WITH SPECTROPYROMETER–

Automatic Process Control of Investment Casting

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It is easy to describe automatic process control of investment casting. Charge the furnace, heat the charge uniformly to the desired temperature, then cast. The resulting casting cycle time would be minimized, which would maximize productivity; temperatures would always be the same, which would maximize quality.

Unfortunately, the second step – heat the charge uniformly to the desired temperature – presents serious problems. The problems are different but no less serious depending on the technique chosen for temperature measurement. Immersion thermocouples can only make a very limited number of measurements per melt cycle. Conventional pyrometers are inaccurate and have poor reproducibility. Consequently, neither thermocouples nor conventional pyrometers are suited for control. Fortunately, third generation pyrometers – Spectropyrometers – can make thousands of fast, accurate temperature measurements during the entire cycle, and many foundries use them successfully to automate the investment casting process.

Immersion Thermocouples

Historically, the most common technique for measuring the temperature of a liquid metal melt has been the immersion thermocouple. There are two types: the ceramic-sheathed thermocouple that slowly equilibrates to some average temperature; and the rapid-rise thermocouple with electronics that stop measuring and present a temperature after a relatively short immersion. Neither of these is commonly used while the melt is being heated at full power. This means heating must be suspended for the period of the measurement, which adds time to the casting cycle.

The traditional c**eramic-sheathed thermocouple** can take several minutes to reach a steady temperature. In some foundries the operator monitors the temperature indication of the thermocouple and decides when it has reached its maximum. While slow, this technique has the potential for reporting accurate temperatures.[1] In other foundries, the time of immersion is set and the temperature at the end of that time is taken as the melt temperature. The common practice in the latter case is to minimize the time of immersion to reduce the overall cycle time and maximize the life of the expensive thermocouple assembly. The result is that the temperature is often under-reported.

Rapid-rise thermocouples have thin thermocouple filaments and small thermal masses. They take the operator out of the timing of the measurement by stopping their reading at a predetermined rate of temperature rise to minimize the immersion time. The result is that they under-report the temperature of the melt.

With both ceramic-sheathed and rapid-rise types the thermocouple is immersed when the operator believes the melt to be near the correct temperature. If the estimate is off the melt temperature is adjusted by the operator's skill. After the adjustment period, the measurement is repeated. A good operator can minimize the number of immersions, but is working against a loaded deck. All there is to go on is a charge weight and power setting. Unfortunately, settings don't yield the same power every time because the efficiency of the power supply varies with time and load, and the heating capacity of the incoming electric power varies with grid behavior.

Optical Pyrometers

The difficulties with immersion thermocouples have prompted many to attempt the non-contact, optical technique of pyrometry. Foundries around the world are littered with the failed hardware of these attempts. The reason is that nature makes it very difficult to determine the temperature of a liquid metal through non-contact optical techniques. All pyrometry is based on a simple understanding of the physics of radiation: every material raised to the same temperature radiates the same amount and same colors of light. However, the simple theory describes ideal behavior, not real behavior. In practice, every material is different; so a factor has been added to make the ideal and the real agree: the poorly-understood emissivity. Emissivity is nothing more than the efficiency of a radiator, and as such, varies between zero and one.

But nature is not done with her practical joking, and she appears to have investment casters on her short list. Emissivity is wildly variable and its variations can be huge: up to 300%. It varies between alloys; it varies with oxidation states (a bit of slag on the surface?); it varies with surface conditions (rough or smooth, and a turbulent, induction-heated liquid rivals the North Sea for changeability); it even varies with temperature (how can temperature be measured if the factor needed to measure the temperature changes with the temperature?). Finally, emissivity varies with the color of the radiation. That is, metals typically over radiate in the blue and under-radiate in the red relative to other materials. And, of course, each alloy is different in this behavior, also. All this variability means errors of hundreds of degrees are common.

For non-contact temperature measurement, the distinction between vacuum and air melting also becomes important. Vacuum melters must contend with windows to the process becoming covered with dirt and evaporated metal; air melters must contend with smoke and slag. It begins to be clear why so many earlier attempts at pyrometry for investment casting have failed. Currently there are three distinct types of pyrometer.

Brightness or one-color pyrometers have been around more than a century; they are merely light meters calibrated in temperature. Anything that changes the amount of light – the emissivity, a dirty window, smoke – changes the reported temperature. Emissivity changes as the metal melts and moves, so these fail.

This failure brought on the development of the next class of pyrometer, the two-color pyrometer. The theory was that the temperature could be calculated by the ratio of two measurements: divide the output of two one-color pyrometers (operating at different colors) and the emissivity cancels out. This is true for some materials, but not metals, where the emissivity also changes with color, so these fail.

The most recent pyrometer type is the many-color, or multi-wavelength instrument. Spectropyrometers, a class of these, use five hundred colors.[2] With this increased capability they automatically determine the emissivity for the given alloy as the temperature and conditions change. This innovation makes continuous accurate temperature measurement possible and allows the metal melting process to be automated successfully.

Comparison of Results

A vacuum investment casting foundry routinely dipped a ceramic-sheathed thermocouple to a depth of one inch for a fixed period. Figure 1 shows temperatures measured continuously by a Spectropyrometer in blue and thermocouple results in red for a casting cycle. Usual practice was a one-minute immersion, resulting in a value 70°F below the Spectropyrometer temperature. When the operator was directed to hold the thermocouple in the melt for an extra 5 minutes, the temperature continued to rise until it nearly reached the pyrometer value. This foundry used a double-sheath arrangement that resulted in a very slow thermocouple response.

Figure 1 illustrates vacuum investment casting, nickel superalloy with temperatures from a Spectropyrometer and a double-sheathed thermocouple. For this cycle and contrary to the usual oneminute immersion, the thermocouple remained in the melt for the duration shown by the dotted line and closely approached the Spectropyrometer result.

In a different vacuum foundry the sheathed thermocouple was routinely immersed deeply for several minutes until the operator observed that its displayed temperature had stabilized. Here months of data showed exact agreement between thermocouple and Spectropyrometer measurements.[3] Rapid-rise thermocouples are manually inserted in air melts, so operator technique is critical. In Figure 2 the Spectropyrometer documents a rapid and fairly smooth rise of temperature with four thermocouple immersions in just over a minute with an experienced, accomplished operator controlling.

Figure 2 shows a casting cycle for air-melted stainless steel with experienced operator. Rapid-rise thermocouple under-reports temperature.

In sharp contrast, Figure 3 shows an inexperienced operator vainly chasing the set-point temperature; here temperature differencesbetween the immersion measurements and the Spectropyrometer are larger and much less reproducible, and the cycle takes longer.

Figure 1

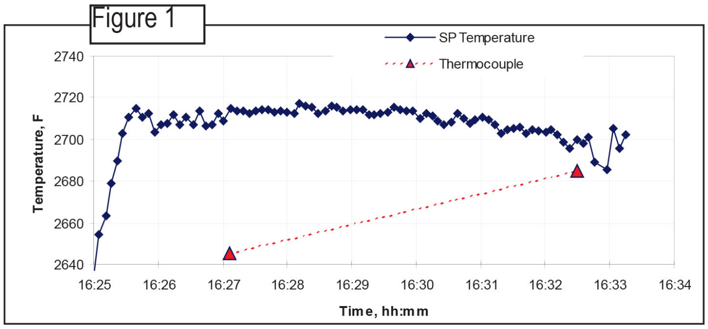


Figure 2

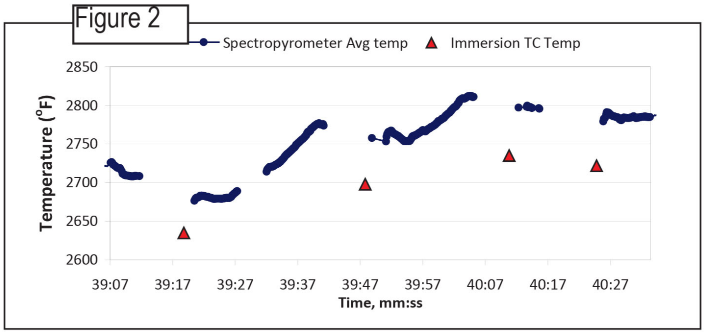
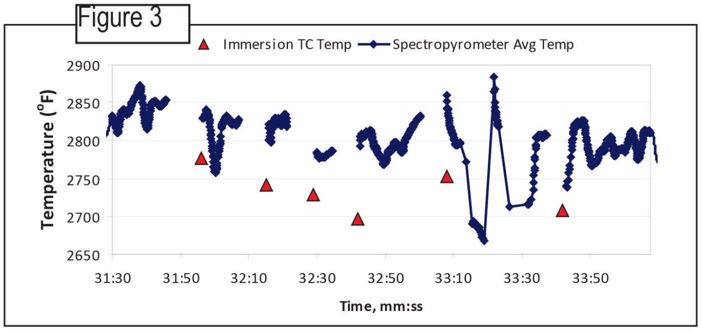


Figure 3



Successful Automatic Process Control – Spectropyrometry

Spectropyrometers have been commercially available for fifteen years, and have been successfully applied to IC since 2006. Figure 4 shows the setup for a Spectropyrometer controlling an air-melt rollover furnace. A ceramic tube connected to the pyrometer lens is brought to close proximity of the melt surface and is purged with argon to remove obstructing smoke. Resulting data show a smooth temperature ramp and stable hold within a few degrees.[4]

Figure 5 is a screen shot of the Spectropyrometer's monitor during a cycle at the facility shown in Figure 4. The Tolerance displays the quality of each temperature measurement in real time. Low tolerances, as shown, mean the temperature is well-known. The Signal Strength is the emissivity of the target, in this case the melt. The value shown is typical of a liquid metal (0.15 – 0.45). Slags have higher values, usually greater than 0.5.[5]

Summary

Automatic process control applied to investment casting has huge benefits. It allows controlled, uniform heating to the desired set point; both ramp and hold times can be optimized. The resulting casting cycles are shorter, improving productivity and reducing energy usage. The improved temperature control yields better quality due to reduced inclusions and other temperature-related flaws. Reducing superheat can allow equipment to last longer and reduces atmospheric emissions. In addition, discarding immersion systems eliminates expensive thermocouple consumables. To achieve automatic process control, a fast, accurate, reproducible temperature measurement system capable of continuous measurement is necessary. Immersion systems are not fast enough and conventional pyrometers are incapable of dealing with the optical properties of the melt. Since 2006, many investment casting foundries have used a type of multi-wavelength pyrometry, Spectropyrometry, to automate process control successfull.

Acknowledgment

The author wishes to thank Kermit Buntrock for his encouragement and support for this article and the technology described within.

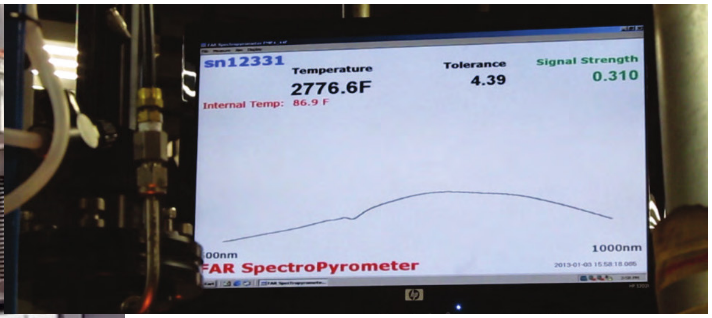


Figure 5.
View of monitor during melt cycle at facility of Figure 4. Tolerance is the on-line measure of the quality of the temperature measurement; signal strength is emissivity of target.

Figure 4. Spectropyrometer optical probe with ceramic tube for smoke suppression in measuring position.

Endnotes

1 Video showing good ceramicsheathed thermocouple technique is available here: http://pyrometry.com/applications/investment-casting-melt-movie/. Note depth and period of insertion
2 US Patents 5772323, 6379038
3 “Successful Pyrometry in Investment Casting” D. M. Olinger, J. V. Figure 4. Spectropyrometer optical probe with ceramic tube for smoke suppression in measuring position. Figure 5. View of monitor during melt cycle at facility of Figure 4. Tolerance is the on-line measure of the quality of the temperature meas urement; signal strength is emissivity of target.Gray, R. A. Felice, Proceedings of the Investment Casting Institute 55th Technical Conference, Oct. 14 – 17, 2007
4 Video available at http://pyrometry.com/pt009.wmv
5 “Pyrometry of Materials With Changing, Spectrally-Dependent Emissivity — Solid & Liquid Metals,” R. A. Felice, D. A. Nash, Proceedings of the 9th International Temperature Symposium, March 19 – 23, 2012 Anaheim, CA; “Temperature: Its Measurement and Control in Science and Industry, Vol. 8,” to be pub lished by the American Institute of Physics.