PYROMETRY FOR LIQUID METALS

Metals producers experience yield and quality issues from inaccurate temperature measurement due to the unusual optical behavior of metals. Multi-wavelength spectropyrometry provides accurate temperature measurement and enables close control of liquid metal processes.

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Fig. 1 — An immersion thermocouple shown in an induction-heated superalloy melt. The bright lines are areas of higher emissivity that would appear as artificially high temperatures to conventional pyrometers. Turbulence disturbs the liquid's surface and increases the emissivity.

Pyrometry is based on the ideal theoretical result that all materials radiate the same color and amount of light at the same temperature. It is an optical technique analogous to our vision: Humans see color and texture for identification of their surroundings.

Pyrometers "see" these two attributes rolled into one to identify the temperature of the target (Fig. 1). The measure of that single attribute is emissivity, and it governs how bright the target appears to the pyrometer. Emissivity is basically the radiation efficiency for each material: the ideal radiator has an emissivity of one, and everything else has an emissivity of less than one.

The two types of conventional pyrometer are the one-color or brightness type, and the two-color or ratio type.

• **One-color:** In these instruments, the amount of light is translated directly into the temperature: the more light, the higher the temperature. But since the target material's emissivity controls the detected brightness, the emissivity must be known for the measured temperature to be accurate. However, emissivity depends on texture, wavelength, composition, and temperature, which means it is almost always unknown. Further, these variables often change with processing, and therefore so does the emissivity. In the case of molten metals, the emissivity also changes with turbulence. Huge errors, often over 100°F, have been caused by incorrect emissivity settings.

• **Two-color:** To address this difficulty of unknown and changing emissivity, instrument manufacturers devised the two-color, or ratio, pyrometer. These instruments include two detectors sensitive at different colors or wavelengths. Mathematically, the division of the amount of light measured by each detector, or the ratio, can be solved for the temperature. In ideal cases, the emissivity is the same at both colors and cancels out in this division. Unfortunately, metals are not ideal targets. Their emissivity routinely changes with wavelength or color, and this "non-greyness" causes difficulty for users of ratio pyrometers.

Therefore, instead of the emissivity, the operator must know the non-greyness, or relative emissivity. Unfortunately, this is no better known than the emissivity itself. And like the emissivity, the non-greyness can change with processing. Non-greyness also is affected by turbulence in liquids. All this change in both emissivity and relative emissivity means conventional pyrometers are mostly wrong. Again, the errors resulting are often large; inaccuracies greater than 100°F have been routinely observed.

Multi wavelengths

SpectroPyrometers are expert system multi-wavelength pyrometers. Anything that measures at more than two "colors" is a multi-wavelength pyrometer. SpectroPyrometers measure at hundreds of colors and use advanced, patented algorithms to make sense of all that data. A simple way to think of a SpectroPyrometer is to consider it as hundreds of thousands of pyrometers in one unit, all measuring the temperature simultaneously at different wavelengths. Then, the instrument compares all these values and decides where the true temperature lies. With the wealth of information it gathers, it can determine more than just the temperature.

For example, SpectroPyrometers report both the tolerance and the signal strength. Tolerance is a measure of the accuracy of each temperature determination; signal strength is a measure of the

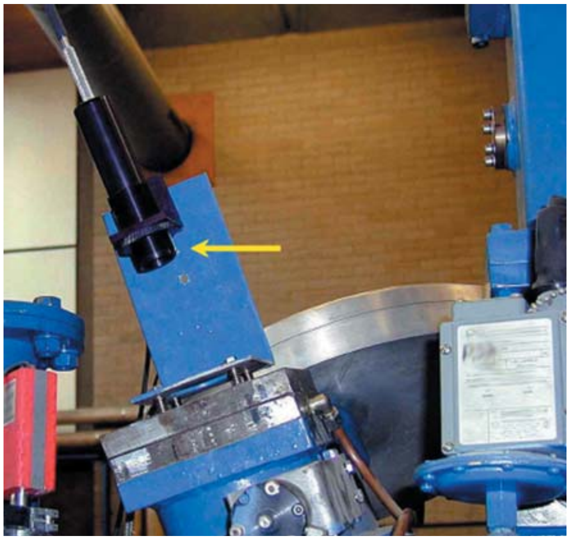

Fig. 2 — *The lens assembly (arrow) and a bit of the fiberoptic cable of a SpectroPyrometer. It's a simple matter to attach the assembly to the sight port of a vacuum furnace as shown.*

The emissivity of some metals has been observed to more than double as they freeze.

amount of emissivity for each measurement.

To be useful, instruments must be robust and easy to deploy. All SpectroPyrometers are modular, with a remote lens connected to the electronic console by armored fiberoptic cable, Fig. 2. This design makes it easy to install sensitive optical instrumentation in harsh metal-producing environments.

Data collection

In both conventional types of pyrometer the operator must either know the elusive emissivity or make assumptions about its behavior. And since the very things he must know are going to change with processing, inaccuracy is sure to result. In contrast, SpectroPyrometers approach each measurement without any built-in assumptions. They determine the optical behavior of the target from the data they collect for each measurement. In this way they can accommodate targets that are constantly changing either their emissivity, or relative emissivity, or both.

An extreme example of a target that changes its optical parameters constantly is a molten pour stream. The pour stream of Fig. 3 can be seen to be turbulent by the changing shape. Darker streamlines indicate locations where either the material may be cooler or the emissivity lower due to lesser turbulence. Solid material inclusions are seen at several locations. Before these pictures were taken, the operators were completely convinced this furnace was uniform in temperature throughout.

SpectroPyrometers have often analyzed pour streams and have recorded the phenomena shown in the picture. Data taken from a titanium pour stream where the lens was focused on the mouth of the pour spout is shown in Fig. 4. It shows a bit of superheat at the beginning of the pour, which vanishes with the lump of semisolid material detected around the five-second mark. (This lump was identified independently on videotape of the pour.) After it passes, temperature remains exactly in the range of the known melting point of titanium, 3020 ± 18°F, until the pour is finished at about seven seconds.

The measure of the emissivity here is called the signal strength; this term is used since there are optical materials of unknown transmission in the optical path. The lump is even more obvious in the emissivity/signal strength trace, where it causes a momentary 50% increase. When the pour is completed, the value can be seen to trend upward another 10 to 15% as the titanium freezes on the spout.

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Storing data

SpectroPyrometers store the thermal spectra, the data behind the temperature values reported. Analysis of the data from Fig. 4 shows that emissivity does in fact change with wavelength. Even worse, it changes a different amount as time goes on and process conditions change. Here that change can be explained by the turbulence of the pour stream. Two examples have been chosen, one in the early superheat phase and one from around the time of the lump. Their spectral emissivity (emissivity plotted against wavelength) is reproduced in Fig. 5. This clearly shows that the emissivity is not constant with wavelength.

• For the trace marked "A," the emissivity varies about 15% from the short wavelength side to the long. A ratio pyrometer operating on this without

Fig. 3 — *A pour stream showing turbulence, solid inclusions, and streamlines of material that are either lower temperature or lower emissivity than their surroundings.*

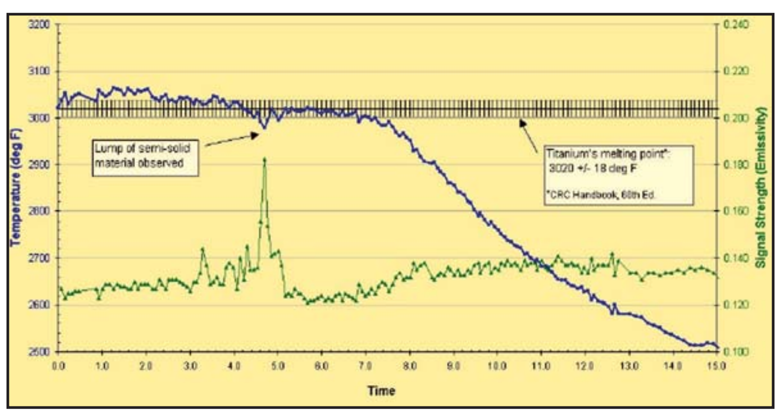

Fig. 4 — *Data taken by a SpectroPyrometer on a titanium pour stream. Video showed a lump of material at the five-second mark, which the instrument saw as both a decrease in temperature and increase in emissivity.*

exact knowledge of this non-greyness would overestimate the temperature by nearly 150°F or almost 5%; the actual temperature is 3037°F, and the ratio instrument would return 3185°F.

• For the trace marked "B", the emissivity varies about 10% from beginning to end. Here the ratio pyrometer would return 3092°F instead of the 3019°F measured by the SpectroPyrometer, and the error is 73°F. This illustrates a very significant fact: not only is the error large, but also the change in error is large. It shows that the reproducibility of conventional pyrometers is as poor as the accuracy.

Wavelength variation

SpectroPyrometers have been used on many molten metals; all have shown emissivities that vary with wavelength. Solid metals have exhibited similar behavior. Extensive comparisons between dip thermocouples and SpectroPyrometers have established that the technologies return the same temperature when each is used in accordance with the manufacturer's directions. A shop floor log of these comparisons is shown in Fig. 6. Of course, the pyrometer returns thousands of measurements, while the thermocouple returns but one.

The high speed of the pyrometer allows it to distinguish material variations within a seemingly uniform melt. And this speed makes the SpectroPyrometer suitable for automatic process control by providing fast, accurate feedback for the process controllers.

Pyrometry has not made the impact on metals producing that had been predicted for the technology. The reason for this is that the difficulties presented by metals, especially molten metals, were too great for the state of the technology until now. The progression from one-color to two-color to multiwavelength pyrometers has resolved seemingly intractable problems at every step. Now, the expert-system multiwavelength SpectroPyrometer solves one of the most difficult problems of pyrometry: liquid metals.

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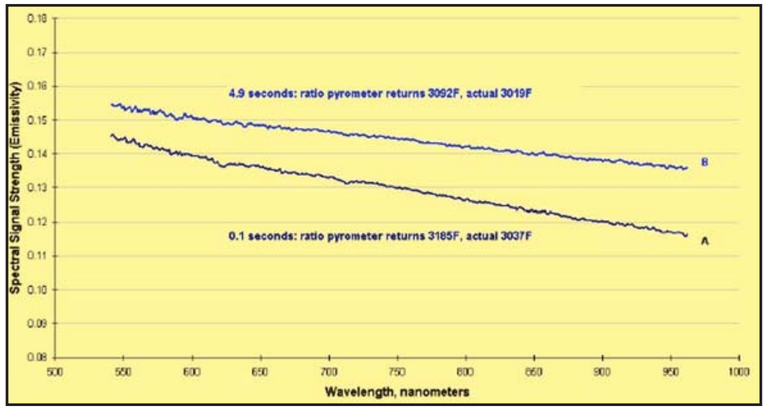

Fig. 5 —Emissivity changing with wavelength for two temperature values during the titanium pour, one near the beginning when the melt was superheated, one near the detected lump. Temperature at points "A" and "B" respectively were 3037 and 3019°F as measured by the SpectroPyrometer. A ratio pyrometer would have been incorrect by about 150 and 75°, respectively.

DATE	OPERATOR	SHIFT	INFRARED TEMP	IMMERSION TC TEMP	DIFFERENCE	5%
11-18-06	L.P.S.	1st	2760	2762	2	↓
↓	↓	↓	2759	2761	2	
			2761	2760	1	
11-20-06	SD		2760	2745	15	
			2760	2755	5	
			2752	2750	2	
			2760	2760	0	
			2760	2760	0	
			2760	2755	5	
			2760	2753	7	
11-21-06	SD		2775	2765	10	
			2780	2776	4	
			2775	2775	0	

Fig. 6 — Comparison of SpectroPyrometer ("Infrared Temp") and immersion thermocouples. The table is extracted from several months of similar data.