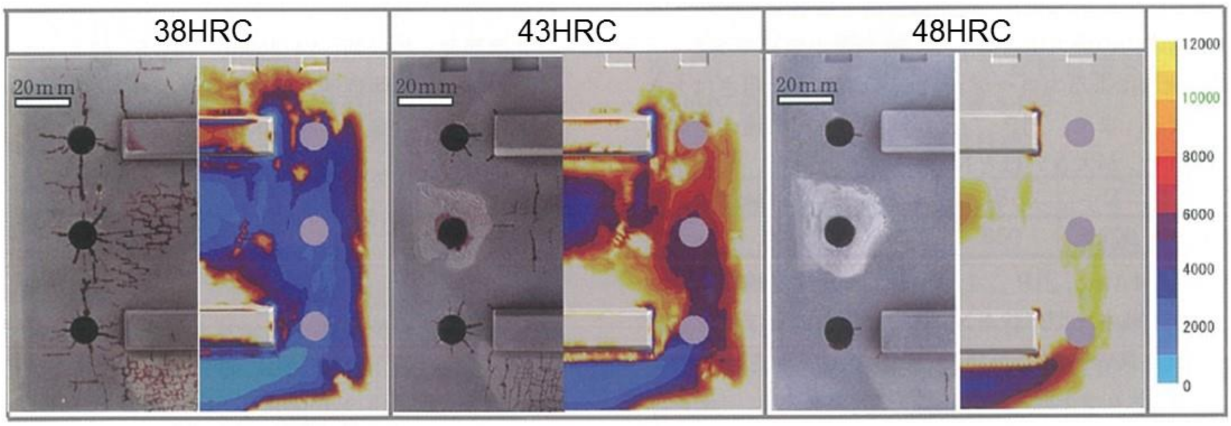


Fig. 12 Influence to $N_C$ distribution on hardness of mold.

## SUMMARY

The material properties effect on heat checking resistance are proof stress $\sigma_y$ at high temperature and thermal conductivity $\lambda$. The higher the $\sigma_y$ and $\lambda$ of mold is, the less heat checking occurrence becomes. Moreover, the higher $\Delta P_S / \sigma_y$ is, the lower the shot number $N_C$ which occurs heat checking become.

$$\Delta P_S = \sigma_1^{max} - \sigma_3^{min}$$

$\sigma_1^{max}$ : maximum principal stress during spray cooling

$\sigma_3^{min}$ : minimum principal stress during contacting with molten aluminum alloy

$N_C$ becomes earlier by increasing time integration $I_{vf}$ of flow speed. It is supposed that heat checking is thermal stress phenomenon accompanied with erosion. Furthermore, through flow and solidification software, we could conduct crack occurrence prediction model of $N_C = f(\sigma_y, \Delta Ps, I_{vf})$ . And this prediction model could predict how times die life becomes when steel grade and hardness are changed.

REFERENCES

1) K. Namiki, M. Kawano, T. Schade: High Thermal Conductivity Steel and its Application to Die Casting Tools, NADCA DIE CASTING CONGRESS & EXPOSITION, (2012)

2) K. Namiki, N. Yokoi, A. Sekiya, T. Yanagisawa: Development and Applications of High Hardenability Special Quality Die Casting Mold Steels, NADCA DIE CASTING CONGRESS & TABLETOP, (2013)

3) N. Umemori, T. Shimizu, T. Masuda, K. Namiki: New Surfacing Material DHW: Repair Welding to Additive Manufacturing in Die Casting Molds, NADCA DIE CASTING CONGRESS & TABLETOP, (2016)

4) H. Kanbe: SOKEIZAI (The Materials Process Technology Center), Vol.57, No.3, P2 (2016)

5) N. Nishi: Journal of the Japan Society for Die and Mould Technology, Vol.17, No.7, P52 (2002)

6) N. Yokoi, K. Inoue: Journal of the Japan Society for Die and Mould Technology, Vol.8, No.23, P150 (2008)

7) M. Kawano, K. Inoue, N. Yokoi: JAPAN DIE CASTING CONGRESS, (2010)

8) Die casting Technologists Hand Book, Journal of NIPPON DIE CASTING CO-OPERATIVE UNION