How to solve complex problems in foundry plants - future of casting simulation -

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Abstract. Although the computer simulation of casting has progressed dramatically over the last decades, there are still many challenges and problems. This paper discusses how to solve complex engineering problems in foundry plants and what we should do in the future, in particular, for casting simulation. First, problem solving procedures including application of computer simulation are demonstrated and various difficulties are pointed out exemplifying mainly porosity defects in sand castings of spheroidal graphite cast irons. Next, looking back conventional scientific and engineering research to understand casting phenomena, challenges and problems are discussed from problem solving viewpoint, followed by discussion on the issues we should challenge such as how to integrate huge amount of dispersed knowledge in various disciplines, differentiation of science-oriented and engineering-oriented models, professional ethics, how to handle fluctuating materials, initial and boundary conditions, error accumulation, simulation codes as black-box, etc. Finally some suggestions are made on how to challenge the issues such as promotion of research on the simulation based on the science-oriented model and publication of reliable data of casting phenomena in complicated-shaped castings including reconsideration of the evaluation system.

1. Introduction
Recent rapid development of computer aided engineering(CAE) has been transforming the heavily experience-dependent foundry technology into a modern and science-based one. Modelling and simulation such as those presented in the MCWASP are crucial elements in the CAE in the foundry industry and they have been progressing toward ICME(Integrated Computational Materials Engineering), by adding multi-scale-analysis for estimation of solidification structure and performances, and by combining various process simulations such as molding and heat treatment, etc.

Although we have now practical commercial casting simulation codes which have been widely used in the foundry and its related industries, foundry engineers still have many difficulties to solve their engineering problems. This paper discusses those problems including the application of casting simulation. Further, the conventional research works are looked back and what we should do in order to solve the challenges and problems are discussed.

2. Procedures to solve the problems and application of computer simulation
First, let us look back how we are now solving real problems in plants and extract issues on the problem solving. As an example of real problems, porosity defects in already produced sand castings of spheroidal graphite cast irons are selected in order to get a clear picture.
When occurrence of porosity defects is reported from the inspection section or customers, the engineers should solve the problem as quickly as possible. The procedures could be as follows and should be carried out with imagining various causes avoiding specific preconception. They include 5W-2H, namely Which casting, When, Where, What kind, Who involved, How and How many. Note that the procedures after finding suitable measures to solve the problem are omitted here because of the limited space.

**Step 1 - Investigate the appearance and morphology of defects, defect sites, and frequency of the occurrence**

The size, morphology (spherical, irregular, inside smoothness and colour, etc), remains in the defects and others are observed and measured by naked eyes or a stereomicroscope, scanning electron-micrometer, etc, depending on time, cost and resources. If possible, it is better to measure gas components in the defects. The dye penetrant testing, ultrasonic testing, etc can be used to find the defect sites. Further, identify when the defects occurred, if possible, the date and time.

**Step 2 - Investigate the change of manufacturing during the period while the defects appeared**

It is helpful to use the effect-cause diagram as shown in figure.1. In actuality it is better to use more detailed effect-cause diagrams specialized for various porosity defects based on engineer's own experiences and information obtained from others. Although the following includes many items to check, they should be limited to important ones by considering the results of step 1.

a) Check charts and numerical values of control items
This includes grade and amount of base metals, chemical composition of inoculants, chemical composition, gas content and carbon equivalent of the melt, consumption rate of new sand and binders, total clay or dust content, moisture content in the mixture, permeability, etc.

b) Check the behaviour of workers or operators and try to see the change in operation, particularly pouring. Careless slag removing, discontinuous pouring, taking no care to keep constant pouring temperature, etc. cause the defect problems.

c) Check machine or equipment change, maintenance situation such as part-change frequency, and wear and deformation of pattern and molding flask, precision control of measuring instruments, etc.

d) Check ambient change such as weather, temperature and humidity.

**Step 3 - Identify the defect type and causes**

Identifying the defect type is very important, because it is closely related to their causes and measures. The porosity defects are classified into shrinkage porosity, gas porosity, hot tearing and cracks. Gas defects are sub-divided into blows or gas holes, pinholes, blisters and others. There are many handbooks[1] explaining their appearance, morphology and causes. We should use such conventional knowledge and experiences to differentiate those defects and find causes.

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**Figure 1.** An example of effect-cause diagram for porosity defects
For example, if they are jagged holes or spongy with dendrites, they are usually shrinkage porosity. Although cavities with smooth, clear and bright inner surface are usually considered as gas defects, sometimes it could be shrinkage cavity generated due to melt or solidification shrinkage at early stage of solidification. However, if the gas content in the melt is higher than a critical value and the shape is spherical or elongated, they are probably gas defects. It should be noted that the gas porosity tend to be located in heavy section or the change of section, causing confusion between shrinkage and gas porosities.

Anyway the identification of detailed gas porosity type except the hot tearing and cracks is usually difficult, and requires integration of existing knowledge and experiences. Further, we should aware that the text books or handbooks are not always correct or do not include the latest research results.

Step 4 - Application of casting simulation

It is useful to apply casting simulation not only for identifying the causes of the defects but also for finding solutions or measures.

1) The case that the simulation has already performed.

1.1) Compare the simulation results with observed defects sites.

If the agreement is not bad, repeat the simulation to find proper conditions which could eliminate the defects. For example, if the defects site is in a heavy section and the defect seems shrinkage porosity, re-run the simulation with changing the risers, cavity dimensions, chills or pouring temperature depending of situation considering available time and cost, etc. The modulus method [2] is useful in this case but the other cases require much more experiences.

If the agreement is bad, re-simulate with revised input data as follows:

a) Check the change of casting condition, gating and risering systems and cavity dimensions.

They could have been changed from the original ones due to various reasons such as defect measures, wear, repair and customer's request.

b) Check what kinds of functions in the simulation code were used.

This requires to imagine the cause of the defects. If the defects look like gas defects and melt gas content is a bit larger than usual, we should select the function which can consider the gas content.

c) Check the change of pouring method, pouring temperature, pouring speed and mold including mold coating.

The real pouring temperatures usually vary with time and date even for the same casting. In particular, if a manual pouring is used, it is often necessary to observe the pouring operation such as pouring interval and if there is a possibility of pouring temperature change, it is better to measure it.

d) Check other input data.

These include physical properties of melt and mold, heat resistance between the casting and the mold, shrinkage coefficients, critical solid fraction for melt flow and criteria used to estimate defects such as Niyama criterion[3], etc.

One of the practical ways to evaluate the properness of the initial and boundary conditions and physical properties is to compare the simulated and measured temperatures.

e) Re-run the simulation

f) Evaluate the results and consider next steps

These require experiences and a comprehensive knowledge about casting including the defect formation mechanisms. If the causes of the defects and measures are found, then proceed to trial casting with the revised casting conditions.

The following is one example of practical ways to evaluate the simulation results:
i) The case where the defect sites are near the observed ones
   Proceed to find proper conditions which eliminate the defects as mentioned above.

ii) The case where the defect sites are far from the observed ones.
   Check the input data and re-run the simulation. In particular, attentions must be paid to the thermal
   conductivity of the sand mold and boundary conditions, because they often change the defect sites.
   If the difference can be explained by using imagination, then it is often useful to go further, namely,
   to find solutions by using the simulation supplementing with imagination. For example, if the real
   defects are located above the estimated one, it is possible that the difference was caused by floating-up
   of gas bubbles or thermal convection during solidification. If such phenomena were considered in the
   simulation, check the input data and re-run the simulation.

iii) The case where the simulation shows no clear defects.
   If defect criteria were used, re-run the simulation with revised ones.

iv) The case where the simulation codes cannot predict the defects.
   Even in this case, some defects can be estimated from the simulation. For example, gas or dross
   entrapment, which are related to the gas porosity defects, could be judged from melt flow behaviour
   during the mold filling.

2) The case that the simulation has not yet been performed.
   Perform the simulation with input data proper to the situation where the defects occurred, following
   the procedures such as shown below:
   1-1) Select proper functions in the simulation code available and run it.
   1-2) Evaluate the results and proceed to next steps
   These are the same as those in the item b and f in 1.1) mentioned above.

3. Difficulties in the application of simulation
   More detailed discussions on some of the following are available in [4].
   3.1 Getting proper input data
   3.1.1 Physical properties.
   Although rather good data bases exist for metallic materials, usually slightly or considerably
   different materials are used in plants. Therefore, it is often difficult to correctly judge the input
   property data, in particular, which are sensitive to minor elements, even when data on materials with
   similar composition exist. Further, there are limited reliable data on the relationship between
   temperature and fraction solid. In particular, in the case of the porosity defects problem in spheroidal
   graphite cast irons, it is often not good to use a constant relationship even when the chemical
   compositions are almost the same, because the graphite precipitation is strongly affected by melt
   treatment including inoculation. The solidification and liquid shrinkage data of practical alloys are also
   not enough, particularly for cast irons. There are many physical properties which cannot be determined
   only by chemical composition. These include surface tension of melt, wetting angle between the melt
   and mold surface, etc.
   The properties of sand mold vary from plant to plant and with time, because the density and
   chemical composition of sand mold are different. For example, because the thermal conductivity is
   affected by apparent density, it varies with molding condition and position in mold. Further, gas
   evolution in mold and condensation also affect the thermal and mechanical properties.
   3.1.2 Initial and boundary conditions.
   The initial conditions such as pouring temperature and speed, mold surface conditions vary with time
   and affect the mold filling and solidification.
   The heat resistance between casting and mold varies with melt flow, gas evolution, deformation of
   solidified region, etc. Although heat resistance data have been reported, it is not sure if the data can be
   generally used, because the casting condition and the cavity shape, etc. are often different. Therefore
   usually we use the values with better fitting with measured temperatures or those provided by the data
   base of simulation code. However, it is not sure if the value used are correct or not.
Further, although estimation methods of the thermal resistance have been reported[5, 6], it is not easy to apply them to real casting, in particular, for sand molds.

3.1.3 Input parameters.
Parameters such as critical solid fractions for the liquid flow through dendrites or mass feeding vary with the shape and distribution of the solid phase which are affected not only by the chemical composition but also by fluid flow and solidification condition and inoculation. In particular, defect estimation criteria such as Niyama criterion vary not only the chemical composition but also with the shape and size of castings, etc. Therefore, the selection of such parameters often requires experiences or research.

In particular, the porosity estimation in spheroidal graphite castings by such criteria is not easy, because of the expansion of graphite precipitation. Although we have developed a simulation code where the defect is estimated by tensile stress in mushy region[7], it requires an empirical critical stress depending on cast alloy and mold strength.

3.2 Selection of proper functions in simulation code
Selecting proper functions requires a comprehensive knowledge about the identification of the defects and their formation mechanisms. Unfortunately or fortunately there are currently not many functions available. For example, there exist few codes having functions which can consider the effects of the change in mold coating, mold additives or gas contents in melt. Therefore currently it is not a big issue but it would be a matter in the future when various functions become available.

Further, it is often not easy to judge the degree of properness of the functions from user's manual of simulation codes. This is because the details of functions are usually not disclosed. For example, the "function of gas entrapment" is greatly affected by how to treat the gas phase at the mold / melt interface including estimation of contact site of melt on the mold, and formation of gas bubbles and their size, and coalescence of bubbles, etc. Since such details are usually not disclosed, it is difficult to theoretically evaluate it. Even if they have been disclosed, the accuracy cannot be evaluated without comparing the results with reliable data. Unfortunately reliable data are difficult to get for many cases such as the gas entrapment. Further, entrapment of gas generated from mold requires the data on gas generation which vary with chemical composition.

3.3 Evaluation of simulation results and modelling
Although simulation codes have to be verified and validated, the verification is almost impossible, because the real phenomena which the simulation aims to realize haven't been known. Therefore, we usually just compare the simulation results with limited measured data and say the code has been validated if they agree.

However, it does not guarantee that the accuracy of the simulation code is good enough or not for the problems to be solved. This is because that the data used for the validation have some errors caused by measurement, errors of input data and fluctuation of real phenomena. Further, it is not sure if the code has the equivalent accuracy for other cases which are different from those used in the validation.

It is much more difficult to evaluate the accuracy of the through-process simulation or the ICME, because the impact of error accumulation on the final results hasn't been well known. One possible way to evaluate the accuracy might be a sensitivity analysis but it becomes more difficult if the number of input data increases.

Although the error due to modelling may become smaller in the future because of its improvement, the error due to input data such as the initial and boundary conditions may not decrease as shown in figure 2.

3.4 There are many cases where the application of the simulation is not enough to solve problems
In reality there are many cases where the application of simulation is not so useful to find proper measures against the problems, though we cannot say it is useless, because at least the simulated mold filling and solidification sequences are more accurate than those estimated from experiences.
The reasons why the simulation fails to find the causes comes mainly from so many things related to the problems. For example, the scrap ratio due to casting defects usually varies with time as shown in figure 3. Namely it increases gradually or abruptly and decreases with time by various measures taken. It is rather easy to identify the real cause if dominated changes occurred in a few related matters such as mentioned in Step 3 of section 1. Even in this case, it is still difficult to solve the problem with simulation codes because they often don't have enough functions. In many cases, various possible measures are taken at the same time, because dominated change cannot be found or the time to solve the problems are very limited, resulting in fail of identifying clear causes of the problems. Such situation is repeated and similar defects repeatedly occur. Particularly, if defects suddenly appeared and disappear in a short period, it is very difficult to identify the cause because the same condition cannot be recreated.

**Figure 2.** Expected simulation error

**Figure 3.** Scrap ratio change with time

4. **Reflection of conventional research on casting**

A great deal of effort has been put into solving engineering problems in casting by many people. Now let us look back on what we have done in the past and consider what we have to improve in the future from the point of view of problem solving.

4.1 **Flow of research**

Over the past several thousand years people have conducted engineering works, in particular, how to produce good castings mainly by trial-and-error approaches. Because the casting process consists of melting, molding, casting and post processing, and each process requires its own special technologies and skills, most of engineering works have been done individually in these processes.

From about the beginning of 20th century the scientific method has been gradually introduced in the casting field. It was natural for people to think that it is necessary to understand the casting phenomena and to be able to predict the consequences of actions taken, because it is very difficult to solve complex casting problems just by trial and error.

From around mid-20th century scientific research has been greatly increased, in particular, for solidification of metals. The scientific research means the research conducted by the scientific method, namely making hypotheses or conjectures, deriving predictions from them as logical consequences, and then carrying out experiments based on those predictions, followed by testing of those hypotheses with experimental data or observations.

The reason why solidification of metal was selected as a major scientific research subject would be that it is a fundamental of metallic materials and related to many processes including casting. Further, the testing of hypotheses is rather easy under the condition where the shape of specimen is limited to simple-shape. This is because that complicated-shape of specimen causes not only a risk of unexpected phenomena but also difficulties in realization of repeatable initial and boundary conditions, therefore, repeatability of observed phenomena or measured data, resulting in difficulty of proving the correctness of the hypotheses.

On the other hand, it is not easy to conduct such scientific research for processing and process-dependent phenomena such as casting defects, because it is usually difficult to realize clear and repeatable initial and boundary conditions. Therefore, rigorous scientific works delayed for those
subjects. However, engineering science-based research has been also greatly developed from about mid-20th century by introducing physical and engineering science such as heat transfer and chemical engineering but without rigorous testing.

From about 1960 together with rapid development of computer, quantitative analysis of phenomena have been developed. Namely, first numerical calculation of temperature and fraction solid has been developed with solving energy balance equation considering the latent heat of solidification, followed by development of mold filling analysis considering moving melt front. Because the accurate estimation requires accurate input data such as thermal properties of alloys and molds, relationship between solid fraction and temperature, thermal resistance between mold and melt, measuring methods of those data have been developed and various useful data have been accumulated. Further, the understanding various phenomena such as the boundary phenomena between mold and casting, and heat and mass transfer in green sand molds have progressed.

From a little later or similar time computer simulation has been developed. The computer simulation is defined here as the reproduction of physical phenomena by using computer and models. It is not just solving established differential equations such as Navier-Stokes equation. Most of casting simulation codes are engineering products based on engineering-oriented models explained later in section 4.2.1.

Together with such rapid progress in research, various casting process and casting alloys have been developed and knowledge on casting have tremendously increased. Further, in order to get deeper understanding, research subjects have been divided into various subjects as shown in figure 4(a) and various equipments necessary to the individual research have been developed. These situations have made it difficult for a single person to handle many subjects. As a result, many disciplines, specialization and specialists have appeared.

4.2 Difficulties and barriers
Although the knowledge obtained by those engineering and scientific activities described above are now very useful to solve various problems, there are still a lot of challenges. Some of them are discussed below:

4.2.1 Science, engineering, science- and engineering-oriented models, and artistic model.
Because scientific research is now so popular that people often confuse the research as science and engineering research. However, the goal of the research as science is to establish a theory or understanding, while the goal of the engineering research is to solve real problems. Therefore as shown in figure 4(b) engineers specify the problems to solve from complex phenomena and create solutions integrating explicit and tacit knowledge obtained from research and experiences. They should

(a) Scientific and engineering research
(b) Engineering activity

Figure 4. Subdividing of scientific and engineering research(a) and Engineering activity(b)
also find proper initial and boundary conditions such as the thermal resistance between the casting and mold. If we confuse them, we may do a lot of useless work.

Also we should not confuse simulations based on science- and engineering-oriented models and artistic model. The science-oriented model aims to real understanding of phenomena and requires rigorous proving or testing, while the engineering-oriented model aims to solve real problems and not only the accuracy but also cost and time are important. The artistic model aims artistic expression of things and can use all methods including equations which are impossible to happen in the real world.

The simulation based on the science-oriented model is necessary to really understand complex phenomena which cannot be understood by analytical methods and it is ideal to develop the engineering-oriented model from it. Unfortunately, however, there are several barriers and difficulties in conducting the research on the science-oriented model. Some of them are the following:

a) It requires a rigorous proving of the models.
First it requires accurate data for rigorous validation and it is not easy to measure them as described in 3.3. Second, it needs good repeatability of the phenomena concerned. This is also difficult, because it is difficult to perform experiments repeatedly with the same initial and boundary conditions.
Third, it requires for third persons to be able to evaluate the correctness of the work and it is too hard for the third persons in the conventional way. It would be necessary for them to perform the same simulation and compare the results with the reliable data.
b) It is not so attractive works for researchers, in particular for young people, because they should wait long time until the evaluation has been finished.

We should differentiate the engineering-oriented model with the science-oriented one. This is because even the results by the engineering-oriented model agree with limited experimental results, it is not sure that the model is really correct. For example, Niyama criterion[3] is a good example of the engineering-oriented model which was derived from the consideration of unidirectional solidification of steels or Al-alloys. If a proper value is selected depending on casting, defect sites can be estimated with short CPU time. However, it doesn't work always, because this model misses many factors affecting porosity formation such as nucleation pore distribution, gas contents and segregation, solid phase movement, deformation of solidified region, etc. Therefore we cannot say that the model explains the porosity formation mechanism itself.

Also we should pay attention to the level of the engineering-oriented model. For example, it is possible to develop a simulation code without sound engineering-oriented models but using parameters to just agree with limited experimental data. If the simulation results defer from the measured data, suitable parameters to fit the data could be used. Although it could be useful, if it works in some useful range, it is dangerous because it is natural that it fails in many cases. The engineering-oriented model requires more rigorous proving and is more reliable.

One problem on engineering-oriented model is the difficulty of disclosure of its detailed information, because it is usually closely connected to business. However, if its assumption and approximation methods are not published as much as possible, their contribution to the progress of science and engineering is limited. In particular, if a simulation based on an engineering-oriented model is published without proper disclosure of the details, it could be a kind of advertisement even if the results agreed well with measured ones.

We should also distinguish between the simulation based on engineering-oriented models and animation based on the artistic model. Animation is sequential display of phenomena causing illusion of real phenomena. When the results are shown together with measurable numeric data such as temperature, we can evaluate the quality of the animation. However, in the case that it just shows picture it is difficult to evaluate it, because often we don't have real observation results in castings. Therefore the developer should pay attention not to try to develop such animation code which just looks like reality. The professional ethics is very important for simulation providers and researchers.

4.2.2 Integration of existing knowledge and solving complex engineering problems.
Although there is a fundamental question such as "can we really solve the engineering problems by integrating knowledge obtained by such conventional research ? or "can we reproduce the complex
phenomena by integrating existing knowledge?", anyway we should do our best to integrate the knowledge. However, we have the following difficulties: 

a) There already exist and are still increasing a huge amount of knowledge related to casting and they are dispersed in various fields and their correctness is not sure. In addition, most of the research results are obtained under limited conditions, namely, simple shape, limited initial and boundary conditions as described before. Actual conditions of the problems are different from those. How can we select proper knowledge?

b) Evaluation of correctness of information is not easy, because it requires wider knowledge beyond the knowledge engineers or researchers usually have.

c) There haven't been enough scientific research on how to integrate and solve complex problems. Today it is mainly just up to each engineers and they often follow the way they got from experienced people with using old and limited knowledge.

4.2.3 Existence of many phenomena which are not so well understood.

There are still many process-related phenomena or subjects which require correct and clear understanding not only qualitatively but also quantitatively. This includes the porosity formation in spheroidal cast iron, nucleation of porosity, gas and inclusion entrapment mechanisms, phenomena at mold-melt boundary, etc.

Although a lot of existing information collected in handbooks[1] is useful, it is not enough from the view point of quantitative estimation of defects. Such knowledge has been obtained mainly from experiences. Namely the causes have been derived mainly by conjectures based on observed phenomena such as morphology of defects, location and casting conditions including casting process, mold coating or mold sand, etc. Therefore, usually the predictions based on the conjectures haven't been tested enough. Further, they often don't show quantitative data of casting conditions such as temperature and pouring velocity. Therefore, it is very difficult to re-produce similar conditions and confirm the correctness of the explanations.

Anyway, most of conventional works are qualitative and have not clear proof of correctness with clear evidence. Therefore even a possible cause of defect is found by using such knowledge, concrete measures have to be found by trial and error, while it is useful to see directions of the trial and error.

However, scientific research on such subjects is not easy because of the following reasons:

a) It is difficult to perform experiments repeatedly with the same initial and boundary conditions.

In the real phenomena the alloys and molds are not constant because their base metals and raw materials vary with time, and processing such as melting and sand preparation and molding vary with time and operators. Pouring temperature and velocity are also fluctuating with time. However if research was carried out under a simple system having clear but limited initial and boundary conditions, then can we guarantee that such works have considered all essential factors in real casting?

In particular, in this context it is very important to accumulate case studies which identify clear causes of the defect change with time such as mentioned at figure 3. From such works we could be able to find out missing factors to solve the problems. Although some of scientific works might have been done in large foundries, they have not been disclosed. It is more difficult to conduct such works in usual research organizations, because such real situations are very difficult to realize.

b) There are not enough human resources who can conduct such works requiring a wide range of knowledge.

For example, although mold flow and solidification have been carried out mainly by researchers belonging to metallic materials, porosity defects problems in sand casting requires also knowledge of sand mold, namely heat and mass transfer and chemical reaction in molds, and chemical reaction between melt and mold or coating. Solving porosity problems in cast iron requires mechanical behaviour of casting and mold. Therefore it is difficult for researchers specializing only in metallic alloys to handle such subject. It is also not easy for researchers who specialize in numerical simulation to conduct complicated experimental works.
4.2.4 **Existence of many properties data necessary for the understanding and simulation.**
As mentioned in section 3.1.1 and 3.1.2 there are many necessary data. Although some data can be measured at laboratories, some data should be measured in foundry plants or in research organizations under similar conditions. However, it is not easy.

4.2.5 **Black box problem.**
With wider use of simulation, more user-friendly code have been developed and tend to become a kind of black-box, because the user-friendliness often means easy operation without deep thinking. Further, as mentioned in section 3.2, the detail of algorithms of various complex phenomena such as phenomena at melt-mold interface or melt-gas interface are often not disclosed. Such codes are kind of black-box.

It might be no problem, if many problems can be solved with such simulation codes. However, it is not expected in a decade or so to realize such situation. If they are used to rely on black-box-like codes, they do not need to accumulate the comprehensive knowledge as the era when problems were solved by experience, and lose the ability to deal with unexpected situations which often occur in practice.

5. **What we should do in the future?**
Let us consider how we solve difficulties such as described above and how to develop science and engineering which can solve complex real problems. Some of the suggestions might be the following:

5.1 **Promotion of simulation based on the science-oriented model**
This requires us to solve problems such as discussed in 4.2.1. Some suggestions are as follows:

a) **Special awards and funding**
As described in 4.2.1, developing the scientific simulation needs a lot of work and requires very hard evaluation. If its appreciation in the academic world is the same with other conventional research, no one would try such research. Therefore we need to figure out special awards for it.

Further, it requires more funding than conventional research. This is because, for example, we cannot soon reproduce the whole real process of porosity formation during pouring and solidification, considering all phenomena. Therefore we have to proceed step by step in the conventional way shown in figure 4, but more quantitatively, for example, measuring the initial and boundary conditions as much as accurately not only for simple-shaped casting but also more complicated-shaped one. It requires more funding resources than conventional research.

b) **Reconsideration of the way of publication of the science-oriented model and engineering-oriented model**
As described before, publication is a must for the science-oriented model but not easy. One of the reasons is that the publication by paper is very expensive, because it requires a lot of pages. However, it may be solved if we use a web system.

In order to properly evaluate scientific works for publishing it may be recommended that the evaluation is carried out by a team consisting of specialists from the most relevant fields for the scientific simulation. Although the team can evaluate the scientific quality and correctness of the theory, complete evaluation is very hard for them. Therefore, the final evaluation should be done after gathering results of comparison with reliable data by third persons who used the simulation codes provided.

The evaluation of engineering simulation should be made by the similar team mentioned above but including experienced engineers, who evaluate it from the viewpoints of application, integration and engineering appropriateness. However, rigorous evaluation such as that for the scientific simulation is not required.

c) **Encourage to disclose reliable data which can be used for validation of simulation results.** It should include not only the data for simple shaped casting but more importantly for rather complex castings. So far, it was difficult to do such works, because they haven't been so well appreciated in academic worlds. We need to appreciate such works and reconsider the evaluation view points for such works.
In particular, direct observation of moving phenomena of small bubbles and oxides during casting and dynamic observation of formation of porosity defects under clear initial and boundary conditions are important. These require not only advanced X-ray techniques but also new methods such as neutron beams, because conventional X-ray do not have enough resolution.

d) Encourage works to make clear the effects of fluctuation of materials, initial and boundary conditions on the final results.

Because it is very difficult to measure, for example, physical properties of every molds used in the industry, it is very important to investigate the effects of minor change in chemical composition or density on the properties and create their estimation methods. For this purposes, it is necessary to investigate how they vary with time or plants, requiring to develop methods to measure various values in process.

5.2 Promotion of works on error accumulation and propagation in integrated process simulation or ICME.

It is necessary to estimate the accuracy of the final results and to develop to decrease the error. It would be necessary to introduce the concept of provability. Although the accuracy would be decreased with improving the modelling, an error due to input data would remain as shown in figure 3.

5.3 Developing of methods to solve complex real problems

Although conventional knowledge is integrated into various books such as[1, 8] which describe from basic to application or explain classified items, they don't contain the latest knowledge which increases rapidly. Further, they are inconvenient for the problem solving, because how to use such knowledge is up to individuals. Simulation codes are also a kind of knowledge-integrated products but it is not yet a complete problem-solving tool.

One solution might be creating new books with using ICT, including simulation. In the new books contents are classified according to problems. For example, it shows the problem solving procedures such as those described in the porosity defect problems in section 2. If a reader cannot well understand the words or requires more detailed information, then the reader clicks the word and immediately can get detailed information, including more fundamental explanations and reliable original papers having scientific evidences. Simulation works well on the understanding, in particular, on the evaluation of simulation results, etc.

Such problem solving document could help to avoid using simulation codes as a black box and the tendency to simply use the default input data.

5.4 Promotion to investigate the real casting phenomena in detail and quantitatively during a long period while problems happen suddenly or occasionally

It is not certain whether fundamental knowledge we have been expecting to know is sufficient to rebuild the complex phenomena or not. There might be something missed and we have to find them. Further, eventually we should evaluate the overall accuracy of the casting simulation.

Although such research might have been performed in large foundries such as automotive foundries where one kind of casting are producing in large quantities with the same line, it is very difficult for small and medium-sized foundries producing various castings in rather small quantities. Further, such works done in industry are not usually disclosed to public, and quality or correctness are not known. Therefore they are not contributing to the progress of engineering problem solving.

Therefore it is hoped to create such a collaborative joint project that some teams consisting of foundry engineers, researchers, simulation specialists, etc. perform the research in foundry plants which are special in the sense that a good measuring system is installed.

6. Concluding remarks

Similar discussion such as described here is possible for many other cases. Although the issues discussed here could be solved if we have enough resources, the biggest problem we face would be the
decrease in research resources, particularly in developed countries. This is because there are many more economically attractive and immersing research fields such as robotics, bioengineering, micro-technology, energy-related issues, each country has to distribute their limited resources to various fields.

To solve this problem, we need a better system where people can use their best abilities and collaborate with each other. Further, we shouldn't forget simulation codes are engineering products similar to cars and airplanes, requiring continuous and endless improvement.

Therefore we need to always learn and apply the knowledge in practices. It requires collaborative learning system. Learning requires four dialogues: 1) Dialogue with problems and phenomena, 2) Dialogues with existing knowledge, experience, mentors such as teachers and experienced engineers, 3) Dialogues with colleagues and 4) Dialogues with ourselves (reflection).

This MCWASP conference is a wonderful opportunity for such learning and could be improved from such view points. For example, although it is good to have all fields related to solidification, if the room is divided into individual field and attendees just listen to their own specific talk and discuss them, it is difficult to integrate them. One solution would be to organize for example, session of porosity defects where all phenomena related porosity defects are presented and discussed to find how to solve porosity defects problems. Then we can better see how many factors are related, what are unknown and what we should do as the next step.

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