Technical Paper

Fewer Sand Inclusion Defects by CAE

Kenji Ogawa
Shinya Kanou
Shigeru Kashihara

The use of casting CAE (solidification analysis and fluidity analysis) technologies, developed through previous research activities, has enabled, to some extent, a reduction in both shrinkage cavities, through an improved feeding method, as well as misruns and cold shut defects, thanks to an improved runner.

On the other hand, however, throughout the entire casting process, the work hours required by longer processing time, damage to tools, reworking and other factors caused by inclusions that result in processing defects represent significant problems. CAE technology was previously unable to resolve such problems due to the lack of a function to analyze fluidity and the difficulty in identifying the sources of inclusions. These problems are, in fact, dealt with by intuition and experience.

To solve these problems encountered in casting, an analytical technique is being scrutinized to forecast the behaviors of inclusions in fluids. Parts of the undercarriage of large bulldozers have presented these problems due to machining defects caused by inclusions. This paper reports on the activities, including a reduction in the inclusion defects, machining margins and machining processes for the undercarriage parts by using a technique to forecast inclusions by CAE.

Key Words: *Fluidity analysis, casting CAE, inclusion defect, improvement of machining, computer simulation*

1. Introduction

Inclusion defects of castings are defects such as slag of oxides and other substances generated in the ladle by the reaction and sand of molds and the cores that flake away and are included in molten metal, flowing into products and appearing on the surfaces of parts as non-metallic inclusions. These defects are inflicted by chips during machining and by other causes. The majority of defects during the machining of cast parts are caused by these inclusions, which can be dealt with as follows:

(1) CaSi processing to react, float and remove slag present in the ladle.
(2) Installation of a strainer or filter to float or filter inclusions by rectification.
(3) Installation of spaces (molten metal drains) to drive inclusions out of the runner.
(4) Increase in the machining margins to altogether remove margins containing inclusions by gouging or rough machining (machining with an extra margin).

Verification of the effects and effectiveness of Methods (1) to (3) is difficult and Method (4), which increases the cost but is more reliable, is often used. Consequently, casting materials require considerable machining margins and more machining processes.

This paper studies an analytical technique that can forecast the behaviors of inclusions in molten metal by CAE and introduces related applicatory examples. As a tangible effect of this technique, the quantity of inclusions is reduced by installing a space capable of trapping inclusions more correctly, reducing machining margins and machining with an extra margin for the removal of inclusions.

2. Technique for Forecasting Inclusion Defects by CAE

2.1 Technique for forecasting inclusion defects by CAE

Analysis of the behaviors of inclusions in molten metal must be performed to forecast inclusion defects, since the mere tracing of behaviors on molten metal interfaces, as was previously done, is insufficient. Simulation of inclusions in a fluid was made by placing marker particles in a fluid in a calculation region and by moving the marker particles using a velocity field near the marker particles.

Firstly, the Navier-Stokes motion equation used in calculations of the fluid velocity field is shown in Eqs. (1) and (2) [2-D notation].

$$\frac{\partial u}{\partial t}+u\frac{\partial u}{\partial x}+v\frac{\partial u}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial x}+\nu\left(\frac{\partial^2 u}{\partial x^2}+\frac{\partial^2 u}{\partial y^2}\right)\cdots(1)$$

$$\frac{\partial v}{\partial t}+u\frac{\partial v}{\partial x}+v\frac{\partial v}{\partial y}=-\frac{1}{\rho}\frac{\partial p}{\partial y}+\nu\left(\frac{\partial^2 v}{\partial x^2}+\frac{\partial^2 v}{\partial y^2}\right)\cdots(2)$$

u: velocity in Direction x, v: velocity in Direction y, t: time, ρ: density,
x: distance in Direction x, y: distance in Direction y, p: pressure,
ν: dynamic viscosity coefficient

Next, the velocity of molten metal in a marker particle position can be obtained by linear interpolation from a nearby point of velocity. The velocity in Direction x is illustrated in **Fig. 1**.

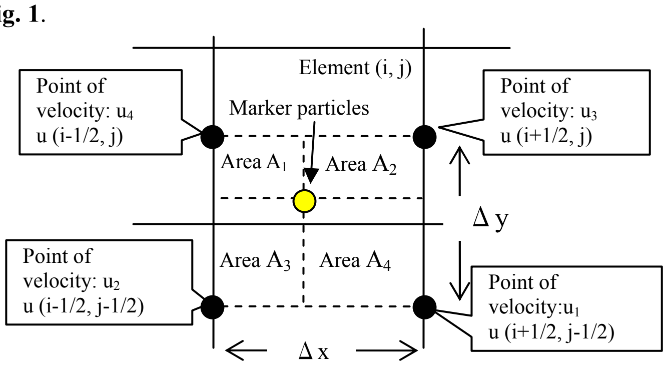

Fig. 1 Relationship of velocity in Direction x interpolated in marker particles in Element (i, j)

The velocity is calculated based on four nearby points of velocity (u_1 to u_4 in **Fig. 1**) relative to the marker particles in Element (i, j). Weighting and a movement formula of the velocity of marker particles for this purpose are shown in Eqs. (3) and (4). (Similar in Direction y also)

$$u=\frac{A_1u_1+A_2u_2+A_3u_3+A_4u_4}{\Delta x\Delta y}\cdots(3)$$

A_1 to A_4: weighting ratios of velocity to marker particles,
Δx: infinitesimal distance in Direction x, Δy: infinitesimal distance in Direction y

$$x^{n+1}=x^n+u\Delta t\cdots(4)$$

x^n: coordinates x at present time, x^{n+1}: coordinates x after Δt seconds

Solving the foregoing equation will obtain the locus of the marker particles. If we presume that molten metal during the initial period of pouring and that flowing on the surfaces of a mold have a high potential to transport inclusions, the marker particles can be said to have been generated in a velocity field in accordance with the following rules:

1) To place marker particles in a random element in advance (**Fig. 2**).
2) To follow the marker particles in molten metal that first passed this region.
3) To calculate the velocity of this particle, based on the point of velocity around the marker particles at each time step and move the particles.
4) To record the path and final point of the marker particles.

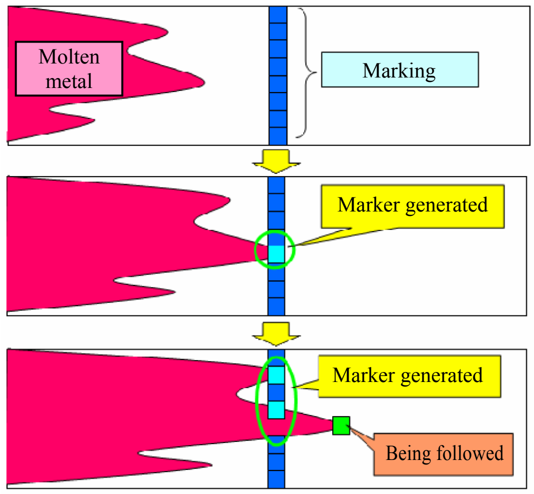

Fig. 2 Function to follow inclusions using marker particles

Figure 3 shows an example of analysis that uses marker particles. As in this example, this technique visualizes the behavior of particles existing in a fluid.

The results of analysis of marker particles (inclusions) applying this analytic technique to a real product are shown in **Fig. 4**. The diagram shows a similarity between the trend of ratios of inclusion defects with real products (the frequency of inclusion defects is higher with Part B than with Part A) and trends of particle distributions in products by analytical results (particles are concentrated more in Part C than in Part D), indicating that real inclusions can be visualized to some extent by using this technique.

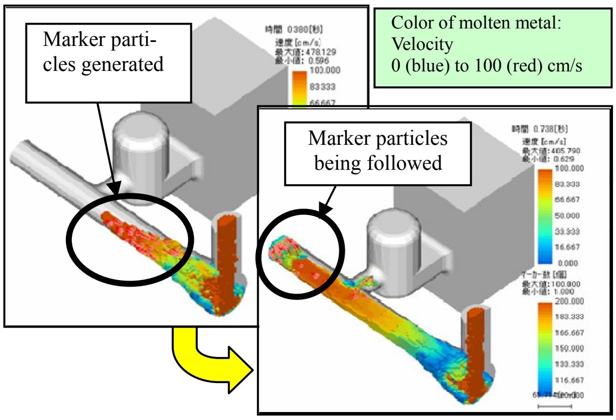

Fig. 3 Example of marker particle analysis

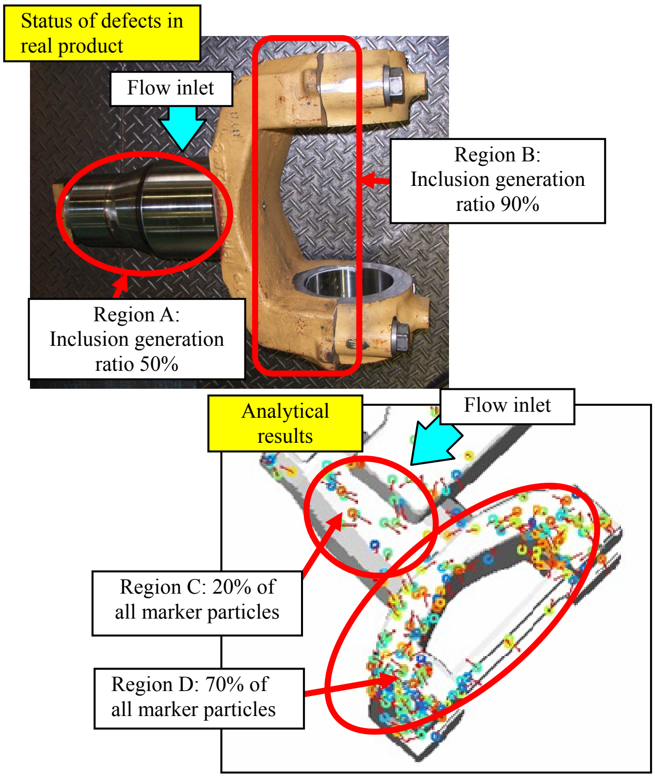

Fig. 4 Analysis of inclusions in a yoke

2.2 Study of method to remove inclusion (sand trap)

Measures to reduce inclusions by employing this technique were studied. Firstly, the effect of a molten metal drain that has been used from early on was studied. (**Fig. 5**)

The molten metal drain is a method to drive molten metal in the initial stages of pouring to the outside of the runner. **Figure 5** analyzes the molten metal drain. Marker particles that were believed to stay in the molten metal drain flowed back to the product part entirely, contrary to the anticipated function. As improvement, the addition of the following two functions was studied:

- A mechanism to prevent the return flow of inclusions after entry
- A space to trap inclusions

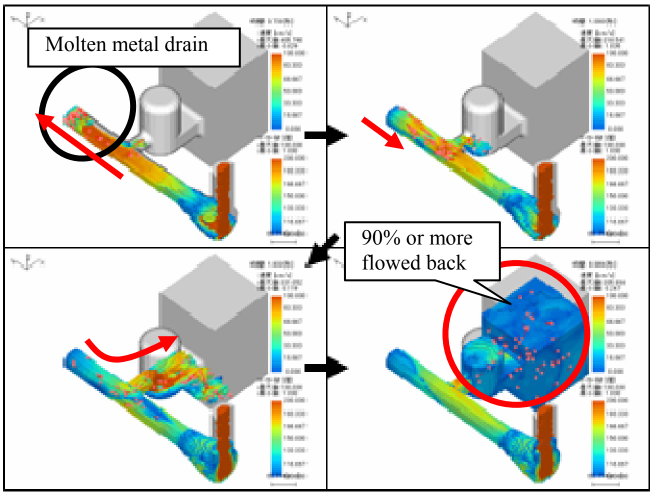

Fig. 5 Verification of the molten metal drain by inclusion function

Firstly, the inlet to the space, used to retain molten metal flowing from the runner to prevent the return flow of drained molten metal, was dented to reduce the area and flow rate, in order to thrust the inclusions into using the pressure from the runner side. To efficiently prevent reverse flow, the level of the reduction direction was studied and it emerged that a reduction of the top and side surfaces would be most efficient in preventing back flow. (**Fig. 6**)

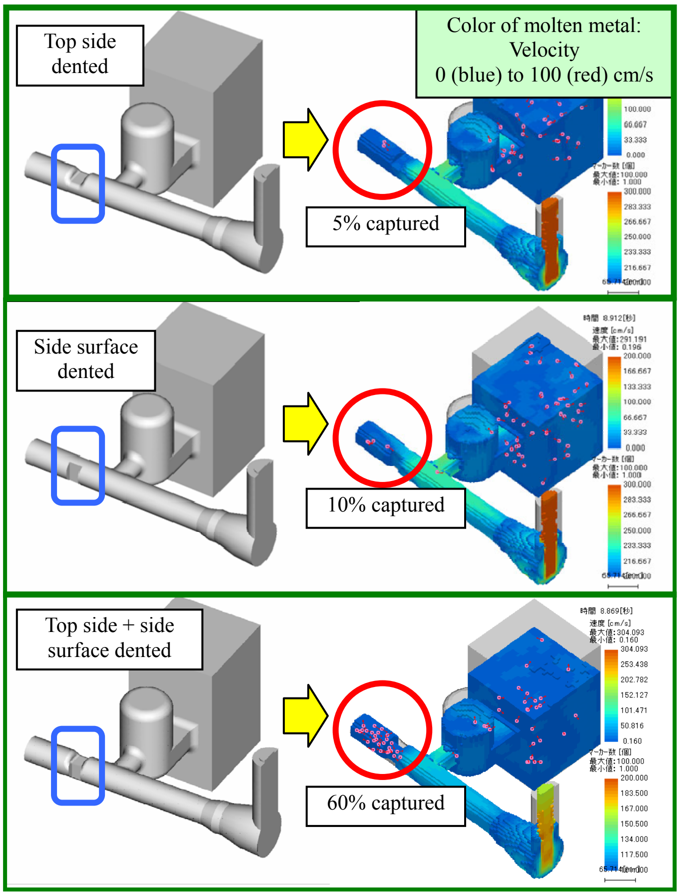

Fig. 6 Effects of the anti-reverse flow by shape of throttle

The reason why the capture rate of the above-mentioned anti-reverse flow method is no more than 60% at best is the insufficient volume of the space provided for retaining inclusions. A shape capable of positively circulating molten metal and that would collect inclusions by forcibly generating an eddy was therefore studied in order to sufficiently secure the inclusions for which removal was desired and create a space to retain them. By analysis, conducted through trial and error, a rectangular space longitudinal from side to side and a spherical space produced good results. (**Fig. 7**)

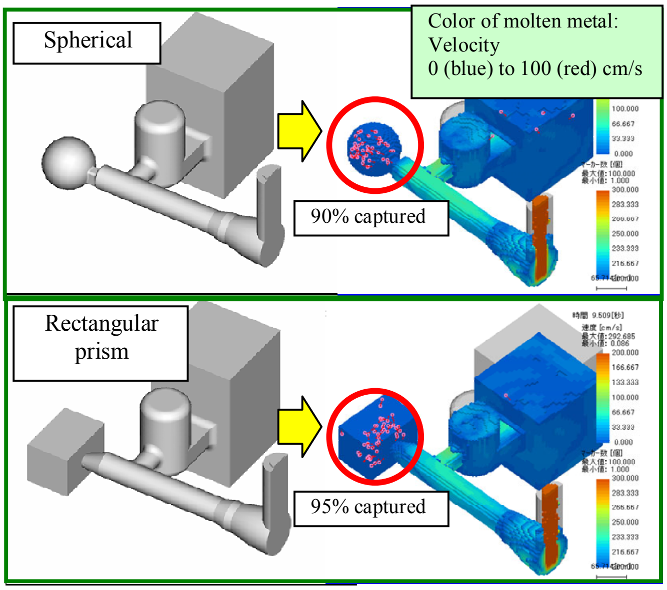

Fig. 7 Effects of anti-reverse flow by denting

These spaces to prevent reverse flow of inclusions and to trap inclusions were called "sand traps." **Figure 8** shows inclusions in a sand trap in a molten metal pouring test using a spherical sand trap. As shown in the photos, many inclusions could be found in the sand trap, which suggests that the use of this analytical technique to study inclusion removal measures will be effective.

Figure 9 shows an example of analysis, in which a sand trap is installed in products, instead of in the runner as was previously the case. This way, it will be possible to reduce the quantity of inclusions in products and moreover, to significantly reduce the risks of inclusion defects being generated with inclusions that flow into products and with those that are generated in product spaces by providing a space (sand trap) that actively traps particles contained in products.

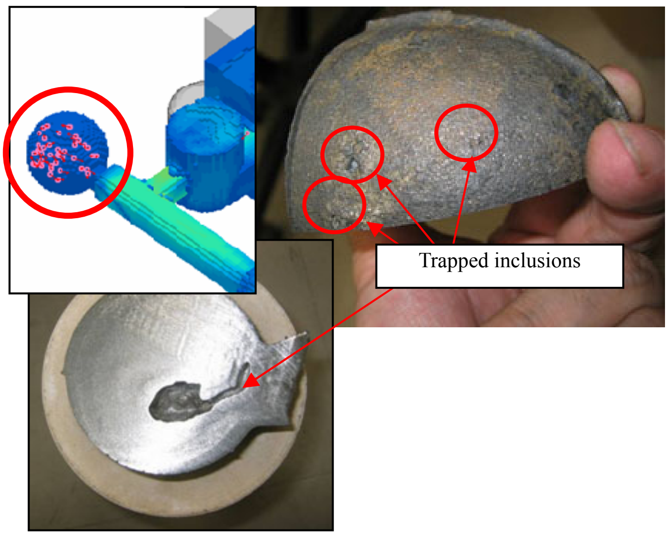

Fig. 8 Inclusions trapped in a spherical sand trap

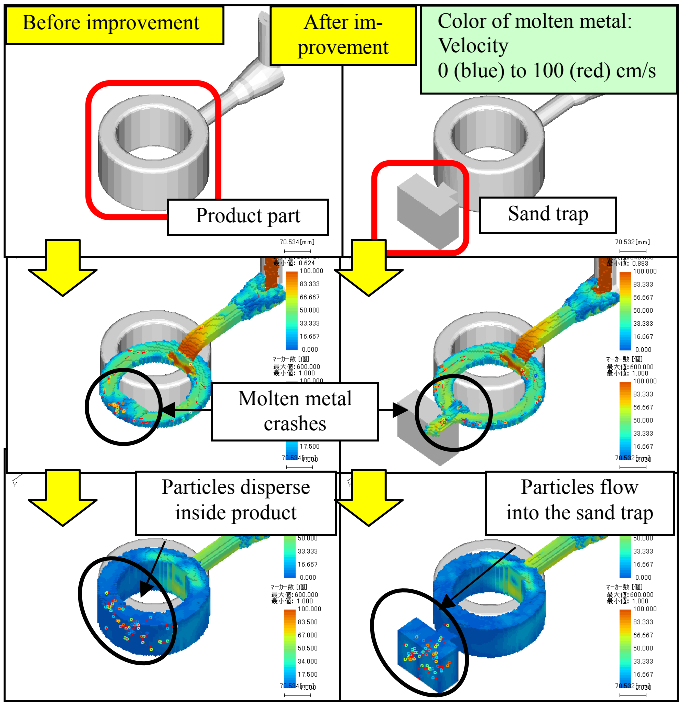

Fig. 9 Sand trap installed in product

As in this case, the sand trap can be used freely in runners, products and other places and will be effective in coping with individual inclusion factors.

3. Examples of Analysis

Based on the results of a cost analysis survey with the cast parts of a large bulldozer D155, the machining cost of the bogie (**Fig. 10**), which was part of the undercarriage, com-

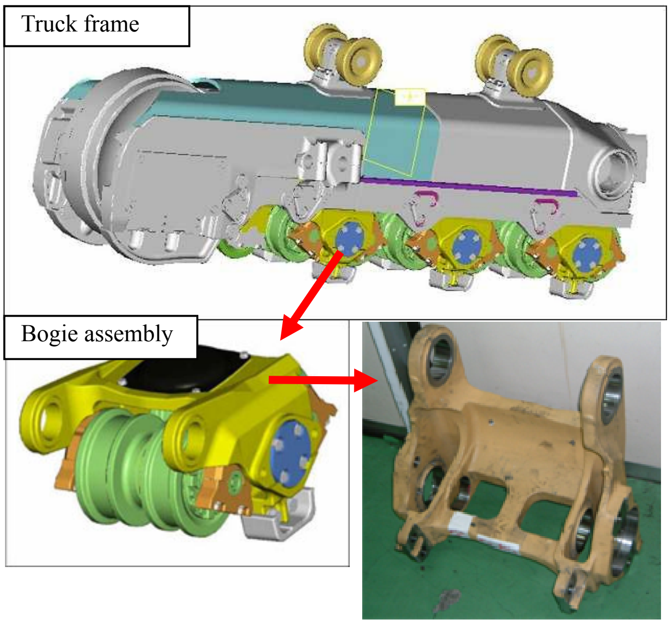

Fig. 10 Bogie (Undercarriage part)

prised a prominently high proportion, while the machining cost accounted for 25% of the material cost. (**Fig. 11**) This material cost does not include the final machining cost and the proportion of this latter is normally about 0 to 10% of the material cost, meaning the cost is considered to be very high.

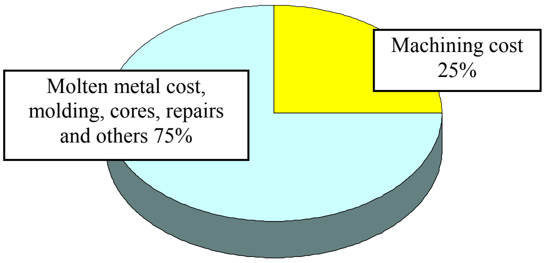

Fig. 11 Manufacturing cost of the bogie material

Examining the manufacturing process of this part, the part was processed roughly by a subcontractor after annealing, and final processing was performed after heat treatment (QT). (**Fig. 12**) The purpose of this preprocessing was studied and it was found that this was extra processing to increase the machining margin and remove inclusions by rough QT preprocessing, to curb the inclusion defects on the final processing surfaces.

Rough QT preprocessing can therefore be eliminated if the inclusion problem can be solved, offering the advantages of a reduction in the processing cost and eliminating the series of logistical burdens of moving the parts to a subcontractor for cutting and bringing them back to the plant for QT.

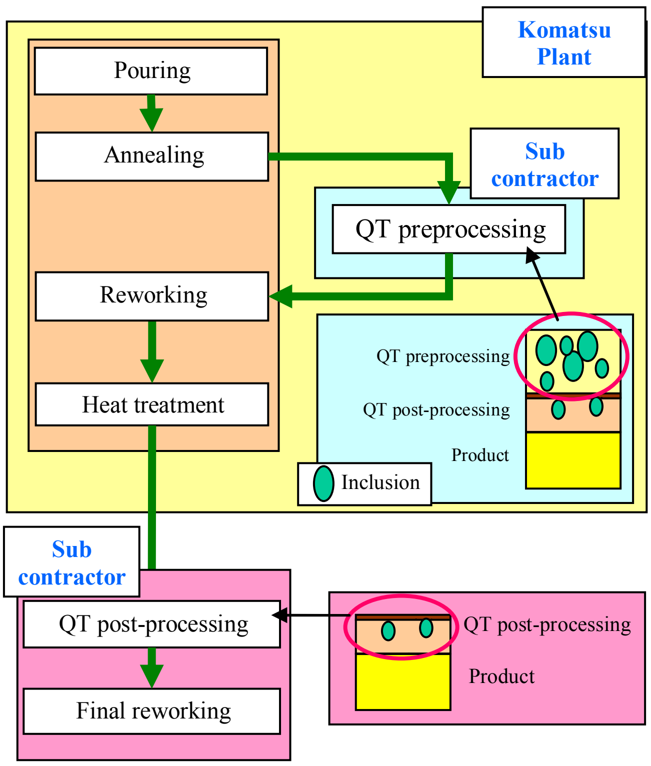

Fig. 12 Flow of bogie production

3.1 Study of inclusion defects in bogie

Prior to using the foregoing inclusion tracking function and sand trapping measure to reduce inclusion defects in bogies, the trend of defect generation with a focus on current inclusion defects was examined for each part of the bogie, as illustrated in **Fig. 13**. The proportions of inclusion defects for individual parts, based on whole inclusion defects defined as 100%, are shown in **Fig. 14**. The proportions show that defects around the hole in the inner boss account for about 40% of the total, while those in the guide account for about 25%; hence these two parts account for the majority of bogie defects. Conversely, the defect ratios of the outer boss, side surfaces, tip bosses and other parts are low, about 10%.

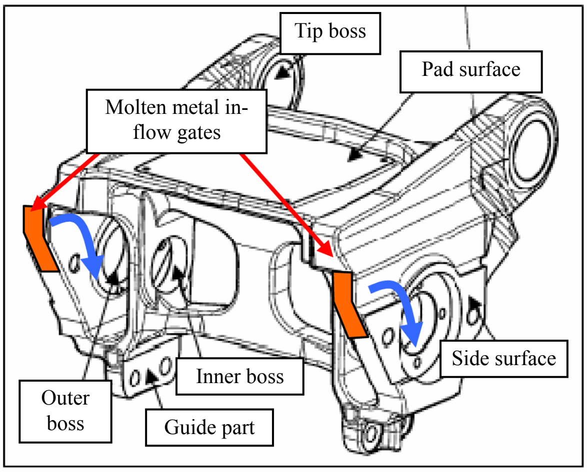

Fig. 13 Parts of a bogie

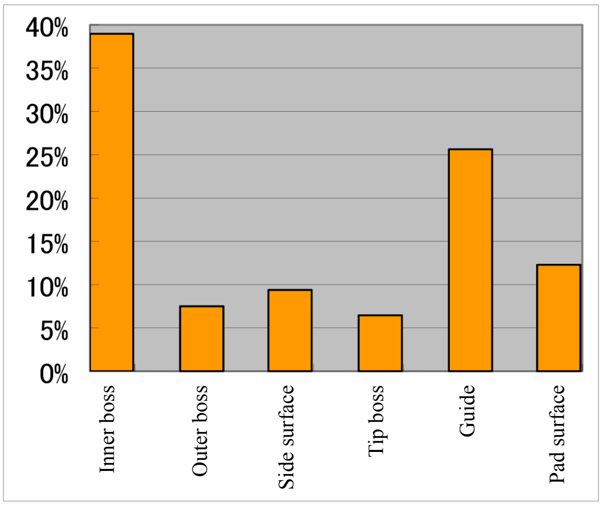

Fig. 14 Proportions of defects of bogie parts

Runner gates are provided in the rears of the surfaces of the left and right sides of this product and the molten metal is introduced through these gates. (**Fig. 13**) The molten metal flows down from the side surfaces and slowly fills upward through the guides in the bottom. In light of the trend for defects to occur and in view of the many cores contained in the bogie, it is safe to conclude that inclusions flow from sand and cores remaining on the mold surfaces between the sprues, attaching to the guides or floating up and attaching to the inner bosses.

Figure 15 shows the analytical results of the present measures. Particles concentrate in the inner bosses, which show a high rate of inclusion defect generation, indicating that the analytical results and trends for inclusion defects to be generated in products that are currently actually produced are identical.

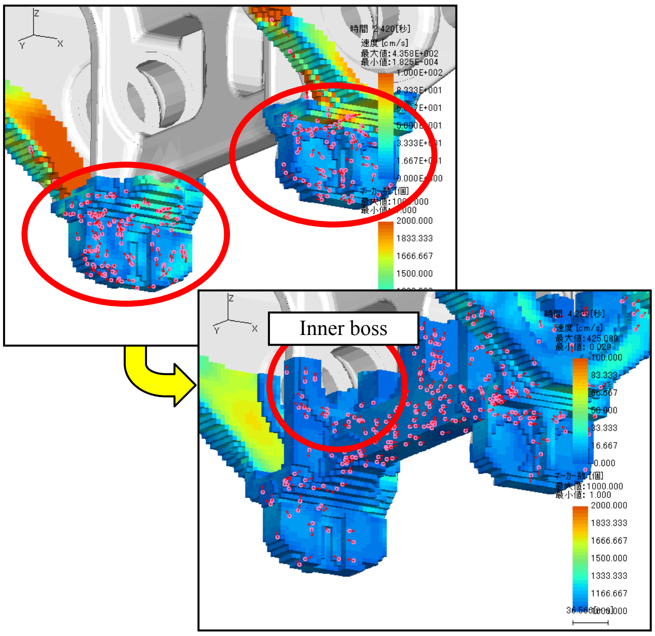

Fig. 15 Current analytical results of bogie defects

3.2 Application of the sand trapping method

Based on the information obtained, a study was conducted to select the most suitable locations in which to use this sand trapping method. The main point in selecting these locations involved identifying the locations which contained inclusions predominantly on the mold and those where inclusions would attach to the mold or float if no measures were taken. Since they satisfied both criteria, the guides were selected as suitable locations for installing the sand traps. It was decided to install sand traps in sites opposite the gates so that inclusion defects would be forced into them via the flow of molten metal. The scheme shown in **Fig. 16** was mapped out and an analysis was conducted.

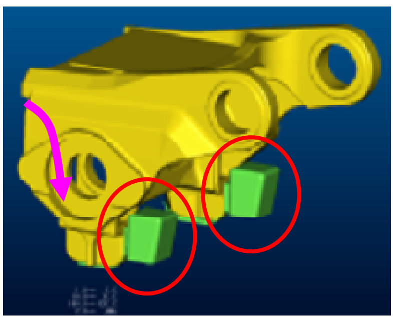

Fig. 16 Sand trapping scheme for bogie

Figure 17 shows the results of analysis incorporating the sand trapping method.

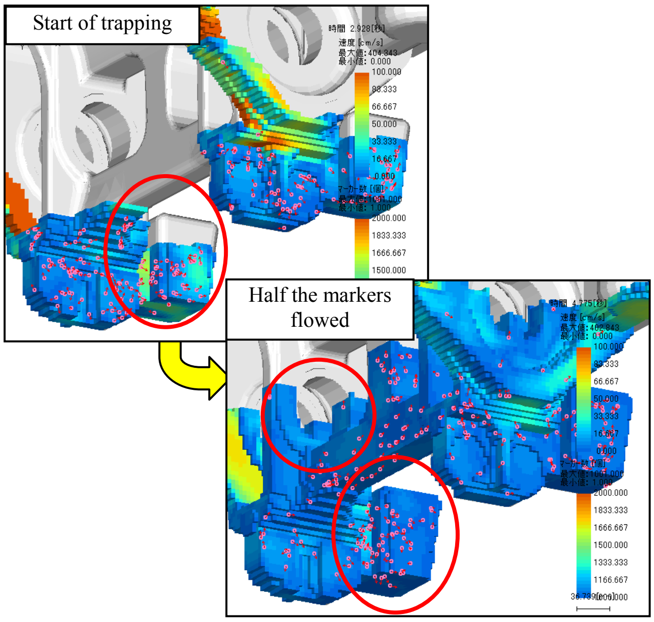

Fig. 17 Analysis of the bogie sand trapping scheme

As shown above, about half the marker particles generated could be captured inside the sand traps by installing them, significantly reducing the number of particles in the inner bosses that revealed inclusion defect problems. This result was used in a survey of sand traps actually installed on a bogie. The sand traps were cut as shown in **Fig. 18**.

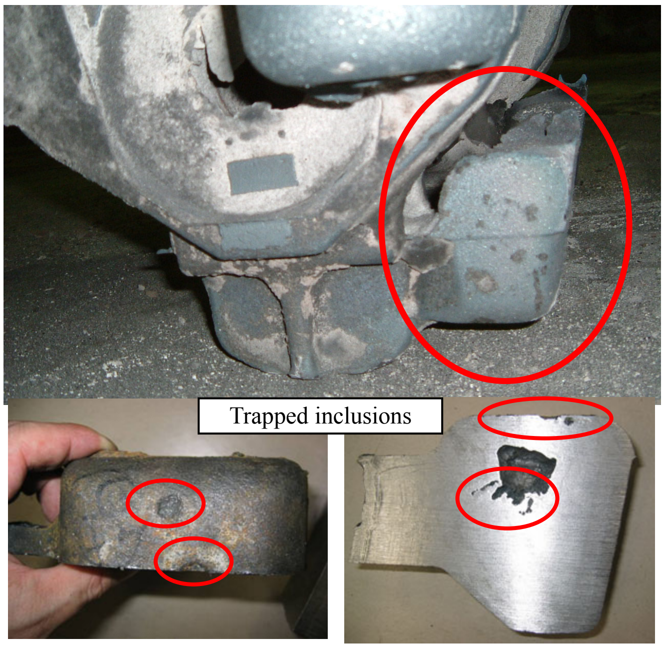

Fig. 18 Effect of the sand trapping scheme with a bogie

As shown in the photos, many inclusions were contained in the sand traps.

An N-repeated test was conducted with parts incorporating the sand trapping scheme by increasing the number of sand traps and showed that the defect rate could be halved. Based on this result, QT preprocessing (machining with an extra margin) was eliminated, allowing the process to be streamlined to QT post-processing only, and simultaneously achieving a reduction in the machining margin.

It will thus be very effective to visualize the movement of inclusions in products via the use of this analytical technique and study methods for sand trapping in dealing with inclusion defects.

4. Conclusion

In the past, behaviors of inclusions were totally unknown and only limited techniques were available to cope with them. Consequently, inclusion defects have been regarded as relatively "unavoidable," increasing the manpower needed to repair them, as well as the machining margins. The weights of the parts have become considerable and these and other harms caused by inclusion defects have been diverse. Despite the fact the whole process remains in an early stage of development, introducing an inclusion defect forecasting function by CAE would represent a great leap forward, along with efficiently implementing a process from the analysis of phenomena to the mapping out of countermeasures.

On the other hand, as mentioned above, the whole process remains in an early stage and many problems remain unsolved. For example, buoyancy has to be considered and the attachment of inclusions to walls must be reproduced to express the behaviors of inclusions in more detail in the analysis. The analysis and scrutiny of starting points where inclusions are generated will become important to collate real phenomena and analysis and these problems will be continually studied to eliminate defects caused by inclusions.

Introduction of the writers

Kenji Ogawa

Entered Komatsu in 1997.
Currently assigned to the Manufacturing Engineering Development Center, Corporate Production Division.

Shinya Kanou

Entered Komatsu in 1989.
Currently assigned to the Manufacturing Engineering Development Center, Corporate Production Division.

Shigeru Kashihara

Entered Komatsu in 1981.
Currently assigned to the Engineering Division, KOMATSU CASTEX LTD.

[A few words from the writers]

Presentations of the analytical results featuring animation and using markers made in various places have become very popular, thanks partly to the visual impacts. The results achieved in terms of the reduction in defects have been greatly influenced by personal senses, with the key points left to individuals – representing a bottleneck of this technique. Nevertheless, there is considerable room for improvement in analytical functions and we have only just started a long journey. We must remain calm and steadfast as we advance and progress further.