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RAPID COMMUNICATION

Glass surface metal deposition with high-power femtosecond fiber laser

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Abstract Using femtosecond fiber laser-based additive manufacturing (AM), metal powder is deposited on glass surface for the first time to change its surface reflection and diffuse its transmission beam. The challenge, due to mismatch between metal and glass on melting temperature, thermal expansion coefficient, brittleness, is resolved by controlling AM parameters such as power, scan speed, hatching, and powder thickness. Metal powder such as iron is successfully deposited and demonstrated functions such as diffusion of light and blackening effects.

1 Introduction

Additive manufacturing (AM), especially laser-aided AM, has attracted lots of attentions in the past two decades [1, 2]. Currently, high-power continuous wave (CW) lasers are widely used, along with some long-pulsed lasers (nanosecond–millisecond pulse duration) [3–5]. Recently, we reported fs fiber laser is used to melt materials with extremely high melting temperature and to manipulate microstructures [6–8]. And various shaped parts (rings, tin walls, gears, and cubes) of iron and tungsten were additively made with fs fiber laser. Those demonstrations showed a great promise of adopting fs fiber lasers in AM.

Though many breakthroughs have been achieved, there are still many challenges to overcome, such as multi-components or multi-material AM.

In this work, for the first time, we reported to use femtosecond (fs) fiber laser AM to deposit or coat metal powders on glass substrate and its applications on stray light reduction. The coatings fabricated by fs fiber laser AM were measured in terms of reflectance and microscopic images. The process is systematically optimized to achieve 100% coverage. Compared with conventional electroplating methods [9–11], this AM method is simpler in operation, environmentally friend, and capable of multi-components.

2 Experiment setup

A high-power mode-locked Yb-doped fiber laser (Laser-Femto, Inc., CA, USA), delivering up to 250-W average power at 80 MHz with central wavelength at 1060 nm, was used in the experiments. Output pulses were compressed to have a full-width-half-maximum (FWHM) pulse duration of 800 fs. Laser beam was guided through a galvanic-mirror-enabled scanner and raster-scanned on the powder surface. The laser beam was focused by a lens with 82-mm-long focal length and had a FWHM diameter of 25 μm on target. Considering the loss through all the components, the maximum power on powder surface is about 170 W. A few parameters, such as laser power, hatching (line spacing), and scanning speed, were varied to study their impact on the powder melting on the glass surface.

The laser beam was guided through an acoustic-optical modulator (AOM, Gooch and Housego, FL, USA), which was used to control the laser on/off and variation of the laser power. The laser scanner was synchronized with the AOM and used to scan the laser beam on the powder surface. The scanner was mounted on a motorized stage to control the focal condition of the laser beam relative to the

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powder surface. The powders were evenly distributed on a substrate with a blade. The sample container was mounted on a *z*-stage and filled with argon gas to prevent oxidation. After one layer of powder was scanned, the sample container was lowered by a certain distance and a new layer of powders was deposited onto it using the blade. The newly deposited powder surface remained the same level as the previous one (Fig. 1).

Iron was chosen as the main material for investigation, since it has the highest melting temperature (~1400 °C). Its heat conductivity at room temperature is 17 W m/K. The iron powders have a size distribution of 1–5 μm (Atlantic Equipment Engineering, NJ, USA). Three-millimeter-thick glass slides were used as the substrates. Table 1 gives a comparison between iron and glass. Glass has comparable melting temperature but with much lower thermal conductivity and thermal expansion coefficient. In addition to those differences, glass is very brittle and easily cracked during laser process. These differences makes the process using fs laser superior to others, since it can balance high-temperature generation (in short time) with thermal dissipation [12].

The experiment parameters, such as scanning speed, hatching, and focal condition, were varied along with laser power. The processed samples were characterized and analyzed with optical microscope and spectrometer.

3 Experiment results and discussion

A single layer AM was conducted by using laser power of 37 W (measured at status of AOM-off, on target power is 70% of the measurement). Powder spreading layer thickness is 40 μm (iron powder) on microscope glass. Hatching space is 20 μm. Different scanning speeds were used to study the effects of coating, and the reflectance was measured accordingly. Figure 2 shows reflectance varies versus different laser scanning speed. Figure 3 shows microscope image of glass surface deposition under different laser scanning speed: (a) 400 mm/s, (b) 300 mm/s, (c) 250 mm/s, (d) 200 mm/s, (e) 150 mm/s, and (f) 100 mm/s. Black spots indicate melt iron powder. The larger the black area, the better coated. The input collimated light is diffused after transmission through the coated glass. The focal point is adjusted right below the powder surface to achieve better performance. It seems, at low scanning speeds, the reflectance is reduced more than those at higher scanning speeds. However, the glass tends to break easily at lower scanning speeds. 300 and 400 mm/s were selected for process optimization.

Since higher scanning speeds are favored, higher laser power must be also used to make the powder melt effectively to form uniform coating on glass substrate. Figure 4a shows reflectance varies versus different laser power with 400 mm/s scanning speed. Figure 4b shows reflectance varies versus different laser power with 300 mm/s scanning speed. Figure 5a, b shows microscope images of glass metal coating under 53 and 37 W laser power after AOM-off reading at 400 mm/s scanning speed, respectively. Figure 5c, d shows microscope images of glass metal coating under 53 and 37 W laser power after AOM-off reading at 300 mm/s scanning speed. It shows that the process window is more sensitive to the scanning speed, compared with the laser power.

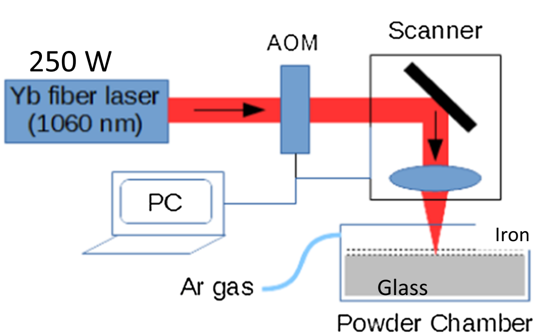

Fig. 1 Schematic of the experimental setup. *AOM* acoustic-optical modulator

Table 1 Comparison between iron and glass

	Iron	Glass
Melting temperature (°C)	1400	1500
Thermal conductivity (W/m K)	17	0.9
Thermal expansion coefficient (μm/m K)	15.9	5.9
Thermal diffusivity (mm^2/s)	3.3	0.34

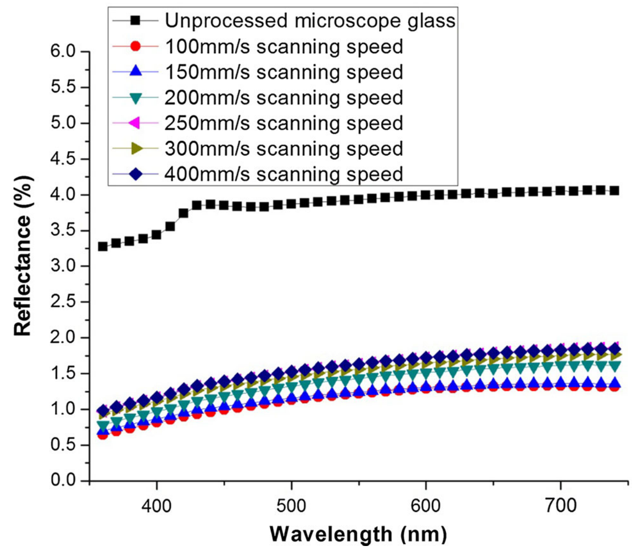

Fig. 2 Reflectance measurement for different scanning speed. Laser average power is 37 W, hatching space is 20 μm, and powder thickness is 40 μm

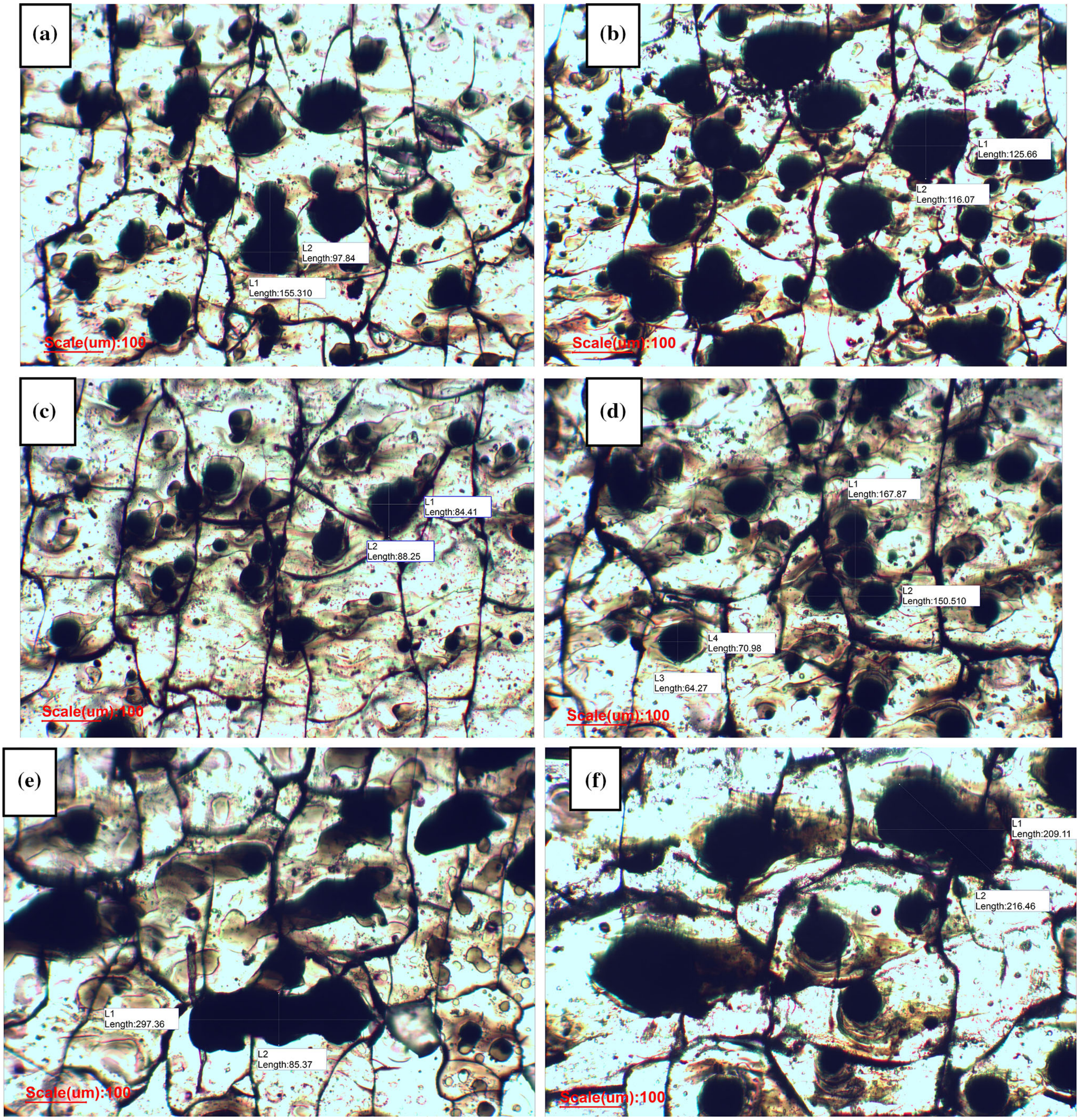

Fig. 3 Microscope image of glass surface metal coating under different laser scanning speed: **a** 400 mm/s, **b** 300 mm/s, **c** 250 mm/s, **d** 200 mm/s, **e** 150 mm/s, and **f** 100 mm/s. Laser average power is 37 W, hatching space is 20 μm, and powder thickness is 40 μm. *Dark areas* or *lines* are coated with melt iron (opaque to light) and are not cracks

Iron powder layer thickness was also varied to study the effects of coating/deposition, and the reflectance was measured accordingly. Figure 6a shows spectral reflectance for different powder layer thickness. Due to the ablation and shock wave impact on the melt powder, the melt layer thickness is not proportional to the powder thickness. It turns out the optimized powder spreading thickness is about 70 μm. The coating layer was bonded strongly with glass. It cannot be removed by scratching the surface with mechanical tools. Figure 6b shows the interface image of iron coating. It indicates a strong melted bond between glass and iron. The coating thickness on glass is about 5 μm.

Further study was done to make side coating of a fused silica glass window to reduce stray light for laser remote sensing. Total of three layers of iron powder was spread

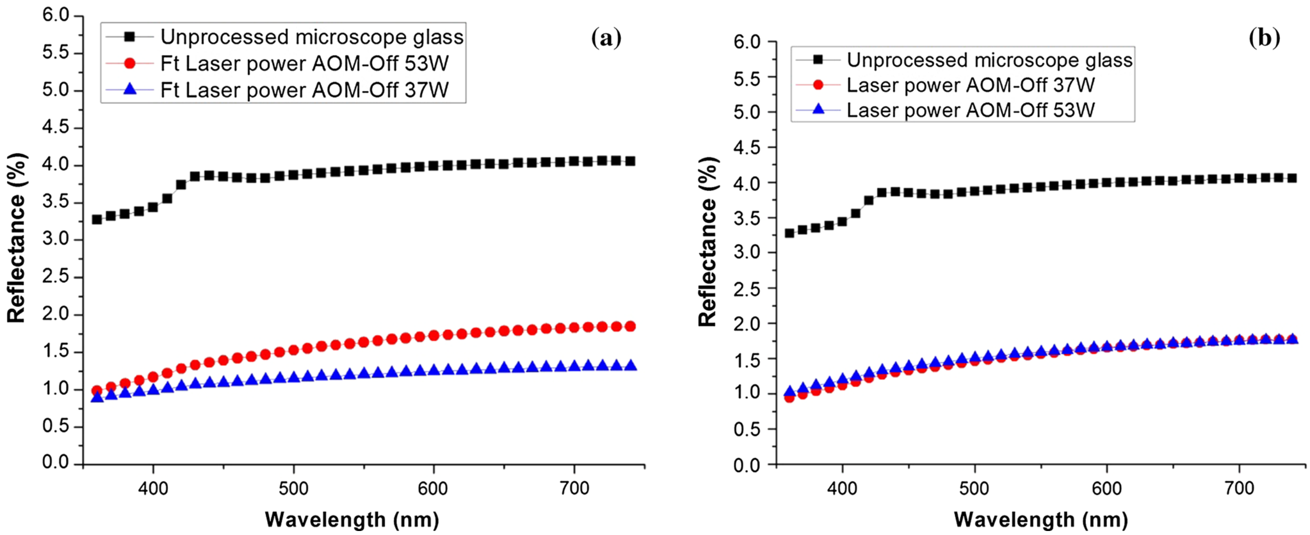

Fig. 4 **a** Reflectance versus wavelength at different laser powers with 400 mm/s scanning speed, **b** reflectance versus wavelength at different laser powers with 300 mm/s scanning speed. Other process parameters are same: hatching space is 20 µm and powder thickness is 40 µm

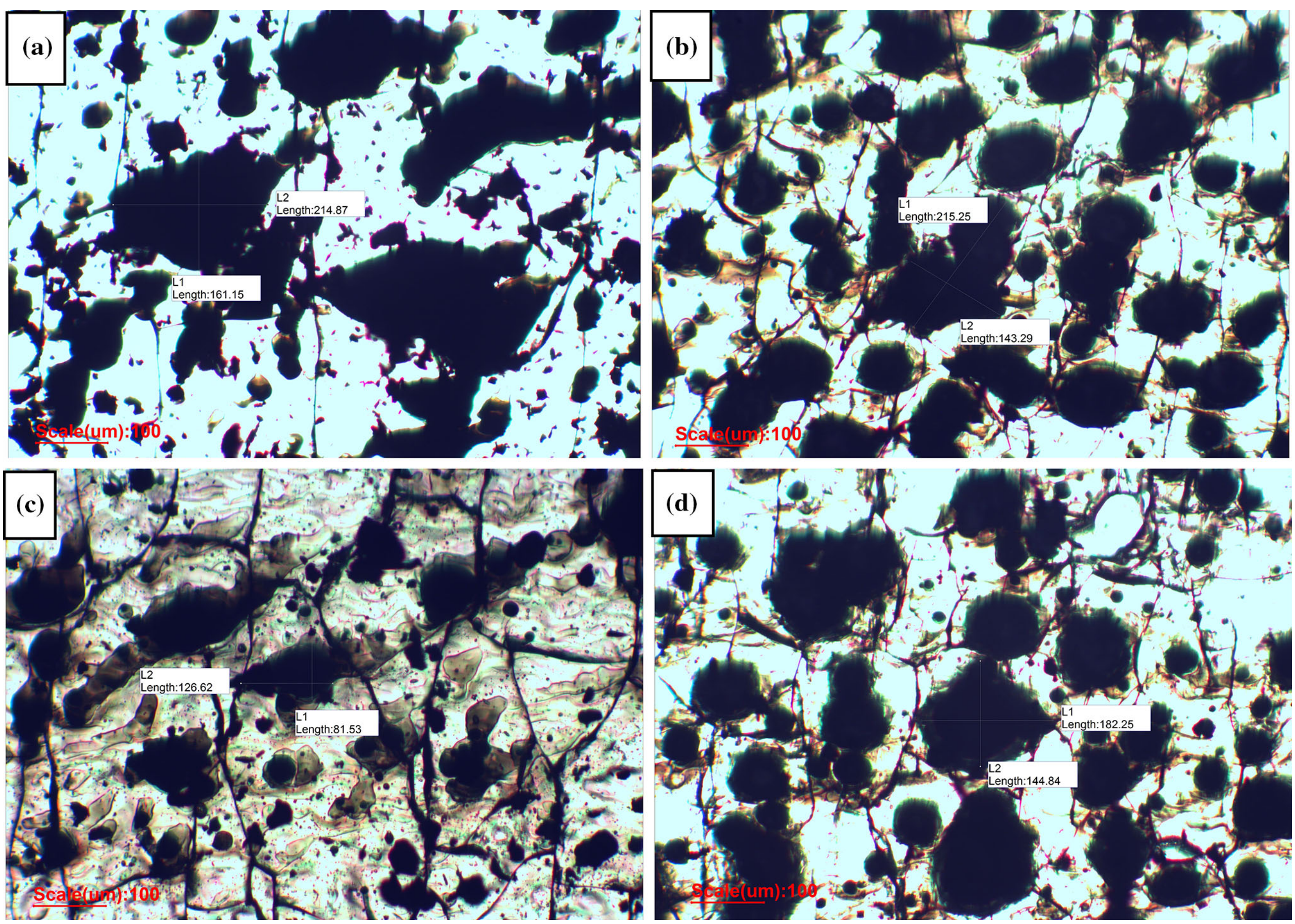

Fig. 5 Microscope image of glass metal coating under different laser power and scanning speed: **a** 53 W, 400 mm/s; **b** 37 W, 400 mm/s; **c** 53 W, 300 mm/s, **d** 37 W, 300 mm/s. Other process parameters are same: hatching space is 20 µm and powder thickness is 40 µm. *Dark areas* or *lines* are coated with melt iron (opaque to light)

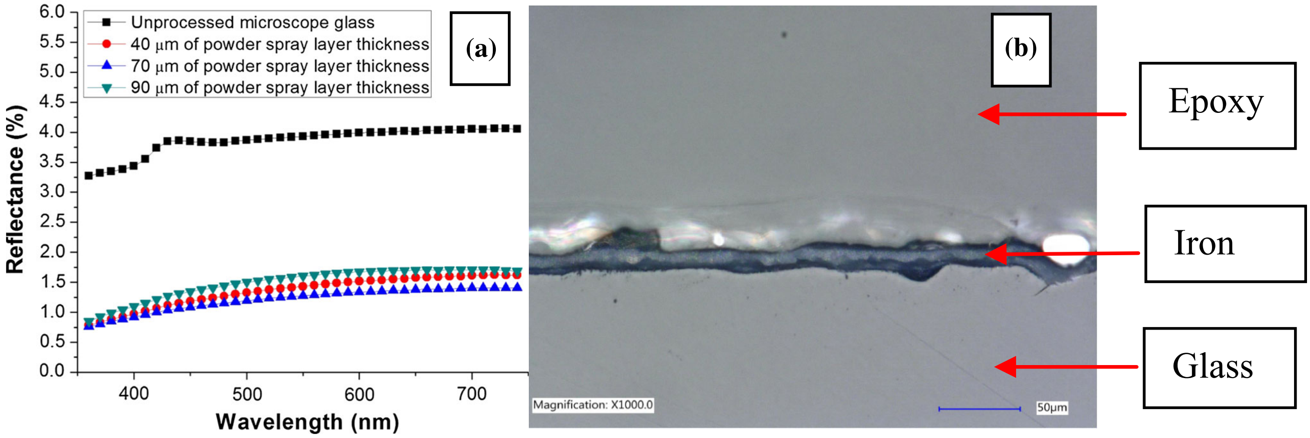

Fig. 6 **a** Reflectance measurement at different powder layer thickness, **b** microscope image of interface between iron and glass (an epoxy is used to help mount the sample and polish the cross section). Laser average power is 53 W, hatching space is 20 μm, and speed is 300 mm/s

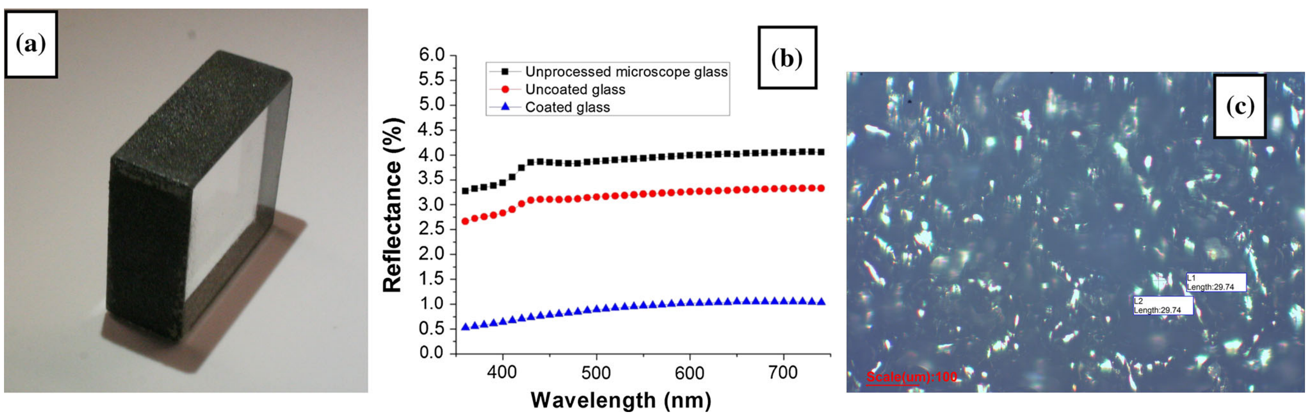

Fig. 7 **a** Iron powder coating on four sides of a fused silica glass window, **b** reflectance measurement, **c** microscope image of coating top surface. *Dark areas* or *lines* are coated with melt iron (opaque to light). Laser average power is 53 W, hatching space is 20 μm, powder thickness is 70 μm, and speed is 300 mm/s

and melt for all four sides of the glass window. Figure 7 shows the experimental results. Reflectance (<1%) improvement is significant over uncoated surfaces of the window. After three layers of iron powder coating, surface of the glass was completely covered with melted iron powder (Fig. 7c). This further confirms that optimization of process parameters is critical to achieve good layer of coating. The sample was put on a hot plate at a temperature of 300 °C, and the coating layer was not peeled off.

4 Conclusions

In conclusion, we demonstrated for the first time that metal powders can be additively coated on glass surfaces/substrates, which have a completely different mechanical and thermal properties. Systematic study has been given to optimize the process and achieve a 100% surface coverage, in terms of laser power, scanning speed, and coating thickness. An excellent blackening effect with <1% reflectance was also achieved. This work provides a breakthrough in developing AM of multi-component materials or dissimilar materials.

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