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Heat Transfer at the Mold - Metal Interface in Permanent Mold Casting of Aluminum Alloys Project

Annual Project Status Report

for the period October 1, 1997 to September 30, 1998

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Executive Summary:

In the first year of this three-year project, substantial progress has been achieved. This project on heat transfer coefficients in metal permanent mold casting is being conducted in three areas. They are the theoretical study at the University of Michigan, the experimental investigations of squeeze casting and semi-solid casting at CMI-Tech Center, and the experimental investigation of low pressure permanent mold casting at Amcast Automotive.

At the University of Michigan, a sensitivity analysis has been conducted. A brief analysis of the role of size on the temperature and fraction of solid distribution was performed for geometry approximating that of a wheel casting. This arose from the interest Amcast had expressed in fabricating a new mold, and the need to establish how closely the geometry of the experimental mold has to match the geometry of molds in production. An initial geometry was defined for ProCAST to solve, and then a geometry half the size was defined and solved using the same boundary conditions. A conceptual mold geometry was examined and is represented as an axisymmetric element. Furthermore, the influences of the localized heat transfer coefficients on the casting process were carefully studied. The evaluation of a 2-D interfacial heat transfer coefficient has been undertaken.

In this year, the HTC Evaluator has been proposed and initially developed by the U-M team. The Reference and the Database Modules of the HTC Evaluator have been developed, and extensively tested. The abstracts, key figures and conclusions of more than 60 papers related to this project have been input. The relevant literature has been sorted and is being sent to the AFS Library. The distribution of 68 papers collected in terms of casting processes are Permanent mold casting: 26, Sand casting: 17, Continuous casting: 5, Investment casting: 4, Squeeze casting: 2, Die casting: 5, Other: 9. The development of a semi-automatic geometry recognizer has been undertaken. A series of technical barriers have been cited and potential solutions have been surveyed. This work is in an early stage.

At the CMI-Tech Center, the Kistler direct cavity pressure measurement system has been purchased and tested. The calibration has been evaluated. The probe is capable of sensing a light finger pressure. The experimental mold has been designed and modified. The first experiment is scheduled for October 14, 1998. The geometry of the experimental hockey-puck casting has been given to the U-M team for numerical analysis.

At Amcast, an experimental mold has been designed and is ready for fabrication. The thermal monitoring system has been investigated. Some ambient temperature data have been collected from a production mold. It was found that quite different heat transfer conditions exist on different parts of the exterior mold faces. A proposed ultrasonic gap formation measurement is regarded as very promising. Three quotations for an ultrasonic gap formation measurement system have been obtained. The quotations

have been forwarded to Amcast for review. Amcast has reached a final stage for review of the cost of the system and its suitability for their purpose.

In this report, some color figures may not be properly printed out with a B/W laser printer. It is suggested to contact Dr. SW Hao at swhao@engin.umich.edu for an electronic file in Microsoft Word 97 format, for an improved presentation.

1. Development of the HTC (Heat Transfer Coefficient) Evaluator

1.1 Framework developed for the HTC Evaluator

The framework for providing a useful database has been proposed conceptually, with the identification of the following tasks which will be required in an HTC evaluator:

HTC Evaluator

1.1.1. Definition and Purpose:

1) To provide guidelines for engineers in the casting industry who need accurate HTCs quickly.
2) To accumulate expertise for using HTCs on a company and industry-wide basis.
3) To provide a framework for future studies of HTCs to follow.

1.1.2. Features:

1) PC based with Windows platform.
2) Codes in C/C++.
3) User amendable.
4) Internet accessible for industry wide access (in the final version).

1.1.3. Specifications:

1) Structure - top to bottom, with user input for different parts of the casting.
2) Processes - includes a selection of the supported casting methods which can be user extended.
3) Materials - includes a database which covers the necessary materials which can be user extended. This would include mold coating materials.
4) Process parameters - user input of pouring temperature, mold pre-heating, machine type, etc.
5) Surface conditions - database from which user can select the appropriate surface conditions to use, including dependence on coating.

6) Geometry Factors - dependence of the IHTC (Interfacial Heat Transfer Coefficient) on the geometry of the mold and numerous subfactors (concave vs. convex, cooling channels, etc.)
7) HTC Evaluator - mathematical model, initially tested with the results from the literature, subsequently tested with the data derived from the geometries of the partner companies. A key difference will be the use of solidification ratio for a given section, as this parameter defines whether sufficient solidification has occurred for a gap to be present, and is therefore more physically meaningful than time or temperature dependent IHTC.

1.1.4. Results Output

Four formats for the results will be provided:
1) The maximum HTC for a given surface.
2) The minimum HTC for a given surface.
3) Average HTC for the surface.
4) Solidification ratio of a section dependent IHTC.

1.2 The Basic Concept of the HTC Evaluator

As the HTC (heat transfer coefficient) is a variable heavily dependent on casting conditions, like thermal properties, metallurgical properties, geometry of the casting and extra pressure, prediction is difficult and is usually based only on experience.

The objective of developing an HTC Evaluator is to provide a means by which engineers can interactively predict the local HTC of a specified casting.

The structure of the HTC Evaluator is given in Fig. 1. It consists of three modules, namely a database module, a reference module and an HTC calculator module.

When the HTC Evaluator is used, the user is asked to provide information for the evaluation. Basically all necessary information, such as thermal properties, can be called from a pre-input database, except for the geometry of the casting.

The geometry of the casting can be input via a de facto standard CAD data interface, like an SLA format. Three side-view windows (X-Y, X-Z, Y-Z) and a 3-D view window will be provided. The user is asked to point to a location in the three side-view windows, whose HTC is of interest. By doing so, the X,Y,Z of the interested location is input. An automatic geometry recognizer based on topology theory will be used to identify the geometrical features of the location. This is extremely important in determining the HTC. It is well known that the HTC of a concave surface is totally different from that of a convex surface.

The HTC Calculator will predict the HTC value, surface by surface, based on the geometrical features and available published data.

With the database module, a user can flexibly input and modify necessary data, like thermal properties of materials. The database is a required module to support the HTC Evaluator.

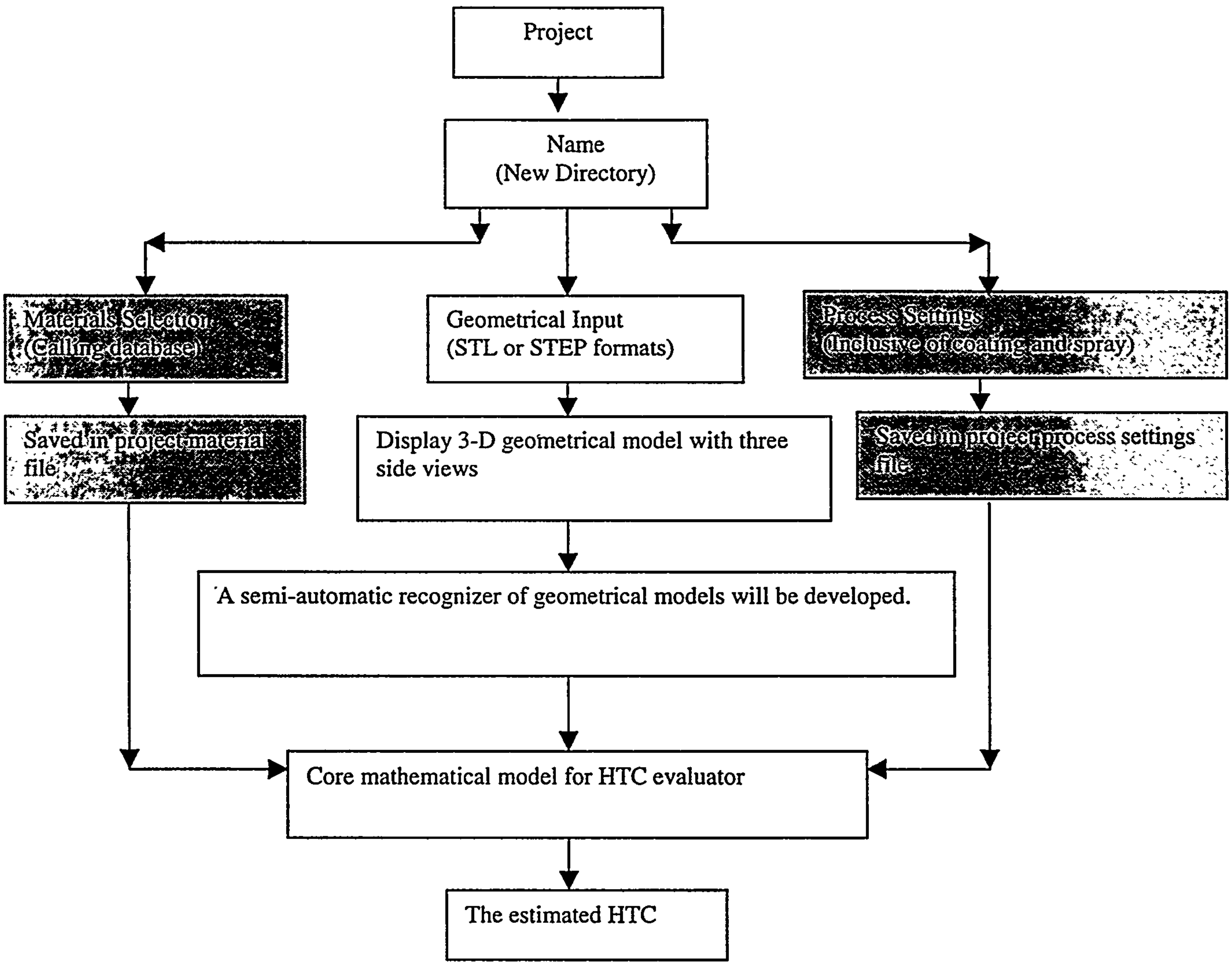


Figure 1: The data structure of the HTC Evaluator

With the reference module, a user is able to input the summary of a published paper into a reference database. So far, more than 100 papers related to the HTC in casting have been cited. Most of them have been collected. All of the collected data on the HTC will be input into the reference database of this software. The data will be divided into 7 process groups; sand casting, permanent mold casting, semi-solid casting, squeeze casting, die casting, continuous casting, and investment casting. A very important supporting module for this project is a state-of-art HTC Evaluator.

The next step in this development is to provide a mathematical algorithm to judge the HTC value in light of casting conditions, materials properties, geometrical features, extra pressure, etc. First of all, a semi-automatic geometry recognizer will be developed, which is a middle link shown in Fig.1.

So far, the interface of the HTC Evaluator with a database module and a reference module has been developed. The main window is shown in Fig.2.

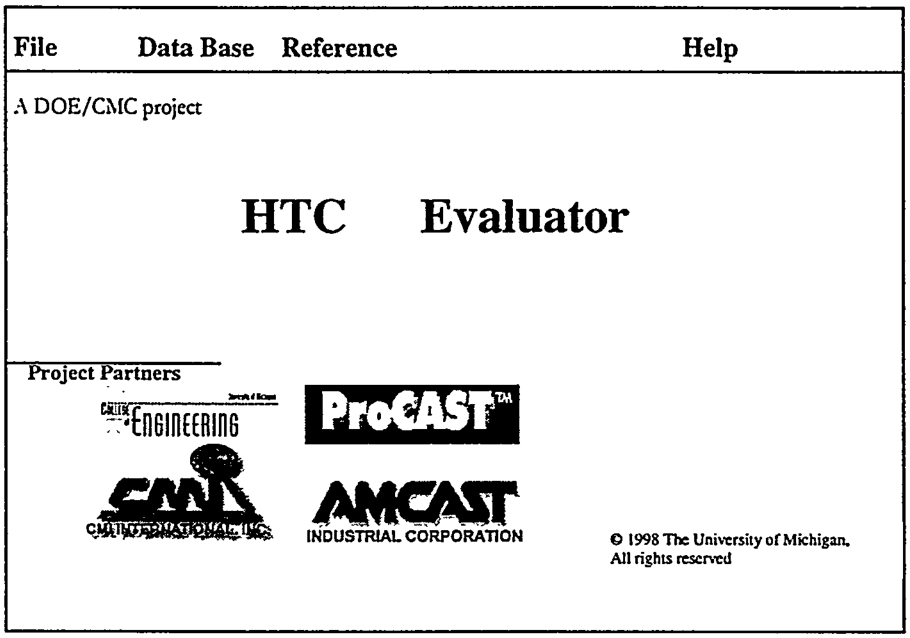


Figure 2: The main window of the HTC Evaluator

Two major technical obstacles are cited.

1) A lack of experimental data ---- The HTC evaluator must be built on a solid base with sufficient and reliable experimental data. However, from a literature review, it is realized that most of the previous studies on the interfacial heat transfer coefficient have been conducted under gravity casting conditions and in a laboratory environment. The experiments at CMI and Amcast should provide some practical and more applicable data.

2)Difficulty in automatic recognition of geometry --- Topologically, it is still very difficult to find a methodology to automatically recognize the geometry of a complicated casting shape. A countermeasure is under investigation to overcome this problem.

1.3 The Status of the Development of the HTC Evaluator

As outlined in previous reports, two modules of the HTC Evaluator have been preliminarily developed. They are the database module and the reference module.

With the database module, a user can flexibly input and modify necessary data, such as thermal properties of materials. The database is a required module to support the HTC Evaluator.

With the reference module, a user is able to input a summary of a published paper into a reference database.

These two modules were tested, and more than 60 papers have been input into the reference module. So far, no bugs have been reported, but several improvements have been suggested.

The reference menu on the HTC evaluator currently contains 68 journal articles. The break down of these entries is as follows:

Permanent mold casting: 26
Sand casting: 17
Continuous casting: 5
Investment casting: 4
Squeeze casting: 2
Die casting: 5
Other: 9

The subdivision "other" contains articles that are largely concerned with the boundary element method of analysis and make no mention of the specific type of casting involved. There are also articles about other types of casting, such as lost foam casting.

The reference menu includes a subdivision for semi-solid casting references. The literature search that was conducted turned up no references on this topic. However, there are still interlibrary loans pending and there may be some additional references in that group.

Each reference includes a bibliography, as well as any pertinent graphics from the article. If the article contained a photo or drawing of the experimental set-up or a graph that displayed results that were directly related to a heat transfer coefficient, it is included in this storage. There are approximately 120 graphics included.

The purpose of this menu is to allow an engineer to source background information concerning his/her work without having to go through the tedious task of a literature search.

The data structure and program structure of the Database and the Reference modules are given in Appendix I in this report.

The next step in this development is to provide a mathematical algorithm to judge the HTC value in light of casting conditions, materials properties, geometrical features, extra pressure, etc. The technical challenge will be in the development of a semi-automatic geometry recognizer. It should be able to determine the geometrical features of a given casting based on the topological information provided in a solid model. This knowledge is also very important to concurrent engineering in the metal casting industry.

The literature survey and technical feasibility study of the semi-automatic geometry recognition were carried out. There seems to be much potential in this approach, but it is not very mature. A great effort is being paid to select the most suitable approach for this project. At this stage, the interface between the HTC and a CAD system should be in the STL format. A layer-by-layer geometrical recognizer should be developed to judge the position of a surface and its topological relationship with the remainder of the casting. Based on the topological relationship cited, the HTC database would be searched to match the topological characteristics of the surface and a HTC value would be given.

2 Numerical Analysis

2.1 Sensitivity Analysis

A brief analysis of the role of size on the temperature and fraction of solid distribution was performed for a geometry approximating that of a wheel casting. This arose from the interest Amcast had expressed in fabricating a new mold, and the need to establish how closely the geometry of the experimental mold should match the geometry of production molds. An initial geometry was defined for ProCAST to solve, and then a geometry half the size was defined and solved using the same boundary conditions. A conceptual mold geometry was examined and is represented as an axisymmetric element (along the left hand edge) in Figure 3. The purpose of this geometry was to provide the significant geometric elements present in wheel castings, without making the geometry excessively complex. The riser would be attached to the central web of the wheel. It is expected that due to thermal contraction following partial solidification, the heat transfer coefficients would vary dramatically depending on the location. Consequently, the outer surfaces would lose contact relatively quickly, while the inner surfaces would maintain good contact throughout the solidification of the component. The differences between the flat sections of the flange and the curved sections of both the flange and the curved web between the upper and lower flanges could be readily determined via this geometry.

The purpose of these calculations was to get a sense of how significant the changes resulting from a change in dimensions would be. For example, could a small mold provide much the same information as a large mold, given appropriate modifications to account for the different scale? As expected, the time scale for solidification was much shorter for the smaller mold geometry. One result of these calculations is shown in Figure 3.

The major limitation resulting from the difference in the size of the mold is the way in which solidification of the cast metal progressed. In the larger mold, the heavier section meant that there were fewer regions isolated from the liquid metal, while in the smaller mold the thinner section resulted in significantly more isolation of liquefied regions. It would be possible to adjust the parameters of the casting to enable comparable solidification of the cast metal, but the risk is that we would now be moving even further away from the geometry of interest. Given that transferring data from one geometry to another geometry is already expected to be non-trivial, it would be preferable to use a mold geometry which approximates the intended application as closely as possible. Consequently, while a smaller mold will certainly provide useful information and would also allow geometrical effects to be measured, it may ultimately be more cost effective to use a larger mold, which matches the intended application more closely.

2.2 Numerical experiments on the influence of the HTC on the casting processes

After more than two decades of investigation, how to define a proper Interfacial Heat Transfer Coefficient (IHTC) for accurate numerical simulation of a casting process is still a challenge. From previous reports, the HTC has been used at values from 80 W/m^2K (Ho, Pehlke[1] for a gravity metal chill) to 25,000 W/m^2K (Jerichow, Altan and Sahm [2] in semi-solid casting). For low pressure permanent mold casting, Sarah Chen of Amcast suggests 2,400 W/m^2K for the liquid contact stage and 800 W/m^2K after gap formation.

It is obvious that the HTC may vary over a wide range. Ho and Pehlke [1] studied the influence of the HTC on solidification in a series of so-called sensitivity studies. It was concluded that the solidification rate in conjunction with mold materials is largely interface controlled. It means that the HTC can dramatically affect the calculated solidification time. The lack of measured temperature data in metal/mold casting processes leaves the calculated solidification results unverified.

In the middle of the eighties, most simulations were conducted for sand gravity casting in which the solidification times for most castings were not so sensitive to the HTC values. Hence, many researchers and engineers believed that a systematic error in choosing an HTC value might not affect the sequence of solidification, but only solidification time (Niyama [3]). So long as the HTC value was larger than a certain level, e.g. 1000 W/m^2K, the influence of the HTC value on the solidification time could be neglected. This is a reasonable assumption in the case of sand gravity casting for higher values of the HTC, and where the mold temperature may not be critical.

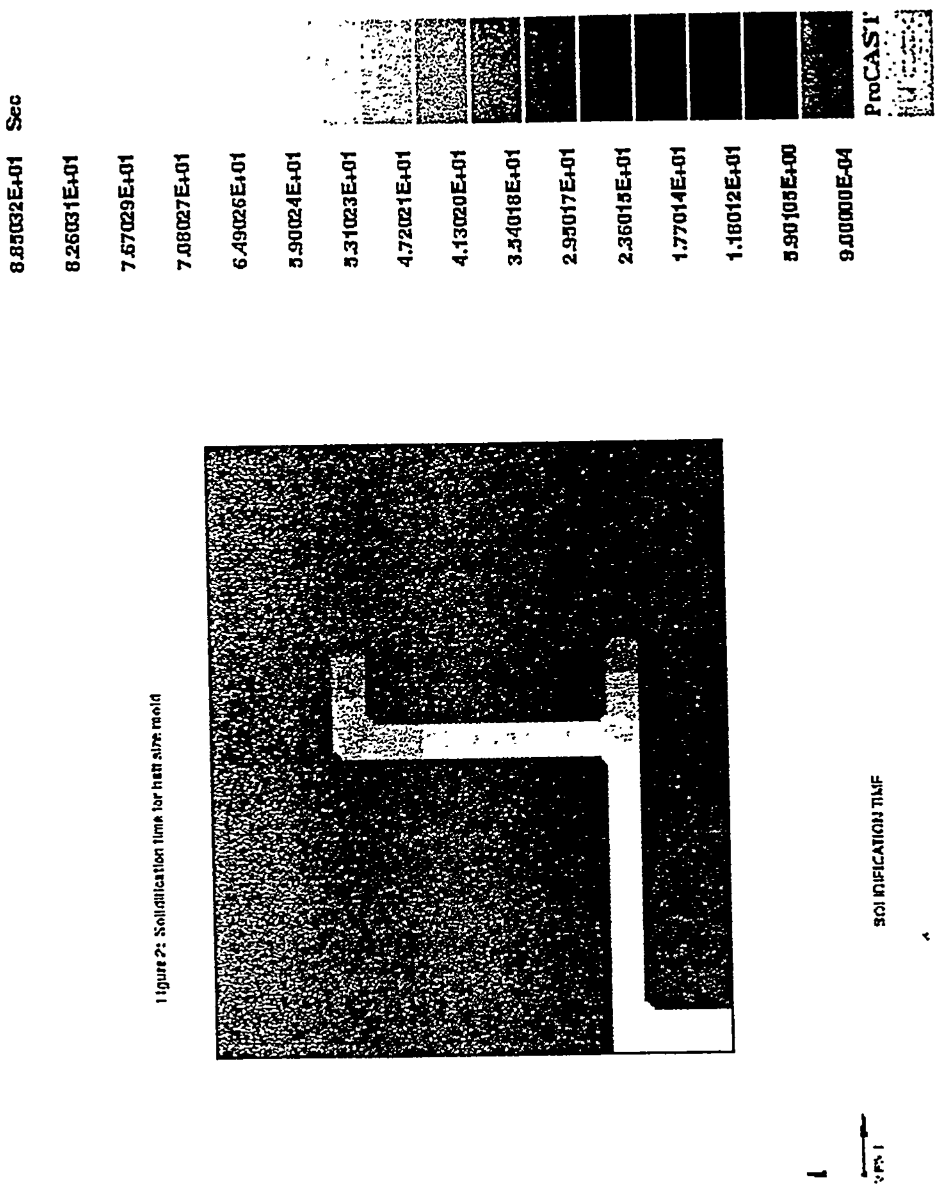


Figure 3: Solidification time for half size mold

However, in metal mold casting processes like die casting, squeeze casting and low pressure permanent mold casting, the mold temperature is very crucial to die life, cycle time and the distortion of casting and mold. Premature solidification during filling may become a problem (Hao, Anzai and Niyama [4]). Die cooling and heating is a must in many processes. All of these processes require accurate HTC values for precise numerical simulation.

The numerical experiments on a wheel-like low pressure permanent mold casting in this report are introduced to present the relation between the HTC and solidification time, the HTC and die temperature, and the influence of the localized HTC.

2.2.1 Conditions of Calculation

The casting and mold materials selected are A356 aluminum alloy and H13 tool steel, respectively. The initial temperatures are 1300 F and 677 F for casting and mold, respectively. The solidification time and the mold temperature are checked at the end of the 11th cycle of calculation, assuming the process has reached a steady-stage. ProCAST has been used for the simulation. Due to the axisymmetry of the casting, only a 2-D calculation was studied. The geometry of the casting and mold is shown in Figure 4.

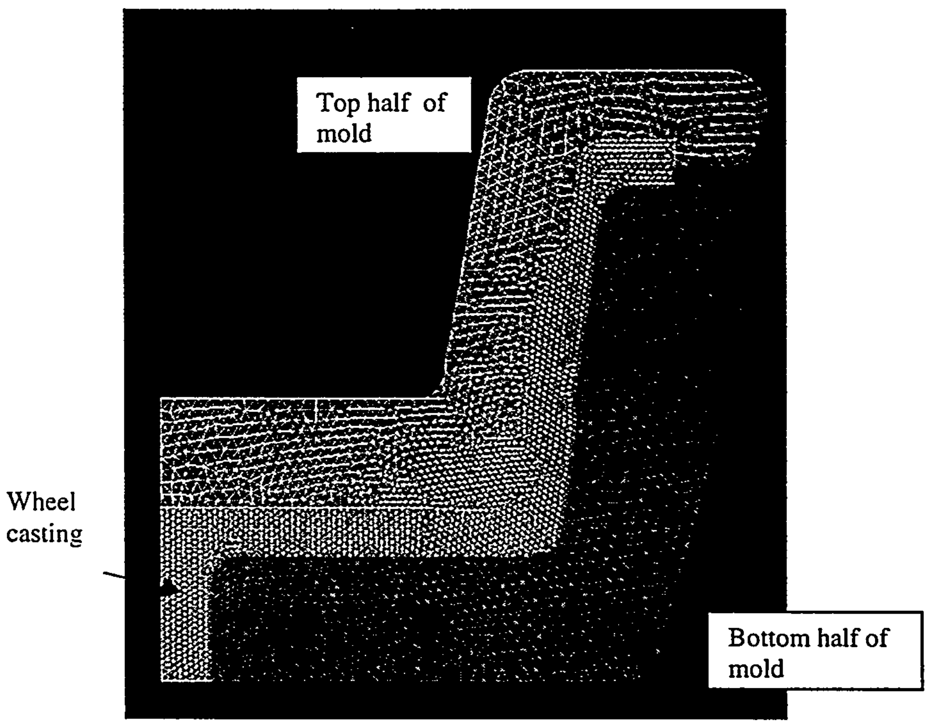


Figure 4: The mesh for the wheel casting with a top half mold and a bottom half mold (Casting thickness: the rim = 15 mm, the remainder = 25 mm)

2.2.2 Solidification Time vs the HTC

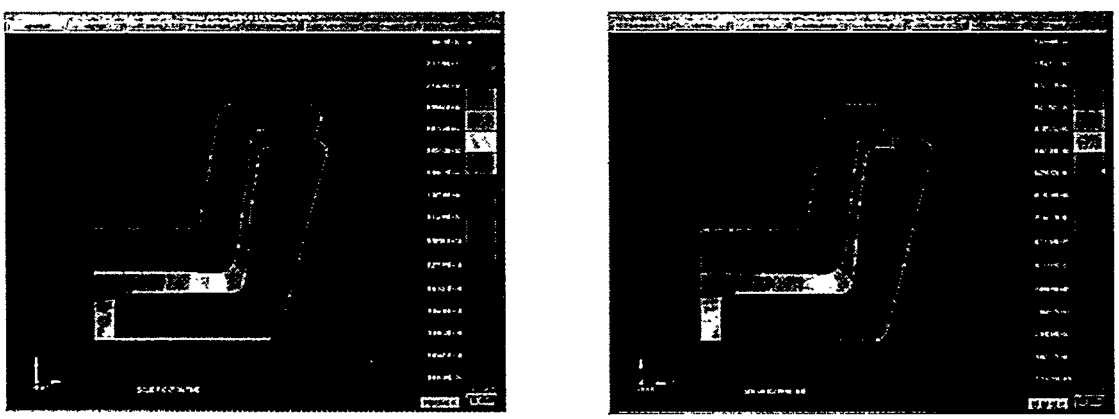
An interfacial HTC value for all interfaces was assumed regardless of the local geometrical features. which is a normal practice in casting simulation. The relationship between the maximum solidification times of the casting and the HTC is given in Table 1.

Table I: Solidification times vs HTC values

HTC (W/m^{2}K)	200	400	600	800	1000	24000
Sol. Time (sec)	315	294	272	209	153	72

It is found that if the HTC increases 33 % from 600 W/m^{2}K to 800 W/m^{2}K, the solidification time decreases 30 %. When the HTC increases 25 % from 800 W/m^{2}K to 1000 W/m^{2}K, the solidification time decreases 36 %. It is clear that the solidification time is very sensitive to changes in HTC values within the range 600 W/m^{2}K ~ 1000 W/m^{2}K, but less sensitive outside of this range. This may in part be caused by the prior 10 cycles of calculations carried out with a certain cycle time (170 sec), regardless of the difference in HTC values. This may result in some castings in the calculation with an extremely low HTC, such as 200 W/m^{2}K, which had not solidified before the end of a cycle, which would lead to a low mold temperature for the 11th cycle.

Nevertheless, there are significant differences in solidification times within a reasonable range of the HTC. In addition to the difference in solidification time, the pattern of the distribution of the solidification time in the cases of HTC-400 W/m^{2}K and HTC-1000 W/m^{2}K are also different, as shown in Figure 5. It was noticed that in Figure 5 (a) the thin rim solidified later than the thicker top portion, but in Figure 5 (b), it was reversed.



(a) HTC-400 W/m^{2}K (b) HTC-1000 W/m^{2}K

Figure 5: The pattern of solidification time distribution affected by HTC values

2.2.3 Influence of localized HTC values

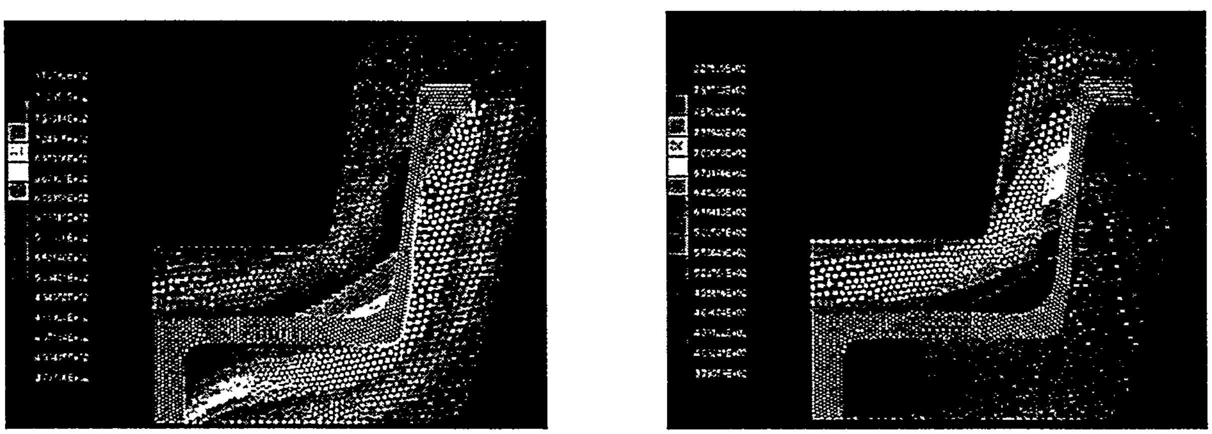
At present, it is normal to use an HTC value, either constant or a temperature-dependent profile, to represent all surfaces of a casting, regardless of the local geometrical features. Little systematic study on the influence of local geometrical features on the casting process has been conducted. However, it is inevitably important for the die design, cooling and heating design and the prediction of distortion of either casting or mold.

Two additional cases were calculated for the wheel casting. In Case One, it was assumed that there would be no gap at the interface between the casting and the bottom-half of the mold, due to gravity, but a gap would exist at the interface between the casting and the top half of the mold. And then, the HTC at the top-casting interface was assigned a value of 200 W/m^2K, and the bottom-casting interface was assigned a value of 1400 W/m^2K. Supposing the contact area between casting and top-mold is the same as that between casting and bottom-mold, the median HTC is then 800 W/m^2K.

In Case Two, it was assumed that there would be no gap at the interface between the casting and the top-half of the mold, because the design keeps the casting stuck to the top-half of the mold when the mold is opened, but a gap would exist at the interface between the casting and the bottom-half of the mold. And then, the HTC at the top-casting interface was assigned a value of 1400 W/m^2K, and at the bottom-casting interface was assigned a value of 200 W/m^2K.

2.2.4 The mold temperature

Because of differences in the HTC at the interfaces, the mold temperature at the top half and bottom half became different, as shown in Figure 6 at the end of the 10th cycle.



(a) Case One (b) Case Two

Figure 6: The localized HTC results in differences of the mold temperature

In Figure 6, it is apparent that the localized HTC is a key factor in affecting the accuracy of a simulation. If the purpose of simulation is for prediction of distortion or stress, any error in the temperature distribution will be misleading. It is also worthwhile to point out that the results shown in Figure 6 could provide substantial information to a die designer in considering die cooling and heating.

Even today, we still can not decide which one of these two cases is closer to reality. It is believed that the real situation may be even more complicated than for Case One and Case Two, due to the concave and convex surface features of the mold.

It is hopeful that the experiments at Amcast can lead to a better understanding of the actual situation.

Due to the limitation of this report, we cannot include all necessary data and results. If you have further interest, please contact us at the University of Michigan.

3. The Experimental Study at CMI-Tech Center

3.1 The experimental mold

After meeting with U-M, CMI has decided to use a "hockey puck" mold for the experiments. The mold required some minor modifications for the experiments. The pressure and temperature measurements will be conducted with four or five pressure probes and four or five thermocouples.

3.2 The objectives of the experiments

The objectives of the experiments at CMI will be, but not limited to:

1) To predict the gate freezing time.
2) To predict whether a gap is formed.
3) To determine the correlation between pressure and porosity (if any).
4) To determine the HTC-pressure profile in squeeze and semi-solid casting.

3.3 The pressure sensors

There are two ways of measuring the cavity pressure in die casting and squeeze casting. They are indirect cavity pressure measurement and direct pressure measurement.

In indirect measurement, a movable pin is used to deliver the pressure from the cavity to a sensor outside the mold. In direct measurement, the sensor is installed to contact directly with the liquid metal. This can provide more accurate data with a shorter response time than the indirect pressure measurement.

The cost of a direct pressure sensor is high, roughly $2000/piece. There is feedback regarding a short lifetime for the direct pressure sensor in the application of squeeze casting from the industry. This issue is under serious investigation. The reason for failure of the sensor is still unknown. It might be caused by high temperature during a relative long solidification time. Dr. SW Hao has experience in using the pressure sensors in

Singapore for high pressure die casting and semi-solid casting experiments. He has not had problems with the pressure sensors up to 500 shots. The supplier of the pressure sensors has some experimental data showing that the direct pressure sensor can last for more than 100,000 shots.

After careful review and discussion with the vendors, CMI and U-M believe that the Kistler pressure sensor can fit the application for this project.

CMI has purchased a system for direct cavity pressure measurement from Kistler based on suggestions from U-M. The system and pressure probes were delivered and checked item by item by both CMI and U-M

The hockey-puck casting has been selected for this project. The modification of the die has been completed. All necessary preparation in the CMI workshop has been finished.

The Kistler pressure sensor is shown in Fig.7 and it is the same type as those used at The Ohio State University [5] and the Gintic Institute of Manufacturing Technology, Singapore [6].

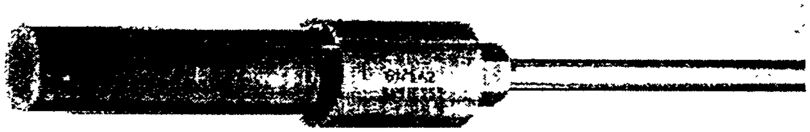


Fig. 7 The Direct cavity pressure probe for Die Casting (Type 6175A2)
(Courtesy Kistler, Switzerland)

A flow-chart of the direct cavity pressure measurement system is illustrated in Fig.8. All of the system, including accessories, have been delivered to CMI.

The hockey-puck casting to be used for the initial experiments is shown in Fig. 9 with the locations of temperature measurement and pressure measurement. At the beginning of a series of experiments, only one point will be measured. It is just in front of the gate close to the centerline of the casting.

A series of experiments were designed at U-M and proposed to CMI-Tech Center for the first round study to be conducted at the CMI-Tech center. The plan of the experimental study was worked out together with CMI-Tech center team members, including Karl Voss, Don Roberts, Gregory Woycik, David Moore and Christopher Rohloff.

3.4 Experimental Plan

Objectives

i. To study the feasibility of the Kistler Pressure Probe and the OMEGA temperature probe.
ii. To investigate the influence of intensification pressure on gate freeze time.
iii. To investigate the influence of the pouring temperature on gate freeze time.
iv. To collect data for predicting the proper heat transfer coefficient near the gate.

Number of Measurements

Each setting should be measured five times after 5 warm-up shots.

The Melt Temperature

Two melt temperatures will be experimentally used, the lower one at 1300 F and a higher one at 1390 F.

The Intensification Pressure

Two pressure settings are to be utilized, a high pressure and a low pressure. The setting should be measured later after the experiments. Targeted pressures are 15000 psi and 7000 psi, respectively.

The Plunger Speed

The gate velocity should be kept at 1 m/s. This can be calculated from the ratio of the gate area and the area of the shot sleeve.

Cycle Time

The cycle time for the first 5 shots should be as usual. For the five shots which are monitored, it is suggested to prolong the cycle time to 60 seconds for data collection purposes.

Die Temperature

If possible, the die should be preheated to 400 F.

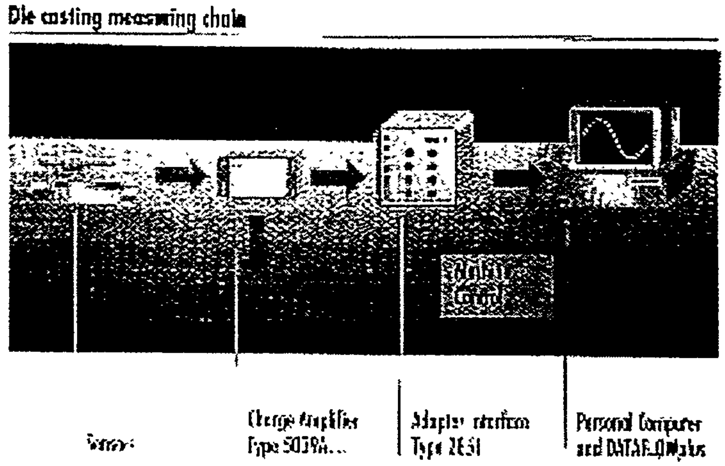


Fig.8 The flow-chart of direct cavity pressure measurement
(Courtesy Kistler, Swizerland)

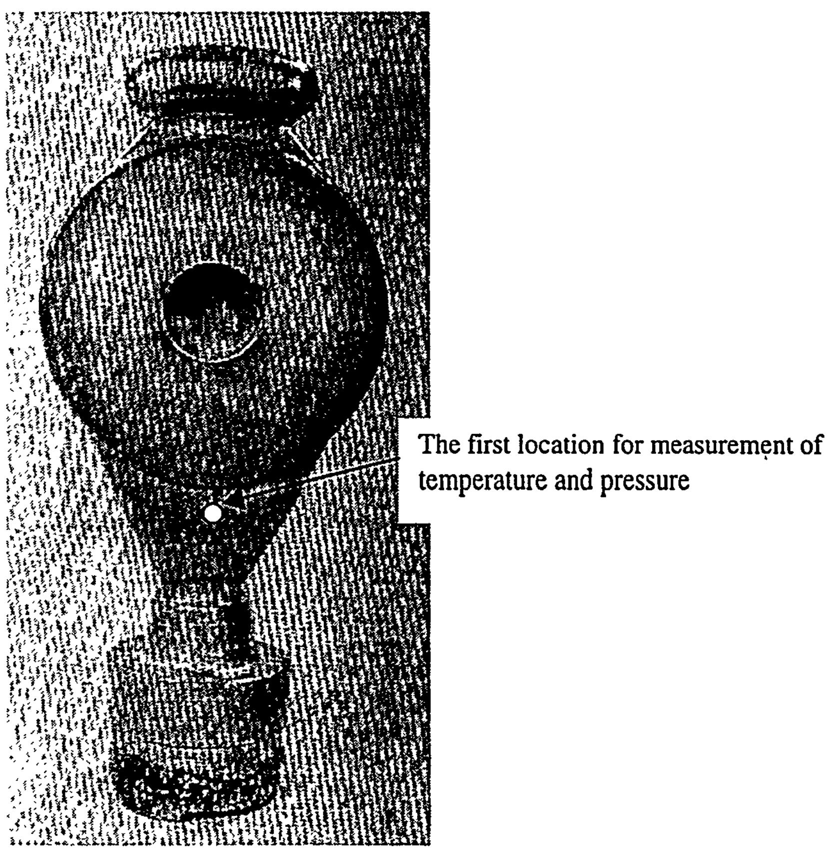


Fig.9 The hockey-puck casting for this project
(Courtesy CMI International)

4 The Experimental Study at Amcast Automotive

4.1 Experimental mold

4.1.1 Discussions

There were two possibilities for an experimental mold at Amcast. One was to use an existing instrumented mold. Another was to fabricate a new mold.

Extensive discussion with Amcast was conducted to select a mold for this project. The advantages and disadvantages of using an existing mold are:

1)Time and Cost

By using the existing mold, we only need to install thermocouples. Cost and time can be saved.

2) The Inverse Conduction Problem

With the existing mold, a 3-D heat transfer problem will be encountered, in which the HTC may not be accurately calculated. With a symmetric newly designed mold, this problem can be avoided. This raises a problem, however; which is how the data from a newly designed mold can be used in simulating the real mold. The inverse conduction problem with the real mold may be solved in the next two years, or be improved soon. In this case, our experiments with a symmetrical mold may be left behind and may be regarded as out of date. At the same time, based on our experience, about half of the wheel is below the liquidus temperature before the mold is completely filled. This means that the heat transfer coefficient during the filling stage is crucial for predicting cold shuts and other defects. However, there is no method to calculate the HTC during the filling stage for low-pressure die casting. Because the filling stage is short and the dynamic temperature changes with time, thermocouples will lag behind. This also means that even if a simplified mold is used, some numerical methods, besides the inverse conduction calculation, are needed to determine the HTC.

3) Installation of the probes

Thermocouples and ultrasonic probes will be used in the experiments. Since the existing mold is hardened, a new mold can make the installation of the probes much easier and more accurately placed.

4) The Meaning of the Experiments to Amcast

This is really dependent on the characteristics of the new mold . If the new mold is too simple, even in a smaller size, the solidification process will be different from the real case. Particularly, the thickness of the wall will significantly influence the HTC. The draft of the rim will affect the interfacial contact conditions. If the new mold can be designed with some selected features, like changeable inserts for different wall thicknesses for the rim portion, a slope in a portion of the rim, etc., this will make the experiments more meaningful for Amcast in future studies.

If the existing mold is used, the influence of the process settings on the HTC, and the influence of the cooling conditions and coatings can also be studied. The data can be directly used in production or design. Previous measurements and calculations will be relevant to our study where comparisons can be made. As a result, the project can be speeded up and more informative data can be collected.

5) Quality Correlation

With a new mold, it is possible to get a casting which will always have defects, and it may be impossible to get a good casting. This would make it impossible to study the correlation between HTC and defects, such as shrinkage porosity.

However, with the existing mold, by changing process conditions, it is possible to study the correlation between the casting and the heat transfer situation. Many investigations can be done, like micro hardness measurements to predict the cooling rate near the surface, then to correlate this with calculations using the newly obtained HTC. The study of porosity distribution can also reveal the influence of the HTC. This may be beyond the scope of this project, but could be done by Amcast engineers.

4.1.2 Decision

The management of Amcast Automotive has made a decision to fabricate a newly designed instrumented mold for this project with exchangeable inserts. This shows Amcast's commitment to the success of the project.

4.2 Ultrasonic gap formation measurement

Dr. Hao has surveyed and contacted more than nine vendors of ultrasonic probes and monitoring systems. It is believed that the technique is suitable for this project.

The so-called pulse-echo ultrasonic measurements can be used to measure the gap formation under casting conditions [7]. The principle is that when ultrasonic waves impinge at the boundary between two different media, some of the energy is transmitted through the boundary and the rest is reflected back. Pulse-echo ultrasonic measurements can be operated in reflection and transmission modes. In the reflection mode, the signal is transmitted and received by the same ultrasonic transducer (UT), while in the transmission mode, the signal is transmitted by one UT and received by another. The reflection mode is preferred because only mold side access is required, which best suits casting conditions.

During the measurement, an UT emits ultrasonic pulses and receives the signal reflected back by the inner surface of the mold. Before the liquid aluminum reaches the point, the emitted signal almost totally reflects back from the steel mold-air (cavity) interface because of the very small acoustic impedance of air compared with that of steel. Hence, the reflection coefficient is almost 1. During the filling, as soon as the molten metal wets the mold inner surface where the ultrasonic waves impinge, a part of the ultrasonic wave energy penetrates the molten material. Thus the reflected ultrasonic wave energy decreases accordingly. After the filling, the part cools down and then becomes solidified. As solidification progresses, the part begins to shrink through its thickness and a gap is likely to be formed. After a sizable (> 1 μm, or larger than the wavelength) gap is developed, the steel-air condition, and therefore, the reflected amplitude returns to the maximum level.

However, there is not any vendor who supplies the system of gap formation measurements for casting conditions. It will take some time for U-M and Amcast to put everything together to do the ultrasonic measurement. Hence, the two organizations have decided to carry out temperature measurements first. At the same time, extensive study of the ultrasonic gap measurement will be going on.

4.3 Preparation of Ultrasonic Measurement of Gap Formation at Amcast

At Amcast, an experimental system has been designed. The newly designed mold has been numerically simulated, as shown in Fig. 10. The measurements of temperature and gap formation will be initially made at the locations shown in Fig.10.

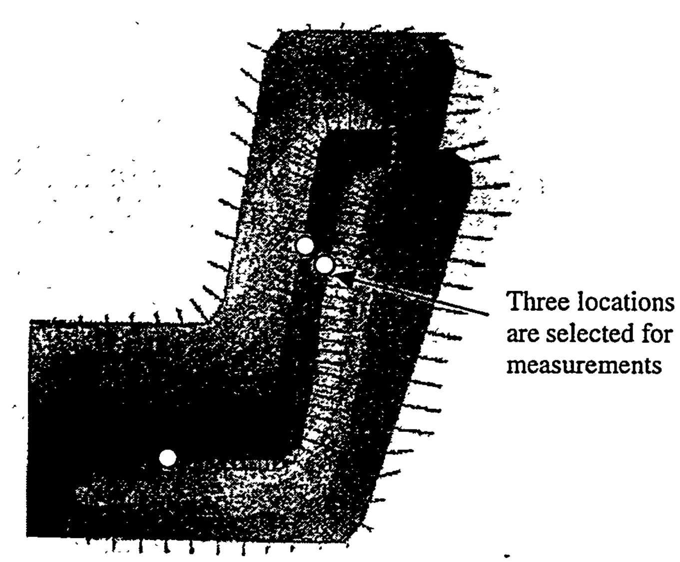


Fig.10 The simulated result of the wheel-like mold (Courtesy Amcast Automotive)

Due to economic and technical reasons, the ultrasonic gap formation measurements for low pressure permanent mold casting at Amcast needs further evaluation. The University of Michigan team has tried to find an ultrasonic device to do a feasibility study before Amcast commits to build a system. However, so far suitable devices haven't been found by the U-M team.

The temperature monitoring of a permanent mold casting has been designed. A suitable probe for in-cavity temperature measurement will be carefully studied.

5. Information Exchange

5.1 The Foundry Association of Michigan

A semi-annual board meeting of the Foundry Association of Michigan was held on September 23, 1998 at the University of Michigan.

Prof. R.D. Pehlke and Dr. S. W. Hao were invited to make presentations at this semi-annual board meeting of the Foundry Association of Michigan on September 23, 1998. The progress of this project was briefed. Prof. R. D. Pehlke was the host of the meeting at the University of Michigan.

After the meeting, the board members and other participants toured the Department of Materials Science and Engineering at the University of Michigan.

5.2 Communication with Dr. Joseph S. Santner

In August of 1998, Dr. Santner, Director of Research, American Foundrymen's Society, offered several comments on this project. We believe they are very valuable with several important issues brought to our attention. Our responses to Dr. Santner's comments and questions follow.

Several key aspects include:

1) "Programmed to a high standard" is our target in developing the HTC. CMI & Amcast haven't used it, but are aware of its development. So far, the software has been tested only at the U-M. Abstracts of 68 papers with key figures and conclusions have been input into the Reference Module. The student, who is not familiar with programming, has used it for more than one month. She reported that it is very easy to use. The Virtual C++ language has been used to develop it. It gives great freedom for us to manage it in the future.

The next stage of development is to develop a semi-automatic geometry recognizer. The geometry recognizer should be able to distinguish local geometrical features, such as a convex or concave surface with the input from a CAD file via the STL, STEP or IGES format and certain interactive actions of the operating engineer.

This development is very important to accurately evaluate the local HTC, which is heavily dependent on the geometry. We believe that without considering the influence of geometry, the HTC is not practically useful in foundry modeling. Our research is attempting to show the industry, particularly in permanent mold casting, that a single HTC cannot represent all surfaces of a casting.

The knowledge of semi-automatic geometry recognition is also very interesting to the pattern and mold makers for setting codes for NC machining. Prof. Jun Ni, Director of the S.M. Wu Manufacturing Center at the U-M (which stations more than 80 staff and students), expressed his interest in this development. We have tentatively agreed to put one of his Ph.D. students on this project. He will join us this month.

However, the HTC Evaluator is still in its infancy. We are open for any suggestions, particularly from the steering committee.

2) The results of Prof. Piwonka's researches at MCTC, University of Alabama, are definitely very important to us. We haven't talked with them at this moment. However, we are receiving their monthly reports.

The work of Joey Parker at MCTC of U-Al has been followed.

However, because we are dealing with permanent mold casting, based on our knowledge, the eddy current displacement technique is usually used for non-contact measurements. The commercial eddy current probe can only be used below 80 C. The maximum possible working temperature is 350 C for a short time.

In our case, the liquid metal will contact the probe first before a gap is formed. How can the probe survive during high temperature contact with liquid metal? On the other hand, to cool down the probe in a permanent mold without disturbing the mold temperature is almost impossible.

We are interested in an ultrasonic probe with a buffer rod to transfer ultrasonic signals from the metal/mold interface to a sensor outside of the hot mold for measurement. This technique is proven and used by the National Research Council of Canada.

As you note concern, the cost of the system may be a big issue to our industrial partner at this moment. We are trying to overcome the cost problem.

3) The data in our database will be organized into seven groups in accordance with seven basic foundry processes, such as die casting, sand casting, investment casting, permanent

mold casting, semi-solid casting, continuous casting, etc. By doing so, the data should be less scattered and better organized.

We have collected more than 60 papers, but most of them are in sand casting or gravity permanent mold casting with simple geometry, like a plate or cylinder. The HTC from previous papers ranges from 80 W/m^2 K to 25,000 W/m^2 K. It is very hard for an engineer to choose an HTC value for his use, based on published literature. That is why we need to develop the HTC evaluator for the industry.

From these publications, the key figures, abstract, conclusions will be collected in the Reference Module for the user's reference.

The data in the database would be protected, but the user would be able to modify values for his specific uses and trials. The experimental data may require modification because of geometry, the process, materials involved, etc.

4) The results of our literature survey will be made available to AFS in its entirety.

5) The "Mochiku" type of temperature monitoring probe is very good. We are going to build a similar one. But, we still believe that direct contact is the best solution to temperature measurement.

For an HTC calculation, measurement is very important, but not everything. A systematic methodology to reduce the errors in measurement by using the principle of the Inverse Thermal Conduction Method is also very important.

6) For several reasons, initially we will measure one location for pressure and one for temperature. Eventually, four locations for both temperatures of the casting and pressure will be measured. A number of locations in the mold will be continuously monitored with thermocouples.

The pressure probe will be flush with the mold surface. The probe is small and the material of the probe is similar to that of the mold. We anticipate relatively small, if any, thermal effects.

7) We are planing to study low pressure permanent mold casting at Amcast, which is different from the experiments for squeeze casting and semi-solid casting at CMI. Therefore we have selected the Kistler system for pressure measurement at CMI. We do not anticipate making any pressure measurements in low pressure permanent mold casting at Amcast.

5.3 Dr. Nguyen, Thang

Dr. Thang T. Nguyen of CSIRO, Australia and Dr. Roderick J. Esdaile of Materials Science and Technology, CSIRO, visited the U-M team on May 7. Dr. Nguyen is a well-known scientist in low pressure permanent mold casting. Prof. Pehlke and Dr. Hao introduced the current program and progress to the visitors. Dr. Nguyen expressed his interest in future collaboration with U-M in this field. He also briefly presented his achievements in research on permanent mold casting.The meeting is regarded as very valuable by both parties. Future information exchanges have been agreed upon.

5.4 Dr. S.W. Hao's presence at 102^{nd} AFS Congress

Dr. S.W. Hao attended the 102^{nd} AFS Congress in Atlanta from May 10 – 12. He had chances to exchange information on the current project with many researchers and engineers. The progress of the project was also introduced to many interested engineers.

5.5 Prof. I. L. Svensson

Prof. Svensson of the Jonkoping University, Sweden visited U-M on June 5. Prof. Pehlke and Dr. Hao had very constructive discussions with him on the technology of numerical simulation in casting. The possibility for exchange of students was also discussed. Prof. Svensson showed great interest in the progress of the DOE project on heat transfer in permanent mold casting. The two sides agreed to enhance information exchange in the future.

5.6 Dr. S.W. Hao's presence at Industrial Oversight Panel meeting

Dr. S.W. Hao attended the IOP meeting of the Department of Energy on June 16 at the headquarters of the American Foundrymen's Society. Even though, Dr. Hao had worked about four years in Japan with Prof. E. Niyama and 3.5 years at a National Institute in Singapore, he is still a new face in the American foundry industry. This was a chance to meet the leaders in both industry and academia in the United States. Also, it was an opportunity to gain an understanding of DOE policies toward researches in metal casting.

5.7 Prof. R. D. Pehlke attended the MCWASP Conference

Professor Pehlke attended the Modeling of Casting, Welding and Advanced Solidification Processes in San Diego, June 7-12, 1998.

6. Meetings with Industrial Partners

Project meetings are routinely organized with the industrial partners. The minutes of recent meetings are summarized below.

6.1. Summary of the minutes of the third project meeting of CMI and U-M

Venue: Meeting Room, CMI-Tech Center, INC, 1600 West Eight Mile Road
Ferndale, MI 48220
Time: 10:00 am – 12:30 PM, April 16 (Monday), 1998

Participants: Karl Voss (CMI, Dir.- R&D), Don Roberts (CMI, Dir -Manufacturing),
Kip Mohler(CMI, Manager- Squeeze), Gregory Woycik (Manager-Materials) ,
Steve Lou (CMI, Proc. Engineer), Rong Pan (CMI, Proc. Engineer)
Robert D. Pehlke (Prof.,U-M), Shouwei Hao(U-M)

6.1.1. Presentation of U-M Program Outline

Dr. Hao presented the proposed U-M program outline. The proposed HTC evaluator was introduced. Pressure measurement was suggested for squeeze casting and semi-solid casting. The experimental design, including location of pressure probes, type of sensors and an acquisition system were proposed and explained by Dr. Hao. Some case studies conducted by Dr. Hao in Japan on the modeling of solidification and mold filling processes were shown and discussed. Some experimental results of the pressure measurement from high pressure die casting conducted by Dr. Hao in Singapore were also presented and discussed. Dr. Hao noted that the purpose of the study at CMI is to find out how the extra pressure in squeeze casting and semi-solid casting affects the HTC, and how high the HTC should be. Pressure measurements can be used to link the pressure with HTC in these processes. Also, contact pressure is an ideal indicator to know whether a gap is formed between casting and mold.

Mr. Voss, Mr. Roberts, Mr. Mohler and Mr. Woycik accepted the experimental design and the proposal. They also asked Dr. Hao and Prof. Pehlke to provide specifications for pressure probes. Mr. Roberts may find a different source to supply a system for the pressure measurement. Ms. Pan expressed her interests in pressure measurements at the top of the hockey puck casting.

6.1.2. Experimental Mold

Mr. Woycik and Mr. Roberts presented several designs of the gating system for the hockey puck casting. Finally, Mr. Voss, Mr. Roberts, Mr. Woycik and Mr. Mohler reached agreement on a thicker gate for the experimental mold.

6.1.3. Positions of pressure probes

The decision was made to place four pressure probes in the experimental mold for the study. But, at the beginning, Prof. Pehlke suggested to test two probes first before all holes are drilled. Dr. Hao suggested installing the probes from the back of the insert. In this case, no holes are needed through the frame of the mold.

All participants agreed that the probes shouldn't block the movement of any existing eject pin. Dr. Hao believes the positions can be flexible to a certain degree. The holes for pressure probes can also be used in temperature measurement experiments.

6.1.4. Information Exchange

Dr. Hao was asked to provide the specification of the pressure monitoring system and a paper of Nishida and Matsubara.

Prof. Pehlke will provide Mr. Voss with the milestones and timeline from the original proposal. Revisions, updating and finer tuning will be discussed with a basis to be developed for continuous updating.

The meeting was adjourned at 12:30.

6.2. Summary of the minutes of the third project meeting of Amcast and U-M

Venue: Meeting Room, Amcast Automotive, Southfield, MI 48034

Time: 2:30 PM, April 20 (Monday), 1998

Participants: Vijay Shende(Amcast), Sarah Chen(Amcast)
Robert D. Pehlke(U-M),Shouwei Hao(U-M)
John Cookson (U-M)

6.2.1. Proposal of U-M on the work plan for the project

A proposal on the development of an HTC evaluator and the expected experiments at Amcast for a better understanding of the HTC in low pressure permanent mold casting was presented by Dr. Hao. A few examples of Dr. Hao's previous researches on squeeze casting (an aluminum wheel) and some experimental results of the mold filling process were also presented. In conclusion, Prof. Pehlke and Dr. Hao suggested to separate the project into three tasks. They are: Task i) Development of an HTC evaluator at U-M: Task ii) Study on the influence of extra pressure on the HTC in squeeze casting and semi-solid casting (CMI): Task iii) Study on HTC in low pressure permanent mold casting (Amcast).

6.2.2. Experimental mold issue

Dr. Chen has identified a possible existing instrumented mold for an aluminum wheel which might be used in this project. Dr. Hao believes it may be suitable for study in this project. However, Dr. Shende expressed his concerns on using this mold. The major concerns include some special features of the mold, the thin rim portion of the mold which may cause measurement difficulties in extracting accurate HTC, the hardened mold may not be easily modified, and the complexity of the mold may cause 3-D heat flow very near the interface which causes problems for inverse calculations in the future. Dr. Shende emphasized that an accurate HTC from inverse conduction calculations, rather than from trial-and-error, is expected. Dr. Shende asked Dr. Chen and Dr. Hao to point out the advantages and the disadvantages of using either a simplified mold or the existing mold as soon as possible. If a newly designed mold is an advantage for this project, it will be possible to fabricate it.

All participants believe that the decision on the experimental mold should be made as soon as possible.

6.2.3. Sensitivity Study

Dr. Cookson presented some preliminary results of a sensitivity study of a simplified mold. Dr. Chen presented some simulation and experimental results of an existing mold and pointed out a few problems with previous measurements on this mold.

6.2.4. The problems cited

Dr. Shende, Dr. Chen and Dr. Hao raised the problem of incapability of inverse conduction calculations for 3-D heat flow. Prof. Pehlke indicated that an allocation of funds for consultation by Professor Beck at Michigan State University is available to the program.

Temperature measurement problems were also raised by Dr. Chen and Dr. Shende. The delayed response time of a thermocouple may yield misleading results. Some previous studies presented by Dr. Hao show that the temperature of aluminum when reaching the rim of a wheel casting may be below the liquidus temperature. Dr. Chen's data show that the temperature is even lower. Dr. Hao also pointed out that the filling stage for a wheel is very critical for this study. The difficulty in extracting HTC during mold filling will be faced, if a wheel casting is selected for study.

The positional error associated with temperature measurement was also discussed. Special design for the installation of thermocouples was analyzed. The solution should involve fixed plugs in the mold body.

6.2.5. Follow-up actions

i) Listing the advantages and the disadvantages of using either the existing mold or a simplified mold ---- Dr. Chen and Dr. Hao.
ii) Identify a supplier of thermocouple inserts for use in the molds --- U-M and Amcast.

The meeting was adjourned at 4:45 PM.

6.3 Summary of the minutes of the fourth project meeting of CMI and U-M

Venue: Mr. Karl Voss's Office, CMI-Tech Center, INC, 1600 West Eight Mile Road
Ferndale, MI 48220
Time: 2:00 PM, June 19 (Friday), 1998

Participants: Karl Voss (CMI, Dir.- R&D), Don Roberts (CMI, Dir -Manufacturing),
Douglas E. Moran(CMI), Rong Pan (CMI, Proc. Engineer), Mike Griff (CMI)
Robert D. Pehlke (Prof.,U-M), Shouwei Hao(U-M)

6.3.1 Confirmation of the minutes of the last meeting

The minutes of the third meeting were reviewed and confirmed by both organizations.

6.3.2 Progress of the Project at CMI in June 1998 (Karl Voss)

The pressure probes and the system have been purchased. The system was delivered by Kistler in June. The experimental mold is designed and will be modified.

6.3.3. Progress of the Project at U-M in June 1998 (R. D. Pehlke, S. W. Hao)

The first stage of the development of the HTC Evaluator has been conducted and almost finished. The initial modeling of the inverse conduction problem with ProCast is in preparation. More than 100 papers related to the project have been cited and most have been collected.

6.3.4. Discussion on the Delivered Pressure Sensors and the System (all participants)

All items delivered by Kistler were checked item by item. There are two 6175A2 direct cavity sensors, one charge amplifier (one channel), one adapter interface and the DATAFLOWplus (a data acquisition software) as well as several heat-resistant cables.

It was noted that some accessories are needed and will be ordered by CMI as soon as possible. It is estimated that it would take about two weeks to get the newly ordered parts.

It was suggested that some calibration and testing could be done at CMI before the entire system is installed in the casting machine.

The installation of the pressure sensors were discussed and finalized. At the beginning, the first pressure sensor will be located just behind the gate. A support for the sensor near the back of the mold is also needed.

6.3.5. Temperature Measurements (All participants)

It was agreed that accurate temperature measurements are as important as the pressure measurement to the success of the project. A temperature probe will be designed and fabricated for this project. The temperature inside of the casting will be measured with direct contact of the thermocouples and the liquid metal. It is quite challenging, but worthwhile doing.

The locations of the temperature probes will be the same as those of the pressure probes.

6.3.6 Mold Modification (All participants)

The hockey-puck casting mold was checked and possible locations for measurement were determined. All measurements will be carried out in the moving half of the die.

Further possible measurements and experiments were also discussed.

6.3.7 Modeling

There is a difference in the software used by our two organizations. It may result in some difficulties in exchanging modeling data. This issue should be resolved as soon as possible.

The meeting was adjourned at 4:30 PM

6.4 Summary of the minutes of the fourth project meeting of Amcast and U-M

Venue: Meeting Room, Amcast Automotive, Southfield, MI 48034

Time: 9:30 am, July 2 (Thursday), 1998

Participants: Vijay Shende(Amcast), Sarah Chen(Amcast)
Robert D. Pehlke(U-M),Shouwei Hao(U-M)

6.4.1 Confirmation of the minutes of the last meeting

The minutes of the third meeting were confirmed by both organizations.

6.4.2. Progress of the Project at Amcast in May and June 1998 (V. Shende, S. Chen)

The new experimental mold with exchangeable inserts was designed and drawn in a CAD file. The plant will have the mold fabricated outside. An update on progress will be received next week.

Modeling of the newly designed experimental mold has been conducted with a 2-dimensional calculation. The directions of heat flux were determined. This information is useful in estimating the positions of both gap formation and thermal profiles.

6.4.3. Progress of the Project at U-M in May and June 1998 (R.D. Pehlke, S. W. Hao)

As well as participating in the discussion with Amcast on the design of the experimental mold, the first stage of the development of the HTC Evaluator has been undertaken and will be finished soon. Some modeling studies have been started with ProCast.

The survey and study on an ultrasonic gap formation measurement system has been initiated and the necessary information has been collected. It is believed that the technique is suitable for this project.

6.4.4. Introduction of the Ultrasonic Probe and its Principles (S. W. Hao, U-M)

Dr. Hao briefly introduced the results of the survey on ultrasonic gap formation measurement.

It is agreed that the technique is suitable for the purpose. Dr. Shende raised some questions on the voltage level and data frequency of the probe to see whether an existing data acquisition system at Amcast can be used, which is a PLC (Allen-Bradley) system with a +/- 10 mv range. Dr. Shende will follow up to find how many channels are available. It is estimated that at least 11 channels are needed for the measurement (3 channels for ultrasonic signals and 8 channels for thermocouples). Dr. Shende is also concerned about the expense of the ultrasonic system. Dr. Hao will respond to these questions.

6.4.5.Thermal Probe (All participants)

The construction of a temperature probe was discussed. The Mochiku type of probe is proposed. The thesis of Mr. Zhang of Ohio State University was loaned to Prof. Pehlke. Dr. Shende will send additional information on the temperature probe. Dr. Shende will contact Ken Dolan at Sandia Lab. The U.S. Car Program is working on fiber optic measurement of temperature and ultrasonic measurement systems.

6.4.6 Positions of Measurement (All participants)

Three positions were firstly identified for measurement. They are:

i) The top surface of the horizontal portion.
ii) The inner surface of the rim.
iii) The external surface of the rim.

6.4.7 Time Table of the Experiments (All participants)

All participants believe that the ultrasonic measurement is not totally settled. The preparation will take some time. It was decided that the temperature measurements would be done first. It is estimated that the first experiment could be done by the end of this August.

6.4.8. Follow-up Actions

6.4.8.1 The quotation of the ultrasonic system (SW Hao)

As Dr. Shende emphasized, this is a major concern before a decision can be made. After that, the specifications of the system should be obtained.

6.4.8.2 The fabrication of the temperature probe carrier and the buffer rod need to be defined and a machine shop source located (S. Chen, SW Hao)

The meeting was adjourned at 11:15 am.

6.5 The Steering Committee Meeting

Minutes of the Steering Committee Meeting
(by conference call)
Friday, February 6th, 1998

Present: Steering Committee: Jiten Shah (K+P Agile), Anand Paul (Concurrent Tech.), Jake Zindel (Ford) & Doug Trinowski (Delta); Joe Santner (AFS), Prof. Robert Pehlke (UM), John Cookson (UM), Sarah Chen (AmCAST) & Karl Voss (CMI).

The call was made at 2:30 p.m. and the meeting came to order at that time.

Prof. Pehlke reviewed the program briefly, outlining the objectives and describing the progress made so far. This included the meetings with the industrial partners, the purchase of the HP J282 computer, the literature search performed to date as well as the initiation of sensitivity analyses. The recent publication of the article by Anderson et al. from The University of Swansea, which described the instrumentation of a permanent mold of a wheel was also reviewed.

At this point, the existence and availability of test molds, which were extensively instrumented, was raised. Karl Voss described a "hockey puck" squeeze cast mold geometry as well as a tensile bar mold geometry, both of which would be available. Joe Santner raised the possibility of using a "Mail Box" casting geometry, and Doug Trinowski confirmed that this had been used for sand casting tests.

Joe Santner encouraged the group to seriously consider using this "Mail Box" geometry as it has been used for sand casting applications. He believes that an appropriately scaled version for permanent mold casting may well be able to take advantage of the understanding, which has been developed, for this geometry in sand casting. He impressed upon the group that this was a good example of how communication and "cross fertilization" between the different areas of cast metal research could be beneficial, and further encouraged the group to use the pooled information as much as possible. John Cookson asked whether the geometry was representative of parts manufactured by permanent mold casting, and Doug Trinowski responded that there were thin wall sections in geometry, which may make it suitable. However, Karl Voss expressed concern at this point and stated that the design would need to be reviewed for its suitability prior to a commitment to fabricate a test mold of this geometry.

The reporting requirements were reviewed following an inquiry about the frequency of reporting to both the AFS as well as the DOE. Joe Santner reiterated that monthly reports were to be generated for the AFS, which would in turn be distributed to the Steering Committee. Prof. Pehlke informed the group that the DOE requirement for reporting (DOE F 4600.2 09/92) stipulated quarterly milestone logs and project status reports. These would also be distributed to the Steering Committee.

The meeting was adjourned at 3:00 p.m., to allow a 1-F meeting to take place immediately afterward.

7. Facilities Development

In addition to the cavity pressure measurement system purchased by CMI-Tech Center, two instrumented molds fabricated by CMI-Tech Center and Amcast, the U-M team for this project purchased a HP J282 workstation and two Dell PCs. ProCast packages have been installed with the HP workstation for numerical analyses. An ultrasonic gap formation measurement system is in the final stage of a feasibility review.

8. Literature Search

An extensive search of the available literature concerning interfacial heat transfer coefficients (IHTCs) has turned up a sizable number of papers. These papers address either the experimental determination of IHTCs or methods to manipulate the experimental data using various computational methods. The literature found appears in the list below in chronological order. It has been difficult to identify data from both smaller conferences as well as internal documentation, such that the literature may not be complete. However, it seems reasonable to suggest that there are no glaring omissions from this list, as these papers tend to cross reference each other, with no relevant references to work with which are not already on this list. The pertinent information will be extracted from these papers and ultimately presented in a descriptive format as well as the tabulated format shown in part below:

Table 1: Heat Transfer Data from the Published Literature

Author(s)	Mold/Metal combination	Geometry	Experimental Interfacial Heat Transfer Coefficient ($W/m^2/K$)	Simulation/ Computation Methods used
Ho & Pehlke	Copper chill/ Aluminum	Cylindrical, planar chill	initially... fell to	Finite diff.
Chiesa	Steel/Aluminum	Wheel mold	solidification front plots	Finite diff. (Magma)
Gunasegaram & Nguyen	composite: H13/Aluminum BeCu/Aluminum	Cylindrical with varying diameter	initially .... fell to	Finite diff. (Magma)

The article by Anderson et al. below represents a very comprehensive treatment, with an attempt made to correlate the geometry of the die with time dependent heat transfer coefficients, as well as the mold coating thickness.

Some Collected Relevant References:

V. Panachanathan, M.R. Seshadri & A. Ramachandran "Thermal Behavior of Metallic Molds with Long Freezing Range Alloys", AFS Transactions, v. 72, (1964), pp. 65-71.

C.W. Nelson "Nature of Heat Transfer at the Die Face", Paper 63, Die Casting Congress, (1970).

E.S. Tillman & J.T. Berry "Influence of Thermal Contact Resistance on the Solidification Rate of Long freezing Range Alloys", AFS Cast Metals Research Journal, (1972), pp. 1-6.

M. Prates, J. Fissolo & H. Biloni "Heat Flow Parameters Affecting the Unidirectional Solidification of Pure Metals", Met Trans., v.3, (1972), pp. 1419-1425.

M. Prates & H. Biloni "Variables Affecting the Nature of the Chill Zone", Met Trans., v. 3, (1972), pp. 1501-1510.

S. Engler, D. Boenisch & B. Kohler "Metal and Mold Wall Movements During Solidification of Cast Iron", AFS Cast Metals Research Journal, (1973), pp. 20-30.

D.R. Durham & J.T. Berry "Role of the Interface During Solidification of a Pure Metal Against a Chill", AFS Transactions, v. 82 (1974), pp. 101-110.

L.J.D. Sully "The Thermal Interface Between Castings and Chill Molds", AFS Transactions, v. 84 (1976), pp. 735-744.

Y. Nishida & H. Matsubura "Effect of Pressure on Heat Transfer at the Metal -Mould Interface", British Foundaryman, v. 69, (1976), pp. 274-278.

S. Hong, D.G. Backman & R. Mehrabian "Heat Transfer Coefficient in Aluminum Alloy Die Casting", Met. Trans. B, vol. 10B, (1979), pp. 299-301.

V. de L. Davies "Heat Transfer in a Gravity Die Castings", British Foundryman, v. 73, (1980), pp. 331-334.

K. Ho & R.D. Pehlke "Transient Methods for Determination of Metal - Mold Interfacial Heat Transfer", AFS Transactions, v. 91, (1983), pp. 689-698.

K. Ho & R.D. Pehlke "Mechanisms of Heat Transfer at a Metal - Mold Interface", AFS Transactions,
v. 92 (1984), pp. 587-598.

K. Ho & R.D. Pehlke "Metal-Mold Interfacial Heat Transfer", Met Trans., 16 B (1985), pp.585-594.

M. Bamberger & M.M. Stupel "Influence of Different Chill Materials on HeatFlux & Dendrite Arm Spacing of 356 Aluminum Casting", Giessereiforshung, v.38, (1986) pp. 77-80

T.X. Hou & R.D. Pehlke "Determination of Mold - Metal Interfacial Heat Transfer & Simulation of Solidfication of an Al 13% Si Casting", AFS Transactions, v. 96, (1988), pp. 129.

M.R. Tadayon & R.W. Lewis "A model of Metal - Mould Interfacial Heat Transfer for Finite Element Simulation of Gravity-Diecasting", Cast Metals, v. 1, n. 1, (1988), pp. 24-28.

H. Huang & J.T. Berry "Solidification Heat Transfer in Aluminum Investment Castings", ASME Heat Transfer Conf., (1988), pp. 93-99.

M.C. Lukens, T.X. Hou, R.D. Pehlke " Mold/ Metal Gap Formation of Al 356 Cylinders Cast Horizontally in Dry & Green Sand", AFS Transactions, v. 98, (1990), pp. 63-70.

F. Chiesa " Measurement of the thermal conductance at the Mold/Metal Interface of Permanent Molds", AFS Transactions, v. 98, (1990), pp. 193.

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Appendix I

Brief Description of HTC Programs

(Database & Reference Modules)

Contents

1. The structure of the HTC programs

The HTC program is implemented by Visual C++ on PC platforms. Object-oriented techniques and a document/view pattern are adopted in the HTC design.

The modules that the HTC includes are:

i) Reference Module

This module is related to the reference processing, which is divided into eight casting categories: squeeze, semi-solid, permanent, die, sand, investment, continuous and others. The functions include reference entering, browsing, finding, printing, modifying and deleting.

The graphics in references also can be processed, displayed and printed.

ii) Material Database Module

The material module is responsible for the processing of various materials. The material properties in this module include density, latent heat, solidus, volume shrinkage, liquidus, linear shrinkage, specific heat, solid fraction and thermal conductivity. Users can enter, modify, delete, browse and find any entry in the library with this module.

2. The interface of the HTC programs

Due to the program being based on the window platform, the interface of the HTC is very user friendly and easy to learn. When you enter the HTC program, the main window is displayed. In the client area of the window, the title, the project partner's mark and copyright will be displayed.

In the main window, there are the following menus and submenus:

File --- New, Open, Save, Save As, and Print view, Print, Print setting, Exit
DataBase --- New, Open
Reference --- Open, New, Find, Next, Previous, Delete
Exit
Option --- Toolbar, Status bar
Help --- Version, Description

----

3. The file description

The following gives the main programs in the HTC and their brief description:

. Htcc.h, Htcc.cpp

These are the main application source files that contain the application class CHtccApp.

. MainFrm.h, MainFrm.cpp

These files contain the frame class CMainFrame, which is derived from CFrameWnd and controls other frame features.

. HtccDoc.h, HtccDoc.cpp - the document

These files contain the CHtccDoc class, which implement file saving and loading.

. HtccView.h, HtccView.cpp - the view of the document

These files contain the CHtccView class.
CHtccView objects are used to view CHtccDoc objects.

. Base_open.h, Base_open.cpp

These files define a class CBase_open that are used to view and modify the Material Database.

. Data_base.h, Data_base.cpp

These files define a class CData_base which are used to renew a Material database entry.

. dibapi.h, dibapi.cpp, myfile.h, myfile.cpp, Frmfig.h, Frmfig.cpp

These files show the BITMAP graphs for reference.

. FileList.h, FileList.cpp

These files list the material category for reference.
Users can select one from the eight items.

. HelpText.h, HelpText.cpp

These files are used to display Help messages.

. MatList.h, MatList.cpp

These files list the material names which are already in the Data_base.

. RefDialog.h, RefDialog.cpp

These files define a Dialog box, which is used to view and modify the existing reference entry.

. RefInput.h, RefInput.cpp

These files define a Dialog box, which is used to add a new reference entry to the Database.

. RefList.h, RefList.cpp

These files define a class, which list the reference name in the current category.

. Temp_heat.h, Temp_heat.cpp

These files define a class which is used to enter heat and temperature and to show the corresponding diagrams.

. Warn.h, Warn.cpp

These files define a class which is used to give various warnings when an error occurs.

---

4. The external data structure

The external data are based in the hierarchy directory management. There are the following directories:

. $HtcRoot:

This variable defines the root directory in which the system will be installed.

. HtcRoot/Database

This directory contains material property information. Every material corresponds to a file. In this directory, the file <MaterialList.dat> contains all the existing material names.

. HtcRoot/Ref

This directory contains eight files, which are data files in correspondence to the eight casting categories, and eight sub-directories, which contain graphic files corresponding to the eight categories.

. HtcRoot/Projects

This directory includes many subdirectories, each of which is in correspondence to a project created by the File->New command.

. HtcRoot/Debug

The executable file is placed in the directory.

---

5. The internal data structure

The internal data structure can be divided into two kinds. The first one is related to the reference, the other one pertains to the material data.

(1) The reference data

```
class CRefEntry : public CObject
{
public:
  CString m_Title;
  CString m_Author;
  CString m_Abstract;
  CString m_Figure;
  CString m_Publ;
};

//reference data in htc
public:
  CObArray m_RefArray;
```

(2) The material data

```
class CDotEntry : public CObject
{
public:
 float m_Temperature;
 float m_Heat;
};

   // the material data in htc
public:
 CObArray m_DensityArr;
 CObArray m_LatentArr;
 CObArray m_SolidousArr;
 CObArray m_LiquidousArr;
 CObArray m_VolumeArr;
 CObArray m_LinearArr;
 CObArray m_SolidArr;
 CObArray m_SpecificArr;
 CObArray m_HeatArr;
```
