On the use of phosphor thermometry for temperature monitoring in manufacturing processes

A.O. Ojo[1]*, F. McCallum[2], A. Andreu[3], and A. L. Heyes[1]

[1] Department of Mechanical and Aerospace Engineering, University of Strathclyde, UK

[2] Department of Design, Manufacture and Engineering Management, University of Strathclyde, UK

[3] Advanced Forming Research Centre, University of Strathclyde, UK

*E-mail: *anthony.ojo@strath.ac.uk*

Abstract: In the metalworking industry, continuous monitoring and control of temperature is vital to enhance process efficiency, reduce wastage, and attain product reliability in high-value manufacturing processes. The capabilities of conventional techniques such as the use of thermocouples and infrared thermometry for measuring temperature in these processes are limited. For example, in forging processes, there may be a need for mechanical alteration of the die to accommodate thermocouples for die surface temperature measurements, and with infrared thermometry, knowledge of the emissivity of the surfaces of process components is required for accurate temperature measurements. Given that phosphor thermometry has not previously been used in manufacturing processes, here, we report its potential implementation using the phosphor Mg4FGeO6:Mn for measurements of die surface temperature in a forging press. First, with this phosphor, laboratory trials were conducted to describe the cyclic heating of a die by pre-heated billets, which is a process leading to thermal fatigue that requires monitoring in practical applications. Then, the phosphor thermometry technique was demonstrated for die temperature measurements on a 2100 tonne screw press at the Advanced Forming and Research Centre (AFRC). The results show that phosphor thermometry is a candidate technique that would potentially enable more accurate measurements not possible by other techniques in this manufacturing process.

***Keywords*:** Surface thermometry, Phosphor thermometry, Manufacturing processes, Forging die

INTRODUCTION

In manufacturing processes of metalworking industries, monitoring and control of temperature is essential in attaining high process efficiency which is directly linked to the finished product and process machinery. Products of a manufacturing process must meet specific standards related to, for example, their surface quality, mechanical properties, and shape, which are all influenced by the operating process temperatures. Also, key components of the process machinery must be able to withstand repeated thermal cycling and mechanical loading at high temperatures. For example, in die-casting dies, where depending on the rate of exposure of the hot work metal, the casting temperature induces thermal gradients between the surface and interior parts of the die and thus affects its performance [1]. Repeated heating and cooling of the die leads to expansion and contractions of the die surface thereby resulting in thermal fatigue cracking. Additional mechanical loading of the die further promotes deterioration of the die, leading to breakdown over time. In such process, as well as other manufacturing processes, temperature monitoring helps in making manufacturing industries sustainable; by reducing operational downtime and costs associated with machinery breakdowns.

A number of well-established thermometry sensors, such as thermocouples, pyrometer, thermal cameras, have been implemented to monitor the temperature in manufacturing processes. However, they possess specific limitations which hinder their use and also contribute to uncertainties in temperature measurements in some of these processes. For example, establishing firm contact with the surface of components is a fundamental requirement when using thermocouples. This is a challenging and inconvenient task in processes where the components are in motion or where excessive forces from mechanical loading are required for metal forming. With non-contact sensors such as pyrometers and thermal camera, the emissivity of the surfaces of components which most times is unknown, and the contributions of background radiation are intrinsic issues with implementing these sensors.

Phosphor thermometry is an alternative technique, which to the author's knowledge is yet to be implemented for temperature monitoring in metalworking industries. This technique was identified as a candidate technique under the third work package (WP3) of a recent project called EMPRESS (enhanced process control through improved temperature measurement) funded by the European Metrology Programme for Innovation and Research (EMPIR), aimed at reducing uncertainty in temperature measurements in manufacturing processes. Here, with the support of the University of Strathclyde's Advanced Forming and Research Centre (AFRC), also an EMPRESS project partner, we describe a laboratory-based implementation, together with the industrial-based implementation of the utility of phosphor thermometry for temperature monitoring in the manufacturing industry.

METHODOLOGY

The phosphor, manganese-doped magnesium fluorogermanate (Mg_4FGeO_6:Mn) was selected for its temperature sensitivity and its broad excitation spectrum which meant it can be excited with light sources such as lasers and LEDs with wavelengths less than 450 nm. The luminescence temporal response of Mg_4FGeO_6:Mn is sensitive over a wide temperature range (23 ^{o}C – 827 ^{o}C) with decay time from around 3 ms to around 50 ns in this temperature range [2]. With this phosphor, a coating was prepared as a mixture of the phosphor powder and high temperature binder (Ceramabind 643-1, Amerco) and was then applied on the die surface for thermometry.

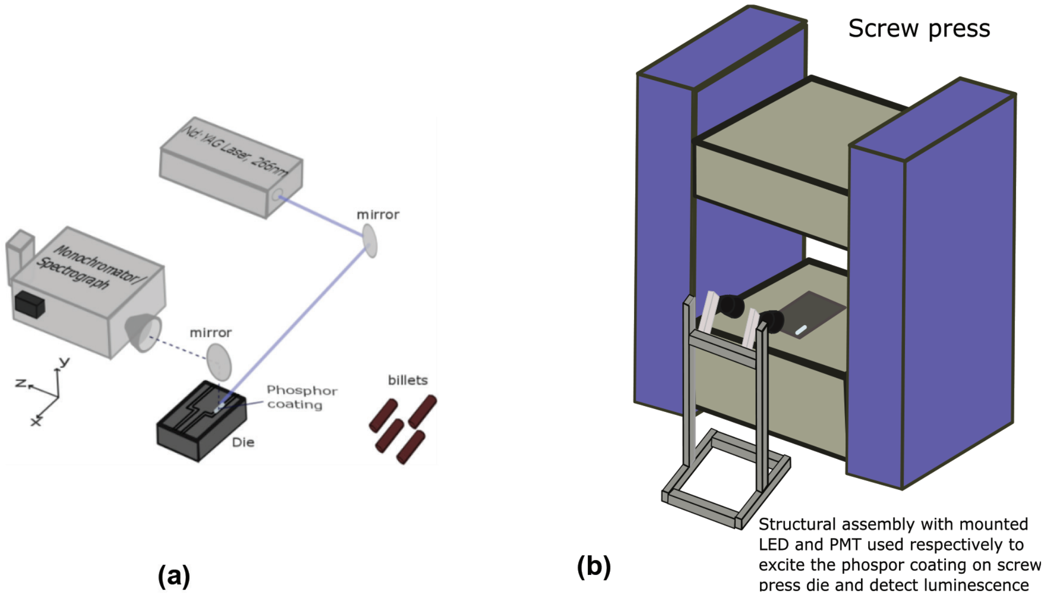

Figure 1. Schematic of (a) laboratory-based demonstration setup for die surface temperature measurements (b) industry-based demonstration setup for die surface temperature measurements on the 2100 tonne screw press at AFRC.

Laboratory-based implementation: Laboratory trials were first performed to demonstrate the utility of phosphor thermometry in capturing the cyclic heating process of a die by a set of heated billets. In manufacturing processes such as in screw press forging, such repeated thermal cycling leads to thermal fatigue of the die and thus requires monitoring. Here, the phosphor coating was applied as a strip (30 × 5 mm) on the die surface just close to the die cavity where the billets would be placed for a typical forging process. A 250 µm diameter type K thermocouple was also attached to the die surface to monitor the die temperature, with its tip placed ~ 5 mm from the end of the coating. Four cylindrical billets (one large billet (20 mm diameter, 59 mm long) and three small billets (each 19 mm diameter, 45 mm long) were heated to 650 ^{o}C in an electrical tube furnace (STF 16/450, Carbolite-Gero) and then alternately transferred and replaced one by another in the initially cold (25 ^{o}C) die cavity. As shown in Fig. 1(a), to excite the phosphor, the coating was illuminated by an unfocused laser beam from a Nd:YAG laser (Nano LG 300-10, Litron lasers) operating at a repetition rate of 10 Hz and wavelength of 266 nm.

Luminescence reflected off a 45 ^{o} inclined mirror was detected at a central wavelength of 660 nm by a monochromator (SpectraPro HRS-300, Princeton instruments) which has a Photomultiplier tube (PMT R955 HA, Hamamatsu) mounted as an optoelectrical detector. Luminescence signals detected by the PMT were digitized by a picoscope (6402D, Picotech) and then processed to evaluate the decay times.

Industry-based implementation: In practical forging applications with a screw press, the bottom die which is embedded in a bolster is preheated to temperatures around 200– 250 ^{o}C before the forging process commences. This decreases the temperature difference between the die and the heated preform which is typically heated to temperatures between 800 -1100 ^{o}C, and allows the preform to flow easily when being deformed under the application of pressure by the top die and also help to reduce die wear. Here, we used phosphor thermometry to monitor the rise in the die preheat temperature of the 2100 tonne screw press at AFRC. The result was compared with measurements taken with two thermocouples fixed to the die surface (180 × 290 mm) at different positions with their tips within 10-30 mm from the edge of applied phosphor coating which is ~ 20 mm in diameter. To do this, given that laser systems, more so, those operating in the UV, generally raise safety concerns in manufacturing industries, a LED (M420L3, Thorlabs) operating at a wavelength of 420 nm was employed as the excitation source. Using a function generator (SFG-1003, gw-instek), the LED was driven by a square wave signal at 10 Hz with a duty cycle of 15 %. The LED light was focused to excite Mg_4FGeO_6:Mn phosphor coating on the die surface. A detection unit comprising of a collecting lens, a 495 nm long pass filter, and a bandpass filter (661±20 nm), detected the luminescence. The LED and the detection unit were both mounted on a structural assembly placed close to the screw press as shown in Fig. 1(b). Luminescence signals detected by the PMT were also digitized by the picoscope and then post-processed to evaluate the decay times.

To calibrate the temperature dependence of luminescence decay times of Mg_4FGeO_6:Mn, an aluminum bar (70 mm long, 40 mm wide,10 mm thick) with the phosphor coating applied on one of its surfaces, was heated to about 450 ^{o}C in the electrical tube furnace and then transferred to the measurement region to cool to room temperature. A thermocouple inserted in the aluminum bar was used to monitor the temperature changes while a calibration routine was performed as the temperature dropped to room temperature.

RESULT AND DISCUSSIONS

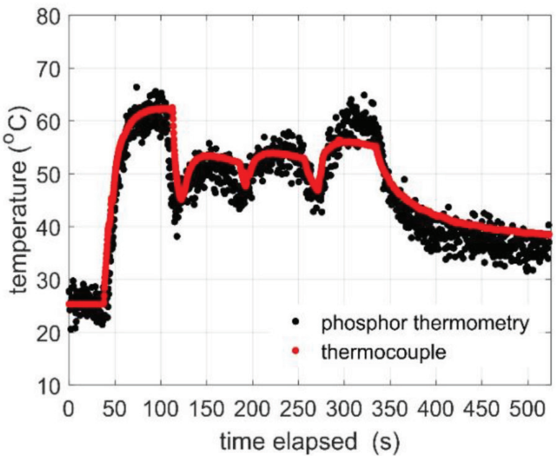

Figure 2. Temperature measurements showing cyclic heating of a die by heated billets.

Laboratory-based implementation: Figure 2 shows the evolution of the die surface temperature over time as the heated billets were transferred into and out of the die cavity one after another. Heat transfer from the hot largest billet, which was first transferred into the cavity, caused the die to heat up rapidly and then, replacing individual billets in the cavity by the next heated billet led to cyclic heating of the die. As shown, there is an excellent agreement between temperature measurements taken by phosphor thermometry and the thermocouple. Here, over the measurement duration, the mean deviation of measurements with phosphor thermometry from the thermocouple measurements is 1.7 ^{o}C with a maximum deviation of 9.2 ^{o}C. These deviations are in part likely due to the local temperature variations on the surface of the die where the coating and the thermocouple were located. Local temperature variation up to 5 ^{o}C was noticed for two thermocouples with tips placed ~ 6 mm apart on the die surface.

Industry-based implementation: The die preheat temperature rise on the screw press at AFRC measured with phosphor thermometry is shown in Fig. 3. Because of the large mass of the bolster which holds the die and the cartridge heaters, the time taken to heat the die to temperatures above 200 ^{o}C is above 2 hours. Over this time period, the mean deviation in temperature measured by the two thermocouples fixed on the die surface close to the phosphor coating is 9.3 ^{o}C, with a maximum deviation of 12.2 ^{o}C. This partly suggests that the temperature across the die surface is not uniform. In Fig. 3, the mean temperature measured by these two thermocouples at individual times of measurement is plotted and compared with the corresponding measurements with phosphor thermometry taken. There is also a good agreement between these measurements as the mean deviation of measurements taken with phosphor thermometry from thermocouple measurements is 5.1 ^{o}C, with a maximum deviation of 10.1 ^{o}C.

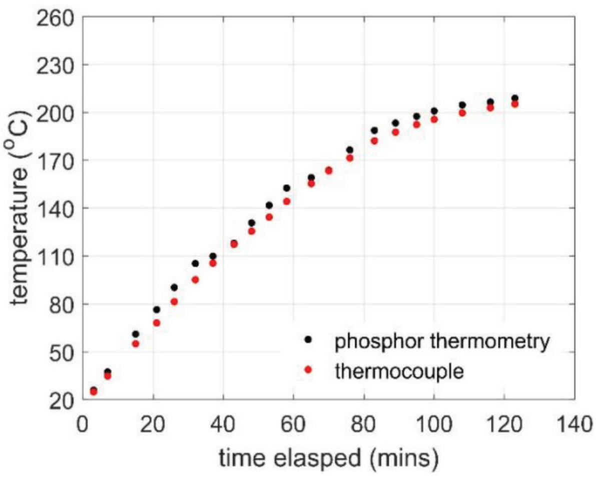

Figure 3. The rise in die preheat temperature measured on a screw press.

CONCLUSIONS

Temperature sensors allow optimisation of process control and enhancement of quality assurance in various manufacturing processes. In this paper, phosphor thermometry was shown to be a candidate technique suited to be implemented for accurate temperature measurements in manufacturing processes. The work reported here acts as a primer for a larger program forming a part of the EMPRESS II project commencing shortly. Further work will be conducted to implement and characterise the technique for real-time screw press die temperature monitoring under typical conditions of cyclic die heating by preforms, mechanical die loading, and application of process lubricants.

REFERENCES

[1] A. J. Norwood, P. M. Dickens, R. C. Soar, and R. A. Harris, "Surface temperature of tools during the high-pressure die casting of Aluminum", P I MECH ENG B J ENG, **221**,1659 - 1664, (2007)

[2] J. Brubach, J. Zetterberg, A. Omrane, Z. S. Li, M. Alden, and A. Dreizler," Determination of surface normal temperature gradients using thermographic phosphors and filtered Rayleigh scattering" Appl. Phys. B **84** 537–41, (2006)