Real-time detection of cooling rate using pyrometers in tandem in laser material processing and directed energy deposition

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ABSTRACT

A novel method of monitoring cooling rates in real-time using two pyrometers arranged in tandem has been demonstrated. First pyrometer monitors the temperature at the center of the molten pool, second monitors the temperature at its tailing end. The difference in two pyrometer signals provides the temperature gradient at 1 kHz frequency from which cooling rate is determined in real-time using Arduino interface. Effectiveness of this method in real-time monitoring of cooling rate during laser remelting and additive manufacturing by directed energy deposition with varying process parameters and layer number is demonstrated.

1. Introduction

Laser as a heat source in several material processing applications like surface modification, welding, cladding, directed energy deposition (DED) has gained a wide popularity due to its intrinsic characteristics that facilitate producing high power density, rapid heating and cooling rate (10^3 –10^6 °C/s) with minimum heat affected zone and distortion. Among these applications, DED a relatively new technology is under extensive study world-wide because of its ability to deposit complex components directly from CAD model in layer-by-layer fashion. However, the process suffers from anisotropy due to heat accumulation during build-up affecting the resulting microstructure, mechanical properties and geometrical integrity [1]. Several studies were reported in quantifying the heat accumulation with respect to peak temperature, molten pool size etc. and controlling process parameters to achieve uniformity. Song and Mazumder [2] developed a control system based on molten pool temperature using a dual-color pyrometer. Laser power was modulated based on the variation in temperature, for improving the surface and geometrical integrity. Ding et al. [3] developed a real-time feedback system for geometrical reproducibility in a robotized laser-based DED system by sensing and controlling the powder flow rate and molten pool size.

Bi et al. [4] demonstrated controlling the melt depth and geometry in laser cladding on shaft and deposition of thin wall respectively, based on the surface temperature. However, monitoring systems based on surface temperature have limitations due to saturation or very little variation of peak temperature with varying process parameters [5,6]. Gopinath et al. [6] reported a large variation in cooling rate compared to temperature with laser process parameters, which carried information about microstructural evolution and geometry; and this could be exploited for developing a feedback control system. Farshidianfar et al. [7] demonstrated online monitoring of cooling rate using an IR camera where the real-time peak temperature of a single point is stored at one instance of time and deducted from the reduced temperature of the same spatial point at later sample times. Further, Table 1 summarizes a few recent patents related to monitoring systems based on similar methods. Most of these systems use IR camera and data intensive driven methods to determine the cooling rate. The present study aims at developing a monitoring system to measure cooling rates in real-time in a simple, economical and faster way with little computational complexity.

2. Experimental details

A 2 kW Yb-fiber laser (IPG photonics, model: YLR 2000) integrated with an in-house fabricated coaxial laser cladding head mounted on a 5-axis CNC was used for remelting and DED of

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Table 1
Patents on monitoring systems for DED.

Authors	Monitoring device	Outcome/Disclosure
Bennett et al. [8]	IR Camera, Pyrometer, Thermocouple	System for monitoring global thermal gradient, activating secondary heat source and cooling system.
Craig [9]	Spectrophotometric sensor	Determining isotherms in AM using a 2D detector array which provides heating, cooling etc., and signal to controller.
Bharadwaj et al. [10]	Photodiode, pyrometer	Monitoring temperature history in AM and comparing with material models to predict defects and mechanical properties
Penny and Hart [11]	Spectrometer	Monitoring temperature, molten pool size and in-situ control of parameters to optimize build quality and microstructure

Inconel 718, a Ni-alloy widely used in hot sections of rocket engines. Inconel 718

powder of particle size in 45 – 90 μm range having spherical morphology was used for DED. Two IR pyrometers (Micro Epsilon, model: CTLM-2HCF3–C3H, operating wavelength- 1.6 μm, acquisition time- 1 ms, vision zone- 0.7 mm diameter, temperature measurement range 385–1600 °C) were used to monitor the molten pool thermal history. The reflected laser radiation that could interfere with the temperature signal was blocked using 1064 ± 25 nm notch filters with pyrometers. Microstructural analysis was carried out using SEM on polished and etched cross sections of remelted tracks near the surface.

2.1. Methodology

Fig. 1a shows the experimental setup and Fig. 1b depicts the temperature monitoring points by two pyrometers in tandem with respect to the molten pool. While first pyrometer monitors the temperature where laser beam is incident on the substrate, the second one monitors temperature at a set distance 'd', typically 5 mm trailing the first, Fig. 1b. Under the condition that molten pool temperature remains almost unchanged in the time scale of laser beam traverse time for 'd' distance, the first pyrometer will measure the instant molten pool temperature, T1 and the second pyrometer essentially will provide the molten pool temperature T2 after a lapse of time, τ = d/v . Here, v is the laser scanning speed. The cooling rate can be estimated by eq. (1).

$$Cooling\,rate = \frac{(T1 - T2)}{d/v} \qquad (1)$$

Voltage signals of both pyrometers were fed to a computer through Arduino (Arduino UNO R3, ATmega16U2 microcontroller) interface where a subroutine converts the voltage signal into temperature, calculates the cooling rate and displays them on the user interface.

3. Results and discussion

3.1. Determining cooling rates in laser remelting

Fig. 2 shows the temperature signals for varying laser scanning speed at a fixed laser power and spot diameter of 1200 W and 3 mm, respectively and its effect on the evolution of microstructure in laser remelted Inconel 718. With the increase in scanning speed in 300–1200 mm/min range corresponding to reduction in line energy $\left(\frac{laser\,power}{scanning\,speed}\right)$ in 240–60 J/mm range, the change in surface temperature is proportionally much less, because laser energy is spent more in increasing the melt pool volume rather than its temperature, Fig. 2a [12]. But, the cooling rate changed significantly from 2650 °C/s to 600 °C/s for the same variation in scanning speed, Fig. 2b. Microstructures evolved at different laser scanning speeds, presented in Fig. 2(c) - (f) can be directly correlated with the cooling rate. While a

relatively slow cooling rate resulted in equiaxed microstructure whose size reduced with increasing cooling rate (Fig. 2(c) and (d)), further increase resulted in columnar dendritic structure (Fig. 2(e) and (f)). It is well reported that the temperature gradient, G / solidification rate, R ratio governs the morphology, where with its decreasing value the columnar to equiaxed transition (CET) occurs, and the cooling rate (G.R) determines the grain size with higher cooling rates yielding smaller size grains [1,13]. As mentioned earlier the increase in molten pool volume at lower scanning speeds may reduce the temperature gradient. The maximum value of R being equal to the scanning speed, reduction in G with decreasing scanning speed reduces the cooling rate which in turn increases the grain size as observed in Fig. 2 (c, d). This could also reduce the G/R which may cross-over the criterion of columnar to equiaxed transition as observed in Fig. 2(d, f) [1,13].

3.2. Determining cooling rate in directed energy deposition

Fig. 3 shows the variation in molten pool thermal history and its size with increasing layer number. As discussed in section 1, with increasing layer number in DED heat accumulates due to reduced temperature gradients and heat conduction, increasing the molten pool size and reducing the cooling rate [1,4]. Increase in the red hot molten pool size is apparent with increasing layer number in Fig. 3. Corresponding to this the cooling rate tends to
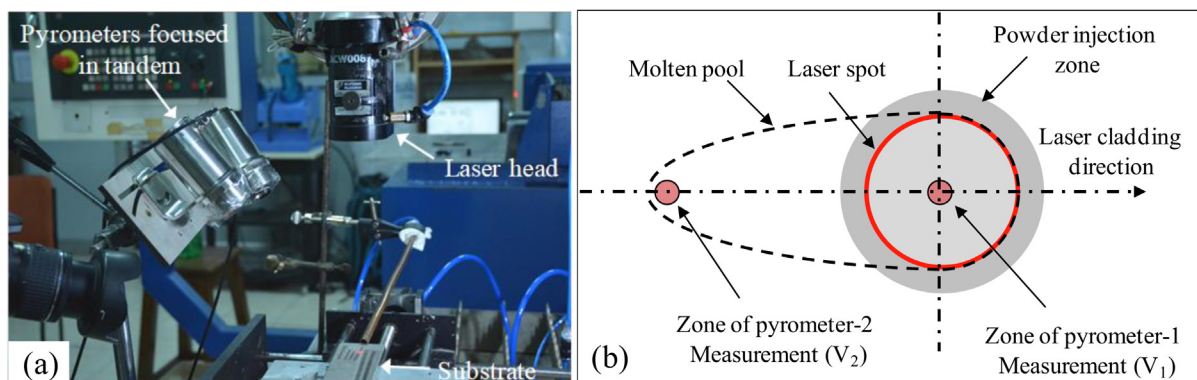

Fig. 1. (a) Experimental setup and (b) Scheme of cooling rate measurement.
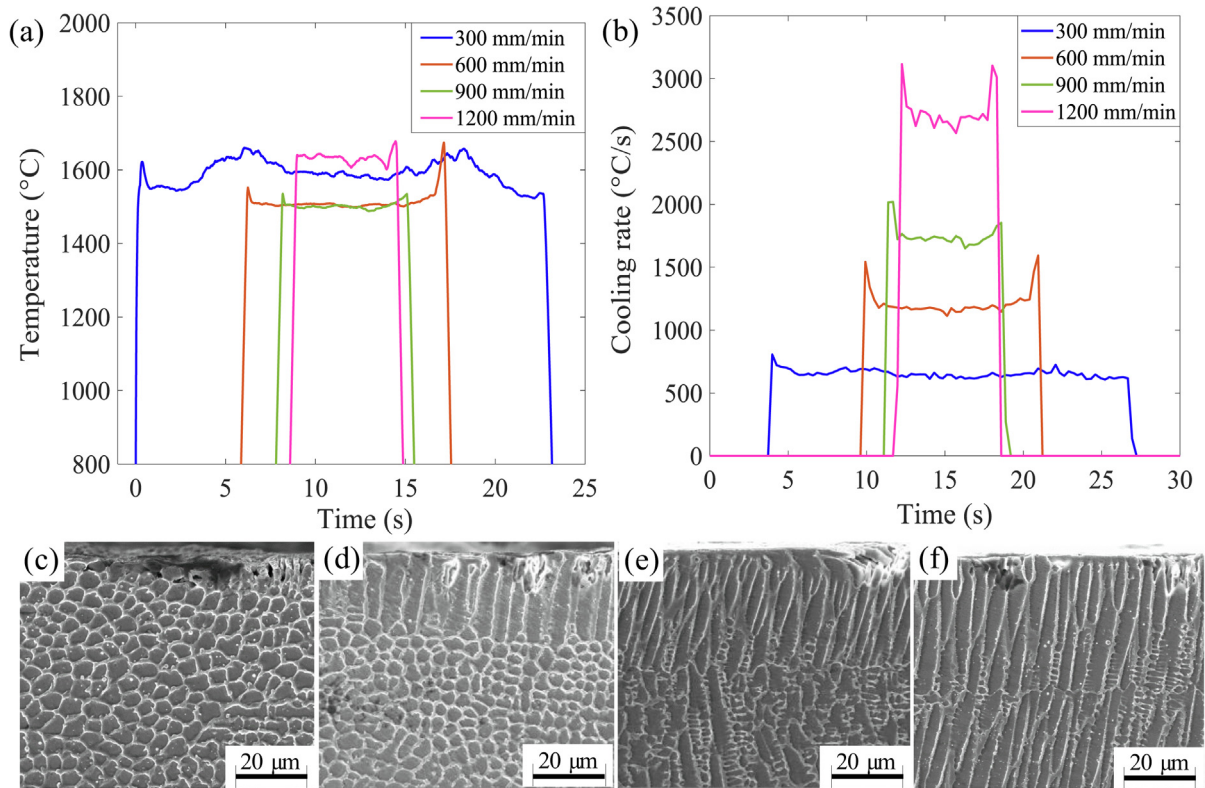
Fig. 2. Effect of scanning speed on (a) surface temperature, (b) cooling rate, and microstructure (c) 300 mm/min (d) 600 mm/min, (e) 900 mm/min and (f) 1200 mm/min; laser power = 1200 W, laser spot diameter = 3 mm.
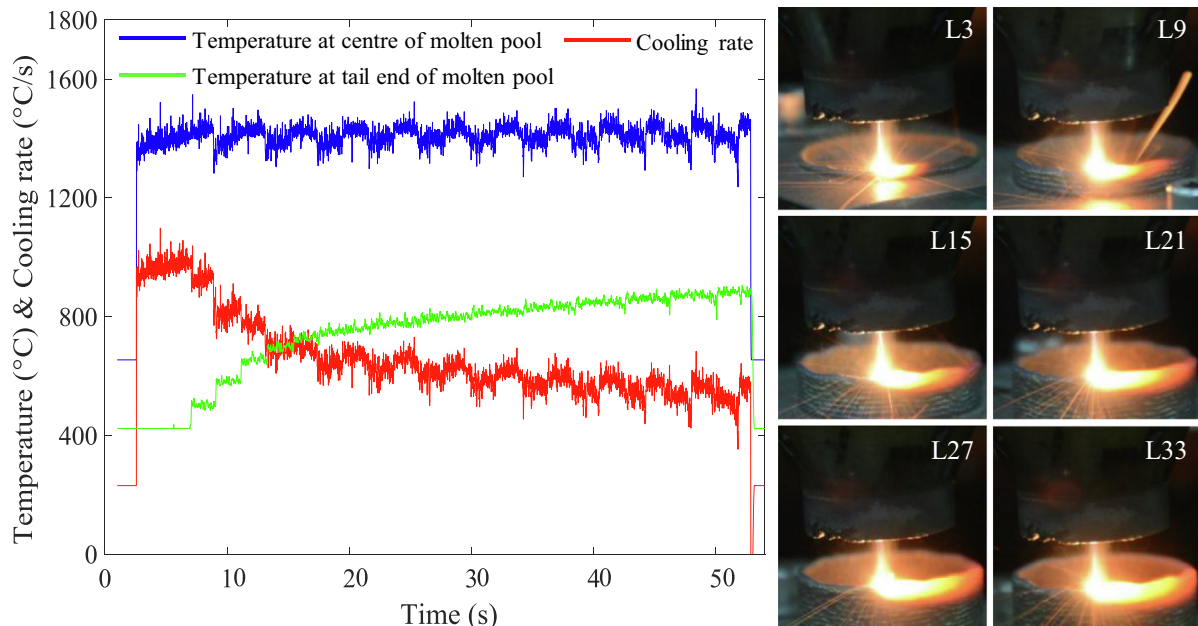

Fig. 3. Variation in cooling rate and molten pool size with layer number (400 W laser power, 2.2 mm spot diameter, 20 g/min powder flow rate and 600 mm/min scanning speed).

decrease with time, i.e. with increasing layer number. The tailing end temperature, T2 gradually increased while the central molten pool temperature, T1 remained almost constant with increasing layer number. However, T1 could vary in composite coatings capturing the information about wt% of different materials deposited at every instance [14] along with the powder flow characteristics. Thus, this method is well capable of determining real-time cooling rates in directed energy deposition and can be utilized for real-time feedback control to ensure reproducibility in multilayer powder deposition.

4. Conclusion

- A novel method of real-time monitoring of cooling rate in laser remelting and directed energy deposition is demonstrated using two pyrometers in tandem.
- Molten pool peak temperature remains almost constant with wide variations in line energy as well as layer number.
- However, cooling rate varies significantly providing information about the evolved microstructure, and this could be exploited for developing real-time feedback control system for improving reproducibility of microstructure.

CRediT authorship contribution statement

Amal M. Nair: Methodology, Conceptualization, Investigation, Writing - original draft, Data curation. **Gopinath Muvvala:** Conceptualization, Investigation, Writing - review & editing, Supervision. **Sagar Sarkar:** Methodology, Investigation, Writing - review & editing, Project administration. **Ashish Kumar Nath:** Methodology, Conceptualization, Supervision, Funding acquisition.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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