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

Quarterly Project Status Report

for the period October 1, 1998 to December 31, 1998

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Executive Summary:

The first series of experiments at the CMI-Tech Center was successfully conducted on October 14 & 15 with the participation of the University of Michigan team (Prof. Pehlke, Dr. S. Hao and Mr. Prasad Krishna). The CMI-Tech team (Karl Voss, Don Roberts, Gregory Woycik, David Moore, Christopher Rohloff, Douglas Moran, and Mike Griff) has successfully designed the die, modified the die and instrumented the die with the help of the U-M team. We gratefully acknowledge their important contributions to the success of the experiments.

The preliminary experimental results indicate that the die surface temperatures (or near the surface) have a close correlation with the metal pressure profiles. Considering the difference in timing of the peak die temperatures, the higher melt temperature and hotter die temperature for Inter 54 might cause a longer solidification time, and the pressure would decrease more slowly than for Inter 12.

The slopes of the metal pressure profiles at the low pressure setting are almost linear. This may mean that the low metal pressure couldn't effectively keep a pressure channel opened. In other words, as temperature decreased, the solid fraction increased and the solidified shell strengthened, and the pressure, which couldn't overcome the resistance, would drop linearly.

However, at the high pressure, there are inflection points in the pressure profiles. The inflection points are at about 8500 psi for both the low and the high melt temperature settings. This suggests that the metal pressure was sufficient enough to overcome the resistance of the solidified shell before the inflection point was reached. This also means that the pressure channel could be opened longer and larger. In our cases, when the inflection points were reached (at about 8500 psi), the solidified shell became strong enough to resist the intensification pressure. As a result, the slopes of the pressure profiles became steeper than before the inflection points.

At the high pressure setting, the higher melt temperature (1375 °F) could slightly prolong the time of pressure influence. The peak pressure values at the low melt temperature and at the high melt temperature conditions are the same. However, at the low pressure setting, the melt temperature had a more significant influence on the pressure profile. This may also suggest that the low pressure was insufficient in our case. As a result, any change in other conditions, such as melt temperature and die temperature, would severely impose a danger to the quality of the castings.

A preliminary microstructure analysis shows that the dendrite arms at the location near the gate are much coarser than that at the top of the casting. The influence of intensification pressure on microstructure needs further verification and study.

1. Experimental Study at CMI-Tech Center

The first series of experiments at the CMI-Tech Center were successfully conducted on October 14 & 15 with the participation of the University of Michigan team (Prof. Pehlke, Dr. S. Hao and Mr. Prasad Krishna). The CMI-Tech team (Karl Voss, Don Roberts, Gregory Woycik, David Moore, Christopher Rohloff, Douglas Moran, and Mike Griff) successfully designed the die, modified the die and instrumented the die with the help of the U-M team. We gratefully acknowledge their contributions to the success of the experiments.

1.1 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 pouring temperature on gate freeze time.
- iv. To collect data for predicting the proper heat transfer coefficient near the gate.

1.2 Experimental Data Sheet

Casting Name: Hockey-Puck-like Casting Machine: UBE-350 (vertical sleeve)
Alloy: A356 Pouring Weight: 1275 g
Melt Temperatures (°F): 1290-1310 (low temp.), 1374-1387 (high temp.)
Mold temperature (°F): 300 - 387 (after warm-up shots)
(Measured by contact thermocouple)
Targeted Intensification Pressure (psi): 7000 (low), 15000 (high)
Gas Level: Level 2
Coating: Graphite powder
Cycle Time (recorded): 70 - 100 seconds

1.3 Experimental Processes Variables

- 1) Low melt temperature, Low intensification pressure (11 shots)
- 2) Low melt temperature, High intensification pressure (10 shots)
- 3) High melt temperature, High intensification pressure (14 shots)
- 4) High melt temperature, Low intensification pressure (10 shots)

1.4 Problems

Before the experimental results are discussed, problems occurring in the experiments are cited.

- 1) Negative outputs of cavity pressure were recorded in the low intensification pressure condition. After discussions with Kistler, the vendor of the pressure probe, we suspect that contaminated connectors might cause an erratic or drifting signal on the output device. To overcome this problem, a special solvent is needed to clean the cables and connectors in the measuring chain.
- 2) Due to effect of the shields of the thermocouples, the peak of the in-cavity temperature and in-mold temperature were offset, and response times were prolonged. A systematic calibration will be carried out at the CMI-Tech Center to match up this offset.

Hence, it is worthwhile to point out that all of the following analyses are based on the raw data, which means the effect of an erratic output of the pressure probe and the effect of the protecting shields of thermocouples have not been quantitatively evaluated. This could result in some errors in explanation of the experimental results.

1.5 Locations of measurements

Figure 1: Locations of temperature and pressure measurements

As shown in Figure 1, both pressure probe and thermocouples were located before the gate. The in-cavity temperature measurement was aborted after the fifth shot, due to the failure of the thermocouple.

1.6 An experimental sample

The result of an experiment at low intensification pressure and low melt temperature is given in Fig. 2.

Figure 2: Metal pressure, casting temperature and die temperature at low intensification pressure and low melt temperature condition

It is noticed that the peak casting temperature in Fig. 2 is just about 1010 °F. It is believed that the protection shield of the thermocouple offset the peak in-cavity temperature. A calibration test should be conducted soon.

Also, the pressure decreased to a negative zone at the 5th second after the sensor firstly sensed a positive pressure signal. Based on the explanation of Kistler, the vendor of the pressure probe, this might be caused by contaminated connectors or cable in a casting workshop, which would result in an erratic output.

2. Experimental Data Analysis

2.1 Temperature measurement

It is not possible to explain the in-casting temperature until a calibration test is completed, see Fig. 2, because the thermocouples with protection could not match the dramatic in-cavity temperature change. However, for the in-mold temperature measurement, due to the relatively slow change of the mold temperature, the thermocouple could be able to measure the mold temperature with a certain degree of accuracy and reliability, see Fig. 3.

It is noticed that no matter how long it takes to reach the peak die temperature, such as 8 seconds in Fig.2, 11 seconds in Fig.3 and 9 seconds in Fig.4, die temperatures started to decrease when the pressure just reached the valley. This can be explained in two aspects. The first, as the interfacial contact situation worsens, then the interfacial heat transfer coefficient decreases dramatically. As a result, the

Figure 3: Metal pressure, die temperature at high intensification pressure and high melt temperature condition

rates of the heat transfer across the interface are reduced, and the mold temperature starts to decline. The second consideration is that, at this moment, most of casting has been solidified, and the latent heat had been released. As a result, less thermal energy is

transferred into the mold. At this point, it is not possible to predict whether a gap was formed at the interface.

This phenomenon strongly indicates that the die surface temperature (or near the surface) has a close correlation with the metal pressure profiles. For the difference in the timing of the peak die temperature in Fig.2 and Fig.4, the higher melt temperature and higher die temperature for Inter 54 might cause a longer solidification time, and the pressure will decrease more slowly than for Inter 12.

However, it is difficult to explain why it took 11 seconds in a high pressure condition to reach the peak die temperature shown in Fig. 3, which is longer than for the low pressure setting. High pressure could enhance interfacial heat transfer, and then the die temperature should increase faster than in the lower pressure condition. One possible interpretation may be that if metal pressures at the interface were higher than a certain level, any increase in pressure would not significantly enhance heat transfer across the interface.

Figure 4: The metal pressure and the mold temperature at low pressure and high melt temperature condition (Inter 54)

2.2 Pressure Measurement

In order to simplify the analysis, the portion of a pressure profile between the first positive recording and the peak pressure can be called the "pressure establishment stage", and the portion between the peak and the valley of a pressure profile can be called the "shell establishment stage". The origin of the time axis is assigned at the time of the first positive pressure recording. The pressure recovery stage from the valley should be further explained.

1) Pressure establishment stage

In Figures 5-8, all peak pressures occurred at 1.18 seconds after the first positive pressures were recorded. The response time of the Kistler pressure probe is within a milli-second.

This is probably caused by the hydraulic characteristics of the UBE machine. When the runner is partially filled, the metal pressure probe starts to sense pressure. As the cavity is filled and the intensification starts, the pressure increases to the peak.

2) Shell establishment stage

Suppose the hydraulic pressure of intensification remained constant until the end of the measurement, then the reason for pressure decreasing from the peak is the solidified shell of the casting is strengthened, which causes the surface of the casting to move apart from the mold surface.

In Fig. 6, the slopes of the metal pressure profiles at the low pressure setting are almost linear. This may mean that the low metal pressure couldn't effectively keep a pressure channel opened. In other words, as temperature decreased, solid fraction increased and the solidified shell strengthened, and the pressure, which couldn't overcome the resistance, dropped linearly.

However, at the high pressure setting (Fig. 5), there are inflection points in the pressure profiles. The inflection points are at about 8500 psi for both the low and the high melt temperature settings. This suggests that the metal pressure was sufficient enough to overcome the resistance of the solidified shell before the inflection point was reached. This also means that the pressure channel remained opened longer and larger. In our cases, when the inflection points were reached (at about 8500 psi), the solidified shell became strong enough to resist the intensification pressure. As a result, the slopes of the pressure profiles became steeper than before the inflection points.

This knowledge (if confirmed) may be helpful in setting the intensification pressure for the squeeze casting process, in which the pressure channel should remain open as long as possible.

3) The Influence of Melt Temperature on Metal Pressure

At the high pressure setting (Fig. 5), the higher melt temperature (1375 °F) could slightly prolong the time of pressure existence. This is because of the longer solidification time of the casting at the higher melt temperature setting.

However, the peak pressure values at the low melt temperature and at the high melt temperature conditions are the same.

At the low pressure setting (Fig.6), the melt temperature had a more significant influence on the pressure profiles. This may also suggest that the low pressure was insufficient in our case. As a result, any change in other conditions, such as melt temperature and die temperature, would severely impose a danger to the quality of the castings.

Figure 5: The influence of melt temperature on pressure profiles at high intensification pressure condition

Figure 6: The influence of melt temperature on pressure profiles at low intensification pressure condition

4) Pressure Profiles at High and Low Intensification Pressure Conditions

At the higher melt temperature (Fig. 7), the peak pressure values are 16900 psi and 4200 psi for high pressure and low pressure settings, respectively. At the low melt temperature (Fig.8), the peak pressure values are 16900 psi and 3720 psi for high pressure and low pressure settings, respectively.

In general, high pressure could keep a casting in contact with a mold surface for a longer

Figure 7: Metal pressure profiles at high melt temperature condition

period of time. It is believed this will result in a higher interfacial heat transfer coefficient for a longer period of time than at the low pressure condition.

It is believed that metal pressure will significantly affect the gate freezing time. This means that a gate will freeze at a higher solid fraction at a higher metal pressure condition. However, the correlation between gate freezing time and metal pressure is still unknown.

Figure 8: Metal pressure profiles at low melt temperature condition

2.3) Microstructure Analysis

The #34 casting (high pressure, high melt temperature) has been sectioned at U-M. So far, two samples (One at the top of the casting, another at the gate of the casting) have been polished, see Fig. 9 & 10.

In Fig.9 (the outer ring at the top of the casting), no defects were found and the dendrite arms are relatively fine, due to the thin wall. However, in Fig. 10 (at the gate), the dendrite arms are coarse, and some gas porosity voids are observed. This indicates that the gate of the casting may be oversized. This would not only result in a coarse microstructure, but also gas entrapment, because of the divergence in the size of the runner from the neck of the biscuit to the gate.

Magnification: 32 mm equal to 100 μm

Figure 9: Microstructure of the outer ring at the top of the No. 34 casting

Magnification: 32 mm equal to 100 μm

Figure 10: Microstructure of the ring at the gate of the No. 34 casting

2.4 The Repeatability of the Experimental Results

The pressure profiles of the last four shots at low intensification pressure and low melt temperature settings are shown in Fig.11. It is noticed that the pressure profiles match each other very well.

Fig.11: The metal pressure profiles at low pressure and low melt temperature settings

In Fig.12, the pressure profiles of the last four shots at high pressure and high melt temperature settings also show a high level of repeatability.

These results indicate that the metal in-cavity pressure measurement can reliably reflect process settings. The repeatability of experimental data is acceptable.

However, because of the decreasing pressure signal, probably caused by contaminated connectors, it is still impossible to judge whether a gap is formed between casting and mold.

Fig. 12: The metal pressure profiles at high pressure and high melt temperature settings

3. Countermeasures

Some countermeasures to improve accuracy of the experimental data were discussed at a Dec. 11, 1998 project meeting at the CMI-Tech Center. Some follow-up actions have been decided as listed below.

- 3.1) Solving the erratic or drifting pressure signal problem by using the specific solvent suggested by Kistler, the vendor of the pressure probe.
- 3.2) Calibration of the temperature measurement.
- 3.3) Repeat of some experiments.
- 3.4) Installation of a second pressure probe, see Fig.13.
- 3.5) Preparation of a few "bare" thermocouples for one-shot in-cavity measurements.
- 3.6) Numerical simulation of the casting.
- 3.7) Microstructure analyses of more castings.

Fig.13: The locations of pressure probes

4. Project Meetings

4.1 Preparation of Experiments at CMI-Tech Center

Minutes of the meeting held on 9 Oct '98 at CMI-TECH Center, Inc., Ferndale, Michigan

Members present:

CMI-Tech Center

Karl D Voss
Don Roberts
Gregory Woycik
David Moore
Christopher Rohloff

U OF M

Prof. R D Pehlke
Dr. S W Hao
Prasad Krishna

After a brief introduction of the team members and the new member Mr. Prasad Krishna, Graduate student, the meeting started off at 11.00 AM with an introduction by Dave on the present experimental set up for monitoring temperature and pressure for the Squeeze casting process. Dave indicated that the DAS (Data Acquisition System) namely 'DataQ' will output both the temperature and pressure signals simultaneously. It was decided to mount limit switches on the safety door of the machine to indicate cycle start. Dave and Chris agreed to fix the switches and keep the DAS ready for the experimental run on Wednesday, the 14th of October at the CMI- Tech center. Dr. Hao presented the experimental plan and many suggestions emerged from the team members. These recommendations are summarized at the end of this report. It was decided to limit the number of variables in the experiment to two, the melt temperature (1300-1390 F) and pressure of intensification (two settings, high/low) while the plunger speed is kept to an optimum value of about 6-9 ips. Prof. Pehlke suggested embedding one thermocouple inside the mold itself and CMI agreed. Members were of the opinion that the cooling behavior of the die need not be varied at this time, otherwise there will be more variables to be controlled in the first set up. It was decided that these aspects might be taken at a later stage. It was pointed out that the die would reach the steady state value of preheat temperature (~ 450 F) after about 5 shots.

It was decided to prepare a matrix sheet (as per the format shown by CMI) for recording the experimental data. The sheet will show all the parameters and experimental conditions as well as the final quality of mold and casting. The matrix sheet must include the temperature of warm up shots, pressure settings (Greg agreed to find the approximate value of the setting) and a column to indicate special remarks if any. It was decided to take a few samples of the finished castings after the run for a U of M detailed microstructure study. The alloy used for testing will be A 356 without any modification.

Given below is the summary of the settings of parameters for the experimental run proposed for the 14th of October 1998 at the CMI- Tech center:

- Number of cycles to reach steady state conditions will be five.
- For each setting, five measurements will be taken.
- The melt temperature, instead of pouring temperature, would be set, initially to 1300 F and then raised to 1390 F.
- Tentatively, the intensification pressure will be set at low and high values and entered in PSI units.
- An optimum plunger speed of about 6-9 ips (Gate velocity of ~ 1 mps) may be maintained for the entire experiment.
- To enable accurate data collection and to settle down any transients in the sensing system, the cycle time may be prolonged to about a minute.
- Normal preheat temperature of about 450 F for the die may be maintained.
- Two persons may be required to simultaneously manipulate the data acquisition for both KISTLER & DATAQ, with a micro switch on the door to trigger the cycle start.
- Observe the level of gas in the squeeze casting process and record.
- Indicate any special observation in the remarks column of the matrix sheet.

(Recorded by Mr. Prasad Krishna)

4.2 Post Experiments Meeting at CMI- Tech Center

Minutes of the meeting held on the 22 of October 1998 at CMI- Tech. center, Ferndale, Michigan.

Members Present: Gregory Woycik, David Moore and Christopher Rohloff from CMI
Dr. SW Hao and Mr. Prasad Krishna from Uof M

1. Abnormal behavior of the mold pressure signal from Kistler Pressure probe.
Dave presented the pressure plot for the two different experimental conditions and members pondered over the peculiar behavior of the curve, especially about the large negative pressure drop. Dr. Hao suggested contacting the technical personnel from Kistler to ensure that the calibration and other electrical requirements are met. Dave agreed to contact Kistler and discuss the pressure curve with them.

2. CAD drawing of the casting for analysis at U of M.
Greg demonstrated a facility (Hand Manipulated arm mounted on the CMM table at the measuring room with a Laser sensor and Camera for image capture) at CMI, which can automatically create an image of the casting . Greg promised to deliver the final drawing to Uof M.

3. Testing with bare thermocouple (without the metallic shield) at CMI.
As per Dr. Hao's memo, Dave agreed to conduct experiments with a bare thermocouple in the mold and to observe the temperature signal behavior. CMI wanted some time to order the new thermocouple for the above tests.

4. Microstructure study of a casting made on 14th of October.
Two sample casings were taken to Uof M to conduct a microstructure analysis.

5. Delivery of the complete data file (Output of DATAQ and Kistler) to U of M.

CMI will deliver the complete Excel file of the experimental data after compression to U of M for further analysis.

The meeting closed at 1.00 PM.

(Recorded by Mr. Prasad Krishna)

4.3 Project meeting at Amcast Automotive

Minutes of the fifth project meeting between U of M and Amcast on the 13th of November 1998 at Amcast Automotive, Southfield, MI 48034

Members present: Dr. Vijay Shende and Dr. Sarah Chen from Amcast

Prof. Pehlke, Dr. Hao and Mr. Prasad Krishna from U of M

The meeting started at 9.00 am with opening remarks by Dr. Shende on some of the difficulties experienced by Amcast to get a new mold fabricated at their site. He assured the group that the mold would be ready by January 1999. Dr. Shende also wanted the reports of the project meetings from the UM team so that the time and cost sharing may be computed. A new staff will also join the project team at Amcast in the month of January 1999.

Prof. Pehlke while explaining the progress of the work at UM , also briefed about his Chicago meeting with Mr. Miller of MAGMASoft . UM now has both MAGMASoft and ProCAST for modeling and the members expressed the need for bench marking both softwares. Mr. Prasad Krishna, a new team member from UM was introduced to the Amcast team. Dr. Hao presented the results of the simulation study and discussed some of the issues in temperature and pressure measurements. The experiments conducted at CMI were also briefed by Dr. Hao to the Amcast team. Dr. Shende recommended trying sapphire coating to protect the pressure sensor used for cavity pressure pick up as used by Ken Dolan at Lawrence Livermore Lab. Dr. Sarah Chen reported that she will continue

with her efforts in contacting the sensor manufacturers (pressure, temperature and Ultrasonic for gap) and arrive at an optimum configuration with minimum equipment cost. One data acquisition system with common A-D board and amplifier for all the sensors needs to be explored.

Dr. Hao agreed to share all details with Amcast regarding the Kistler pressure sensor calibration and to check the low and high-pressure range for the sensor. Amcast agreed to send details of the thermocouple locations and mold design to UM. The meeting closed at 11 am.

(Recorded by Prasad Krishna)

4.4 Presentation of the experimental results and preparation for a new round of experiments

Minutes of the Sixth Project meeting between UM and CMI

Date and Venue: December 11, 1998 at CMI-Tech Center, Ferndale, MI 48220

Members Present: *Dr.S.W.Hao and Prasad Krishna from UM; Karl Voss, Greg Woycik, Dave Moore, Bill Cole, Rong Pan, Steve Lou, Guy Vitali and Jeff Smith from CMI; Dr. Kim from EKK.*

The meeting started at 9.45 am with a brief presentation of the experimental results by Dr.S.W.Hao from UM. Dr. Hao presented the differences in microstructure of the casting made on the 14th of October near the gate and at the top of the hockey puck-shaped casting. Dr. Hao pointed out that gas porosity observed near the gate might be the result of an oversized gate. Dr. Hao also mentioned that temperature measurements will be useful only after calibration, and recommended doing testing with bare thermocouples as against the shielded ones currently used. Several participants expressed concern over the delay in the response of the thermocouple. Greg also suggested to adopt constant heating of the die and then to pour metal for testing. As explained by Dr. Hao, since die temperature does influence the pressure profiles, it is very important to maintain steady state conditions during the measurement. Dr. Kim from EKK mentioned the Ken Dolan data on thermocouple response delay, and he urged the team to contact Dr. Dolan for details. Karl Voss indicated that he would get the required information from the US Car project team. Dr. Kim also cautioned the team that high pressure might not always aid in feeding the casting because some portion of the casting away from the gate would have already frozen. Dr. Hao indicated that an oversized gate is a common practice, even in Japan, and that it helps to feed shrinkage.

CMI will perform another set of experiments with one more thermocouple and pressure sensor at the top of the casting and also with a bare thermocouple to study the temperature behavior. UM will inspect another casting sample (low-pressure test on 14th

of October, 98) and check for any differences in the microstructure. Dave will contact Kistler and clean up the contaminated cables of the pressure sensor with the recommended solvent, and test the sensor for any abnormal behavior as observed in the pressure measurements during the testing on 14th of October, 98.

The meeting came to a close at 11 am.

(Recorded by Mr. Prasad Krishna)