Thermal Control with Image Processing and Fuzzy Controllers

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Abstract
Image processing is used to identify areas of different temperatures in die thermal images for thermal control of high pressure die casting. Areas of higher and lower temperature ranges than the optimum empirical/experimental range can be identified. Using the heat index developed, the heat stored in different areas of the die can be quantitatively calculated and controlled using fuzzy neural networks. This fuzzy neural networks control system makes the decision about whether to take more (H_-) or less heat (H_+) away from a specific area.

1. Introduction

As there are many heat flow paths available in the high pressure die pressure casting process for heat loss/transfer, the conventional approach to thermal management of dies is based on trial and error, and the experience of operators and engineers. This provides a significant difficulty for the die designer to effectively explore the potential of cooling systems.

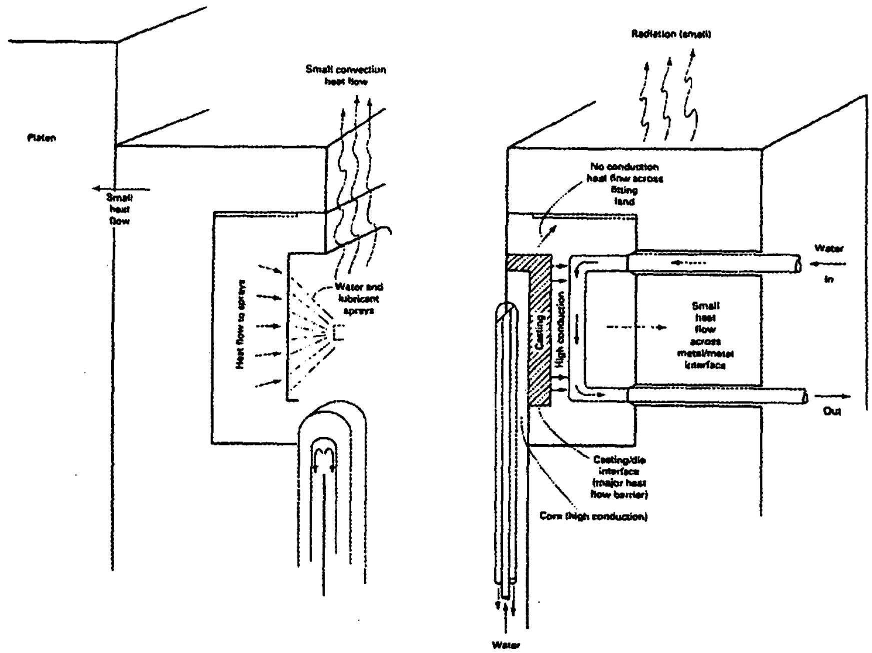
Thermal stability plays a critical role in the high pressure die casting process since either a higher or a lower temperature on the die surface will lead to the production of defective castings. It is, therefore, well established that proper thermal management of dies yields a higher casting production rate and improved part quality. However, the die temperature is dependent on many process parameters, particularly these related to cycle time, internal cooling system, and external spraying system if the casting volume and geometry remain the same.

Bishenden and Bhola [1] proposed a die thermal control system that relied upon measurement of temperature at one position away from the die surface with a thermocouple. The system measured the temperature at a given time and performed PID control based on these measurements to regulate the coolant to the die. However, since the size of castings varies and the design of the internal cooling system and die needs to consider the effect of other aspects such as thermal stress on the die surface, thermal control is not effective if only one position is used.
The understanding of fuzzy logic and artificial neural networks has advanced dramatically in recent years and consequently, they have been widely applied in industry for system control [2]. An example of the application of these systems is the cruise control used in automobiles [3]. As the die temperature can be controlled by adjusting the volume of internal coolant and cycle time, fuzzy controllers provide an excellent technique for this application.

In this paper a fuzzy thermal control system is proposed based on the thermal information obtained from the processing of thermal images taken at a certain time together with the information from thermocouples. An even temperature distribution on the die surface will be achieved if the proposed system is implemented, as the whole die surface will be monitored and controlled.

2. High Pressure Die Casting and heat transfer in HPDC

The die in high pressure die casting is normally composed of two parts: a fixed section and a moveable section (Figure 1). The cycle to manufacture a casting can be divided into three phases: injection of molten metal and solidification, part extraction, and spraying of the die surface. During the solidification stage, the metal is fed into the die and kept in the die for a certain period depending on the size and shape of the casting. Following this, the casting is extracted with to cool the die in addition to a small amount of convection through the air. The geometry of the casting is critical as it also determines the geometry of



(a) (b)

Figure 1. Heat paths available in HPDC. (a) Die open for service (b) Die closed after shot [2]

a robot, immersed in a water tank and then transported for trimming and quality inspection. The dies are sprayed with lubricant, water (and air) for die cooling and cleaning before the next cycle starts. Internal cooling during the solidification phase and the cooling provided by spraying are two critical processes for control of the die temperature.

The die temperature during the whole casting process must be monitored and accurately controlled, as the quality of the casting is very sensitive to variations in temperature. When the molten alloy is in the die cavity, the heat in the alloy needs to be removed in order to allow solidification and consequent cooling to occur. Here the die acts as a heat exchanger. There are a number of heat flow paths when the die is closed (Figure 1) and there are two main courses for this heat exchange ie by high conduction to the flowing water on both fixed and moveable dies. After the die is open, the water and lubricant spray is the major way

the die and consequently, the geometry of the heat exchanger. Another critical effect of casting shape is the possibility of large differences in cooling times creating stresses within both the die and the casting.

Heat removal has to be at such a high rate that cooling is significant even during the die filling process. Therefore, superheat and latent heat are transferred to the die before the alloy is stationary in the die and metal remote from the gate will be partially solid before the end of die filling. This transient heat flow results in more heat being transferred to the die near the gate. In addition, the cooling system is targeted to remove the heat from the hotter spots and therefore, the design of the layout and inlet/outlet are component related.

3. Thermal Image processing

Die temperature is dependent on a number of process variables [4] such as cycle time, spray distribution and duration, water layout and flow rate, casting volume/geometry, and molten metal temperature and composition and there is a very complicated inter-relationship between the 150 or more variables involved in the HPDC process.

The thermal image shown in Figure 2 was taken after the die was fully open during monitoring of the high pressure die casting process. It can be seen that the temperature is highest in the central area, with a maximum temperature of about 380°C. However, it is difficult to know from these images how the temperature can be accurately and quantitatively controlled by adjusting the flow rate of coolant.

Image processing is used in this work to correlate the colors in thermal images to areas of different temperatures The identification of regions of high temperature involves identifying regions of different colors which signify known temperatures.

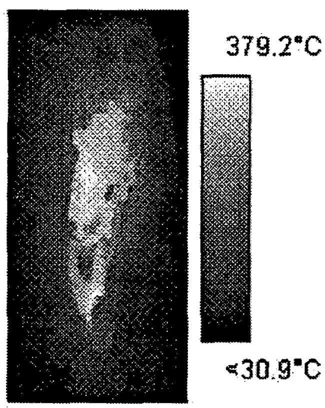


Figure 2. Thermal images

The color images consisting of three primary colors - red, green, and blue - were treated as three separate gray-scale images, which have 24 bits/pixel – 8 bits for each of the three color bands (R, G, B). The actual information stored in the digital image is the brightness information in each band. In these images, some rapid changes in brightness in a small area could be detected by human vision systems while some gradual changes are not easily observed due to the brightness adaptation of the human vision system. Furthermore, it is impossible for the human vision system to perform exact measurements corresponding to specified temperature ranges.

After analysis of the images and in particular high temperature and low temperature regions, the method to segment those images into a few regions of interest can be applied by operating principally in Green (G) - based images. A thresholding technique at different levels corresponding to designated temperature boundaries (ie 300°C, 150°C) is used to segment images into three areas. This multilevel thresholding produces an 8-bit binary image based on a specified threshold range and the values of image pixels. For the thresholding operation, a low value and a high value are used to select a range of pixel values, which correspond to an interval of temperatures. Any pixel falling into the threshold range is set as background while others are set as background.

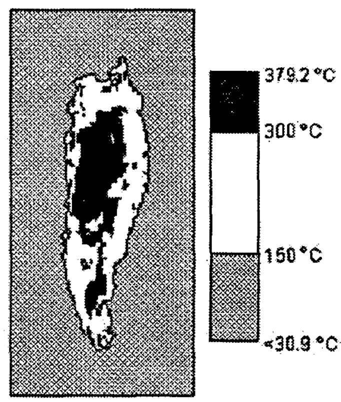


Figure 3. Processed thermal images indicating regions of different temperatures

Figure 3 shows the areas of three temperature regions in which the optimum temperature range is (150°C ~ 300°C). It is obvious which area of the die surface needs to be cooled down or take less heat.

4. Heat Calculation

It is known that the heat stored in a metal material is proportional to the temperature T and its volume $V(T)$,

$$Q_{V,T} = KVT \qquad (1)$$

where K is a constant related to material properties.

If the temperature in a given volume varies with its position, Eq (1) becomes,

$$Q_{V,T} = \int_{T_0}^{T} KV(T)dT \qquad (2)$$

However, the volume is a function of the area and the thickness. If the thickness for an area of a certain temperature is considered to be constant, Eq (2) becomes,

$$Q_{V,T} = \int_{T_0}^{T} Kt(T)A_D(T)dT \qquad (3)$$

where $t(T)$, $A_D(T)$ are the thickness and area of the die at a temperature of T, respectively. The real die area at a constant temperature T can be correlated to the area in the image (pixels). Therefore,

$$\begin{aligned} Q_{V,T} &= \int_{T_0}^{T} Kt(T)K_I^D A_I(T)dT \\ &= Kt_0K_I^D \int_{T_0}^{T} A_I(T)dT \qquad (4) \\ &= Kt_0K_I^D \sum_{T=T_0}^{T_{Max}} Q_i \end{aligned}$$

where t_0 is the die thickness if it is constant for the whole range, K_I^D is a constant correlating real and image areas, and Q_i is the heat index defined from the image. If t is not a constant, it can be included in the heat index.

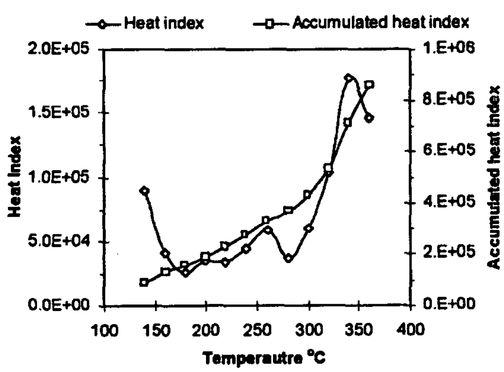


Figure 4. Distribution of heat index and accumulated heat index from 140°C to 380°C

To eliminate defects resulting from the high temperature and extra heat deposited in the die eg flash, more oxide formation, greater sleeve and die erosion, soldering etc, the areas with high temperature need to be identified and cooled with a specifically designed spraying and cooling system. Actually it is the areas of different temperatures, which need to be precisely computed to accurately calculate the heat accumulated in the die after the elimination of air spraying and reduction in cycle time. Figure 4 illustrates the distribution of the heat index and accumulated heat index from 140°C (reference temperature) to the highest temperature (380°C) of the image shown in Figure 2. It is found from Figure 4 that half of the heat stored in the die is in the central area where the temperature is higher than 300°C.

5. Fuzzy control of die temperature

As indicated above, the temperature in the central area is higher than the desired maximum temperature (ie 300°C) while in the surrounding area, it is lower than the desired minimum temperature (ie 150°C). While the distribution of die temperature can be made more favorable, by changing the flow layout for the die cooling system, active temperature control cannot be achieved through such system optimization.

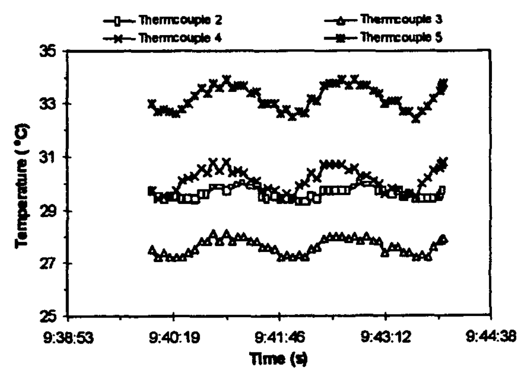


Figure 5. Coolant temperature at stable state

5.1. Temperature distribution in a cycle

The temperature within the die fluctuates in a stablized casting cycle. When the die is closed and filling ofmolten metal starts , the die and coolant temperature are at their lowest. This can be observed in Figure 5 where various thermocouples reach their lowest value simultaneously. The die (coolant) temperature starts increasing once the filling of molten metal is initiated. When the die cavity is fully filled, the heat stored in the die reaches its highest level and consequently, the die temperature is at its maximum. After this, the die temperature decreases as there is no further heat is added and the internal cooling system keeps taking heat from the die. This die temperature fluctuation continues as the casting cycle is repeated.

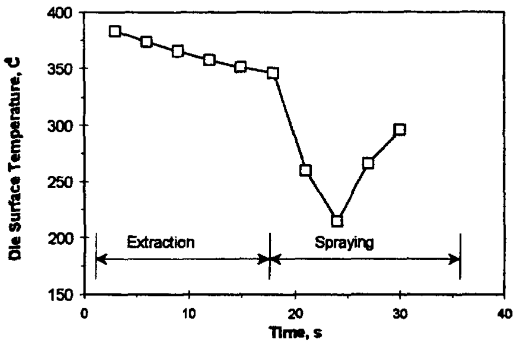


Figure 6. Variation in die temperature when die is open

The external spray system also takes a limited amount of heat away from the die surface and this can contribute substantially to temperature variations on the die surface (Figure 6). However, compared to the internal cooling system, the external spraying system doesn't reduce the overall die temperature dramatically as the distribution of coolant temperature doesn't show any steep reduction like the one observed on the die surface (Figure 6).

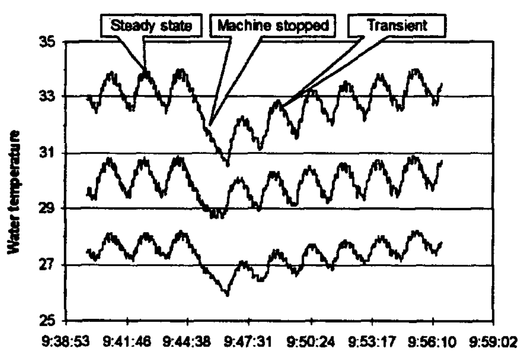


Figure 7. Effect of processs stability on thermal balance

5.2. Variation in die temperature with cycle time

As shown in Figure 5, the coolant temperature in the stable state varies in a certain way with the cycle time, and this repeats periodically if the cycle time remains the same and other variables are not altered. This is because a dynamic thermal equilibrium is achieved in the casting cycle.

However, the thermal equilibrium is interrupted if the process conditions are changed. For example, if the machine stops for a very short time (Figure 7), the die (coolant) temperature will drop significantly. Consequently, some castings following this period may have to be scrapped due to quality issues related to the change in die temperature.

5.3. Control of die temperature

The high pressure die casting process is a highly nonlinear system with many independent parameters affecting cycle time and die temperature. As a consequence of this complexity, the (quality and process) stability of the process depends not only on the die temperature but also on the cycle time that is used. Active control of the process therefore requires control of a combination of different parameters, among them die temperature and cycle time.

As the die temperature varies primarily with the cycle time and the internal cooling system, the fuzzy control system has to take both issues into account. Figure 7 shows the proposed fuzzy control system.

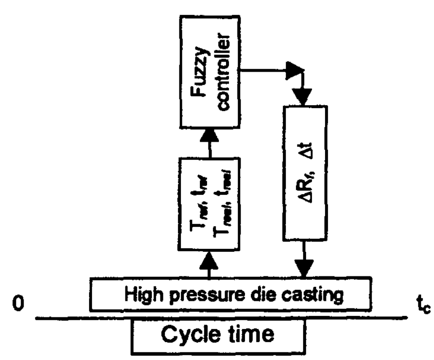


Figure 7. Adaptive fuzzy controller for high pressure die casting

The high pressure die casting process consists of many sequential elements or actions. If a cycle time t_c is specified for a casting, there is an optimum elemental distribution of cycle time during the sequential actions. In Figure 7, this is referred as t_{ref}. The corresponding optimum die temperature at a specific location is T_{ref}.

However, the real temperature T_{real} and real cycle time t_{real} may be different from T_{ref} and t_{ref} due to unexpected circumstances. To control the die temperature effectively, two primary actions are required from the fuzzy controller: adjust the coolant flow rate and cycle time.
The difference between real and optimum die temperatures and cycle times is used to tune the process. Based on current information, the fuzzy controller fulfills the tasks by adjusting first the coolant flow rate and then the cycle time. Reduction of cycle time is a major route to improve productivity.

The fuzzy controller makes the following justifications:

- Evaluate the die temperature and decide whether it is within the optimum range. If T_{real} is higher than T_{ref}, ΔT=POSITIVE, otherwise is NEGATIVE.
- Control elemental cycle time to reduce the total cycle time.
- Evaluate the impact of other parameters and adjust these attributes.

As a simple example of this fuzzy controller, only the die temperature is discussed here. Based on the above tasks, the rule table, which describes what action should be taken depending on how the die temperature, cycle time, and flow rate of the coolant change, can be formulated as follows:

If ΔT is ZERO **and** R_f is ANY **and** Δt^0 is ANY **then** ΔR_f is ZERO
If ΔT is POSITIVE **and** R_f is LOW **and** Δt^0 is ANY **then** ΔR_f is POSITIVE
If ΔT is POSITIVE **and** R_f is HIGH **and** Δt^0 is ANY **then** ΔR_f is ZERO **and** Δt is POSITIVE *
If ΔT is NEGATIVE **and** R_f is NOT ZERO **and** Δt^0 is ANY **then** ΔR_f is NEGATIVE
If ΔT is NEGATIVE **and** R_f is ZERO **and** Δt^0 is ANY **then** ΔR_f is ZERO **and** Δt is NAGETIVE **

* If the die temperature is too high and the flow rate of the coolant cannot be adjusted (increased) to cool down the die, the only option is to extend the cycle time.

** If the die is being warmed up, the coolant should be turned off and all the actions sped up to accelerate achievement of a stable state.

*** Adjustment of coolant flow rate ΔR_f is based on the heat calculated using heat index.

5.4. Limitations of fuzzy controller without system optimization

Once die design has been completed, the potential for a fuzzy controller to control the die temperature is limited. It can be seen from Figure 8 that increase in coolant flow rate beyond a certain level has a very limited effect on die temperature. Therefore, the die and internal cooling system should be optimized to provide more potential for the fuzzy controller to function effectively.

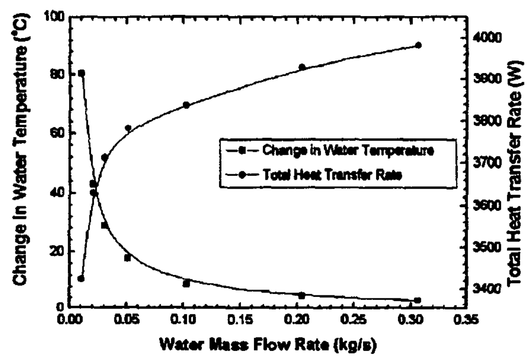


Figure 8. Variation in water temperature and total heat transfer rate with coolant flow rate

6. Conclusions

The thermal images from a high pressure die casting processes have been analyzed to provide information for temperature control of the die by fuzzy logic with and consequently impact on the quality of the castings. An image processing technique has been developed to correlate the thermal image to areas of different temperatures and a fuzzy thermal controller has been proposed. However, the potential of the fuzzy controller cannot be fully exploited without optimization of the engineering system.

7. References

1. Bishenden, W. and R. Bhola. *Die temperature Control*. in *NADCA Conference 1999*. 1999. Cleveland: NADCA.
2. Tsoukals, L.H. and R.E. Uhrig, *Fuzzy and Neural Approaches in Engineering*. Adaptive and Learning Systems for Signal Processing, Communications, and Control, ed. S. Haykin. 1997, New York: John Wiley & Sons, Inc.
3. Reznik, L., *Fuzzy controllers*. 1997: Butterworth-Heinemann.
4. Association, N.A.D.C., *Die casting defects textbook*. 1997, Rosemont, IL, USA: North American Die Casting Association.