THERMAL ANALYSES FROM THERMALLY-CONTROLLED SOLIDIFICATION (TCS)
TRIALS ON LARGE INVESTMENT CASTINGS

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Abstract

Thermally controlled solidification (TCS) has been developed as a patented process for casting complex components with minimal shrink. The principle of TCS is based on the controlled advancement of the solidification front in an investment casting mold. Benefits of the TCS process include reduced as-cast shrink levels, and enhanced abilities to cast thin walls and feed complex configurations.

The development of the TCS process began at Precision Castparts Corporation in 1988, using a modified directional-solidification furnace. In 1992, PCC procured a laboratory-scale TCS furnace and tested the capabilities of the TCS process with pour weights up to 45 kg. In 1995, PCC completed the construction of a TCS furnace with the capability for pour weights up to 370 kg.

One of the primary differences between castings made by the TCS process and castings made by directional solidification or single crystal processes is in the resultant as-cast grain size. Directional solidification and single-crystal processes produce as-cast microstructures with a large average grain size, and the TCS process results in an as-cast microstructure with grain sizes typical of that observed on conventionally-cast parts. Additionally, the TCS process results in a consistent and uniform grain size in all areas of a cast part.

To correlate observed as-cast results with known processing parameters, several techniques using thermocouple data have been investigated. For example, the ratio of the thermal gradient at the solidification front (G) to the solidification front advancement rate (R) is an indicator of the as-cast microstructure. Relatively large G/R ratios

tend to produce microstructures with large, unidirectional grains and with relatively little shrink. By comparison, relatively low G/R ratios tend to result in microstructures with a generally higher degree of shrink, and a finer structure depending upon the solidification front advancement rate R. Under optimal conditions, the TCS process uses G/R ratios that result in microstructures with relatively small, equiaxed grains and with minimal shrink.

Besides use of the G/R ratio to characterize solidification conditions during TCS trials, additional thermal analyses have been investigated. One analysis uses the equivalent time calculation to quantify the thermal conditions during solidification at several physical locations on the mold.

Background

Directional solidification and single crystal casting techniques have been part of the superalloys industry since at least 1960 [1]. The objective of directional-solidification and single-crystal casting techniques is to produce components with minimal grain boundaries, and to improve high-temperature properties of cast components.

The TCS process evolved from the directional-solidification and single-crystal casting techniques. The TCS casting process is different from directional-solidification and single-crystal casting techniques in that TCS produces components with equiaxed grain structure and with minimal shrink.

The scope of this paper includes examples of thermal analyses that have been used to characterize the TCS process during early furnace trials. The purpose of thermal

analyses of TCS thermocouple data is to provide quantitative methods to correlate observed metallurgical results with input process parameters. The two thermal analyses presented here are the G/R analysis and an analysis that calculates the equivalent time at a constant temperature during solidification. An example from one TCS casting trial is provided.

Procedure

The TCS process utilizes a cylindrical resistance-heater, or retort, which heats up a shell to establish a vertical gradient in the shell prior to pouring. The retort has a working zone of 110 cm diameter and 100 cm height, and has the capability to heat shells up to 1480°C. The diameter of the chill plate is 105 cm. Figure 1, from a PCC-held patent [2], shows a schematic diagram of the TCS furnace.

Prior to TCS casting, the invested and de-waxed shells are heated prior to transferring to the TCS furnace. When a shell is transferred from the burnout furnace to the TCS furnace, the shell is lowered onto the copper chill plate, ensuring that the shell is centered on the chill plate. Centering the shell allows uniform heat distribution on the shell during preheat and withdrawal.

Fig. 1: Schematic diagram of the TCS furnace, indicating how molds are withdrawn from a cylindrical hot zone [2].

With the shell in the vacuum TCS chamber, the TCS heater is lowered to surround the shell. The shell is heated up to a thermal profile prior to pouring metal. Thermocouples are used on the shell to control the final shell thermal profile before pouring. A temperature differential on the order of 110°C or more, from the top of the shell to the bottom of the shell (near the chill plate), may be observed.

While the shell is being preheated, the alloy is vacuum-induction melted and stabilized at the final pouring temperature. The alloy is poured into the shell over the lip of the crucible. After the alloy has been poured into the shell, the heater is lifted up and away from the shell at a programmed rate, called the withdrawal rate.

Results

Thermocouples on the shell indicate the solidification conditions in the shell during the TCS withdrawal. One of the main objectives of monitoring the shell and alloy temperatures during solidification is to quantify the thermal conditions that correspond with minimal shrink conditions in the casting. Two analyses used to quantify the thermal conditions during solidification are 1) the G/R analysis and 2) the equivalent time analysis.

G/R Analysis

The G/R analysis refers to the ratio of the temperature gradient (G) across the solidification front to the solidification front advancement rate (R). G/R has been referenced in the solidification literature [3] as an indicator of as-cast microstructure. Relatively high G/R ratios tend to correlate with single-crystal and columnar types of microstructures, and generally with minimal shrink. Conversely, relatively low G/R ratios tend to correlate with equiaxed microstructures with generally high shrink levels.

In the present work, Type S thermocouples were placed on the outside of the shell to provide an indicator of solidification conditions inside the shell. Previous work has shown that shell thermocouples are at least representative of thermal conditions in the metal, at the solidification front. Shell thermocouples give an output which is generally lower than thermocouples in the mold cavity, and also generally appear to lag thermocouples in the

mold cavity. The advantages of using shell thermocouples include (1) a high degree of re-usability and (2) easier to use in a production environment. Thermocouples are generally placed in a vertical orientation on a shell to allow for G/R calculations at different locations and at different times during solidification.

In practice, G/R is calculated by the following approximation:

$$\frac{G}{R} = \frac{G^2}{GR} \quad (1)$$

$$\frac{G^2}{GR} = \frac{\left(\frac{T_{1,t} - T_{2,t}}{z1 - z2} \right)^2}{\left(\frac{T_{1,t-M} - T_{1,t}}{\Delta t} \right)} \quad (2)$$

$$[=] \quad ^\circ\text{C s cm}^{-2}$$

The approximation shown in equation (2) allows for the estimation of G/R using data from two thermocouples, at locations 1 and 2, at time t. Thermocouples 1 and 2 are located at distances z1 and z2, measured in centimeters from the chill plate.

Figures 2 to 5 show examples of graphs giving G/R as a function of deviation from the liquidus (referred to as delta liquidus) for one mold. The chemical composition of the alloy used in this experiment (in wt %) was 22 Cr, 17.9 Fe, 8.5 Mo, 1.3 Co, 0.55 W, 0.67 Si, 0.02 Mn, 0.01 C, 0.004 P, 0.002 S, bal. Ni. The liquidus and solidus for the alloy was 1357 C and 1329 C. The thermocouple data were obtained from a test mold which comprised of four 24 x 84 cm panels, each less than 1 cm nominal thickness. Type S thermocouples were located at five locations along the length of the shell, at 75, 60, 46, 28 and 11 cm from the chill plate for thermocouples 1 through 5 respectively. The graphs provide calculated G/R values from thermocouple data received from thermocouples 1 and 2 (fig. 2), thermocouples 2 and 3 (fig. 3), thermocouples 3 and 4 (fig. 4) and thermocouples 4 and 5 (fig. 5).

G/R as a function of temperature, such as those shown in figs. 2 to 5, are useful for determining baseline ranges of parameters which result in minimal shrink in a casting. One method for quantifying and comparing data from TCS casting trials involves determining the G/R value when the upper thermocouple, for a given location, reads 1260°C.

Comparing the graphs shown in figs. 2 through 5 indicates that G/R values were generally highest at lower positions in the casting. For example, the G/R data shown in figs. 4 and 5 are generally higher than comparable data shown in figs. 2 and 3, especially at relatively higher temperatures i.e. at lower delta liquidus, where delta liquidus is the difference in the liquidus temperature of the alloy and the temperature recorded by the thermocouple on the top end of the part. Since figs. 2 and 3 correspond with higher relative positions on the casting (farthest distances from the chill plate), the data indicates that G/R levels were higher at lower positions in the casting, for the experimental data shown.

Fig. 2.: G/R as a function of shell temperature (delta liquidus) during solidification. Thermocouples 1 and 2 were 75 and 60 cm from the chill plate respectively.

Fig. 3: G/R as a function of shell temperature (delta liquidus) during solidification. Thermocouples 2 and 3 were 60 and 46 cm from the chill plate respectively.

Table I. Example of Thermal Data from a TCS Trial

Thermo-couple number	Distance from chill plate	G/R at liquidus - 100°C (°C s cm ⁻²)	t _{equiv} at 1200°C (minutes)	Temp. before pour, dev. from liquidus	Peak temp. after pour, dev. from liquidus
1	75 cm	160	43.8	25°C	21°C
2	60 cm	26	43.5	27°C	19°C
3	46 cm	1438	42.3	33°C	22°C
4	28 cm	341	35.3	86°C	28°C
5	11 cm	--	25.7	136°C	34°C

Fig. 4: G/R as a function of shell temperature (delta liquidus) during solidification. Thermocouples 3 and 4 were 46 and 28 cm from the chill plate respectively.

Fig. 5: G/R as a function of shell temperature (delta liquidus) during solidification. Thermocouples 4 and 5 were 28 and 11 cm from the chill plate respectively.

Equivalent time analysis

The objective of the equivalent time analysis is the same as that for the G/R analysis: to determine a thermal 'signature' that corresponds with minimal shrink and optimal grain size in TCS castings. The basis for the equivalent time calculation is an exponential function of temperature given by:

$$t_{equiv,1200C} = \sum_{t=0}^{20 \text{ min}} \left[\frac{\exp \left(\frac{-\Delta H}{RT} \right)}{\exp \left(\frac{-\Delta H}{R(1200C)} \right)} \right] \cdot \Delta t$$

$$= 29382 \sum_{t=0}^{20 \text{ min}} \left[\left(\exp \left(\frac{-15154}{T^2} \right) \right) \cdot \Delta t \right] \quad (3)$$

[=] minutes at 1200°C

In equation (3), t_{equiv} is the equivalent time at 1200°C as measured by a thermocouple on the shell. The activation energy for solidification (ΔH) that was used in eq'n (3) was 126 kJ mole⁻¹. Data from thermocouples for the first twenty minutes after pour is used in the calculation. Depending on where the thermocouple is located on a given shell, t_{equiv} as calculated with eq'n (3) may range between approximately 10 minutes and 60 minutes.

Other data used to provide a means for comparing thermal parameters for TCS casting trials include shell thermal profile before pour and peak temperatures reached by individual shell thermocouples after pour. Table I provides an example of thermal data summarized from a TCS casting trial.

Discussion

TCS is a relatively new casting process which has undergone steady progress since its inception nearly ten years ago. For pour weights up to 45 kg TCS is now a reliable process that gives consistent results for production parts.

The present paper has discussed TCS development for larger parts, with pour weights up to 370 kg. One of the challenges in developing TCS for large parts is in the determination of which aspects of the TCS process for small parts applies to the TCS process for large parts. The heavier and taller parts of the large parts TCS process requires different heat management methods before, during and after pour, compared with the small parts TCS process. For example, the mold thermal profile before pour for small parts may be defined by specifying required temperatures at two thermocouples, one each at the top and the bottom of a small parts mold. For some large TCS parts, the required mold thermal profile before pour may be defined by a gradient between the lowest adjacent thermocouples on a given mold, and with the upper thermocouples all at the same temperature which is higher than the lowest two thermocouples. As a result, further development is proceeding on many large parts that are candidates for the TCS process.

In the examples presented, the analyzed thermal data (G/R and t_{equiv}) were not correlated with microstructural information such as degree of shrink and grain size. One reason why this data was not correlated with microstructural information was due to the relative stage of development of the large parts TCS process. With continuing parts pouring trials, the analyzed thermal data will be correlated with metallurgical results to determine relationships between input process parameters and resultant microstructure.

Summary

Thermally controlled solidification (TCS) process trials are ongoing for large investment casting parts. The TCS process depends on the controlled advancement of the solidification front, to provide castings with minimal shrink. Other benefits of the TCS process include enhanced abilities to cast thin walls and to feed complex configurations.

Two analysis methods for correlating observed as-cast results with known processing parameters are provided. Each analysis method depends on a function of mold temperature after pour and provides a quantitative method of comparing casting trials. TCS trials on large parts, up to 370 kg pour weight, are ongoing.

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References

1. F.L. Versnyder, M.E. Shank, "The Development of Columnar Grain and Single Crystal High Temperature Materials Through Directional Solidification", Mater. Sci. Eng., v. 6 (1970), pp. 213-247.
2. Ronald R. Brookes, United States Patent no. 4,724,891; Feb. 16, 1988.
3. W. Kurz, D. Fisher, Fundamentals of Solidification, Trans Tech Publishing, Aedermannsdorf, Switzerland (1984).