EMISSIVITY CHARACTERIZATION OF THERMOPLASTIC CFRP FOR THERMOGRAPHIC MEASUREMENT DURING LASER-ASSISTED AUTOMATED FIBRE PLACEMENT

Cheng. Chen[1], Qingjiang. Hou[2], Wenlong. Chen[3], Wei. Jiang[4], Zhigao. Huang[5] and Huamin. Zhou[6]

[1] State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan, 430074, PR China, 2021505002@hust.edu.cn, http://hscae.mat.hust.edu.cn/index.htm

[2] State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan, 430074, PR China, 2226432983@qq.com, http://hscae.mat.hust.edu.cn/index.htm

[3] State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan, 430074, PR China, m202271051@hust.edu.cn, http://hscae.mat.hust.edu.cn/index.htm

[4] State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan, 430074, PR China, jwupup@hust.edu.cn, http://hscae.mat.hust.edu.cn/index.htm

[5] State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan, 430074, PR China, huangzhigao@hust.edu.cn, http://hscae.mat.hust.edu.cn/index.htm

[6] State Key Laboratory of Materials Processing and Die & Mould Technology, Huazhong University of Science and Technology, Wuhan, 430074, PR China, hmzhou@hust.edu.cn, http://hscae.mat.hust.edu.cn/index.htm

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ABSTRACT

Laser-assisted automated fibre placement (LAFP) is an emerging technology used to manufacture large-scale complex thermoplastic composite parts efficiently, with in-situ consolidation. To achieve precise processing temperature monitoring and control during this process, an infrared (IR) camera is frequently employed to achieve the melting of thermoplastic tapes and prevent thermal degradation. The emissivity setting is crucial for the thermographic measurement of thermoplastic tapes during LAFP, but it can be affected by multiple factors, such as material temperature, surface incident angle, and fibre orientation. This study investigates the effect of temperature and incident angle on the emissivity of carbon fibre (CF) reinforced polyphenylene sulfide (PPS) composites and their impact on the thermographic measurement. The emissivity of CF/PPS tapes at varying temperatures and incident angles was measured using thermocouples and thermographic measurements. Results show that the dependency of thermographic measurement on emissivity increases with temperature, indicating the importance of emissivity calibration at high temperatures. Additionally, the emissivity of tapes remains constant below the melting point and decreases with increasing temperature above the melting point. The emissivity is constant at an incident angle from 0° to 60° but decreases rapidly as the angle changes from 60° to 90°. Furthermore, temperature-dependent and angular-dependent emissivity were utilized to calibrate the processing temperature of the prepreg surface by an infrared camera. Compared to thermocouple measurements, a small error of 2% was achieved for thermographic measurements during the LAFP process. In conclusion, this study provides insights into the complex interplay of temperature, incident angle, and emissivity during the LAFP, offering new ways to achieve accurate and efficient thermographic measurements for the LAFP process.

1 INTRODUCTION

Carbon fibre-reinforced thermoplastic composites offer a promising solution to enhance performance, reduce costs, and promote sustainability in the aerospace industry due to their unique properties, such as exceptional recyclability, unlimited shelf life, and high impact resistance [1]. Laser-assisted automated fibre placement (LAFP) is an emerging process for producing large-scale thermoplastic composite structures with complex shapes [2]. This process involves the use of a near-infrared (NIR) laser to melt the thermoplastic tape and substrate, followed by pressing the tape onto the substrate using a roller to improve interlaminar adhesion. During the LAFP process, excessive laser heating can lead to high temperatures that cause degradation of the prepreg tapes [3]. Conversely, insufficient laser heating can result in low processing temperatures and resulting weak interlaminar adhesion [4]. Therefore, controlling the surface temperature of the thermoplastic tapes is crucial for achieving a high-quality LAFP process.

Infrared cameras are widely used in the LAFP process to monitor the surface temperature of the thermoplastic tapes during placement [5,6]. The infrared camera provides real-time, high-resolution thermal images of the workpiece and enables precise control of the laser heating process by adjusting the power output to maintain optimal temperatures. This is critical for ensuring that the thermoplastic tapes do not get overheated, which can result in reduced mechanical properties [3] and poor interlaminar adhesion, or underheated [4], which can cause weak bond strength between layers. Infrared cameras can also detect any defects or anomalies in the placement process, allowing for immediate corrective action to be taken to ensure a high-quality product. Overall, the use of infrared cameras has become an indispensable tool in LAFP processes, providing essential monitoring and control capabilities to achieve reliable and high-quality temperature measurement.

The emissivity of prepreg tapes plays a critical role in thermographic measurement as it directly affects the accuracy of temperature measurements during the LAFP process [7]. Emissivity is a measure of the ability to emit thermal radiation, and it varies depending on factors, such as material type, surface roughness, temperature, and measurement angle [7]. During the LAFP process, the tapes are typically exposed to varying temperatures ranging from room temperature to processing temperature above melting temperature [8]. However, the emissivity measurement for thermoplastic tapes was mainly performed below the melting temperature of the thermoplastic polymer [9]. In addition, the measurement angle of the IR camera varies with the position of the measurement region due to the curvature of the roller [10]. These factors can significantly affect the emissivity of tapes but the surface emissivity is frequently kept constant in IR camera software during the LAFP process. To address these issues, this work establishes an experimental apparatus and utilizes a Fourier transform infrared microscope to measure the emissivity of carbon fibre (CF)-reinforced poly(phenylene sulfide) (PPS) tapes at varying angles and temperatures. The measured emissivity values are then utilized to calibrate the thermographic measurement of tape surface temperature during the LAFP process. This calibration ensures precise and reliable temperature control during laser processing by accurately measuring the tape surface temperature.

2 EXPERIMENTAL

2.1 Materials

This work used a commercial CF-PPS tape (Nanjing Advanced Thermoplastic Composite Co., LTD) with a width of 12.7 mm. The single-ply thickness of the tapes is around 150 µm. The areal weight is 242 g/m^2. The mass fraction of the resin is around 34%. The density of the tapes is 1.57 g/cm^3. The KEYENCE VHX-1000C digital microscope was used to measure the three-dimensional (3D) profile and calculate the surface roughness of both sides of prepreg tapes. The arithmetic average roughness, *Ra,* was used by calculating the arithmetic average of profile height deviations from the mean line.

2.2 Emissivity measurement

The emissivity spectrum (4-7 µm) of prepreg tapes was measured using thermographic measurement at varying temperatures from 40 °C to 370 °C and varying measurement angles from 0° to 80°, as shown in Figure 1 (a). A ceramic heater was used to control the high temperature of the sample, Figure 1 (b-c).

A thermocouple was used to measure the temperature of the sample. An IR camera infrared camera (618C-L29, FOTRIC infrared technology Co.) was used to measure the temperature near the region whose temperature was measured. The emissivity setting in the IR camera software interface was adjusted until the temperature measured by the IR camera matched the value by thermocouples. This emissivity value was defined as the emissivity of prepreg tapes.

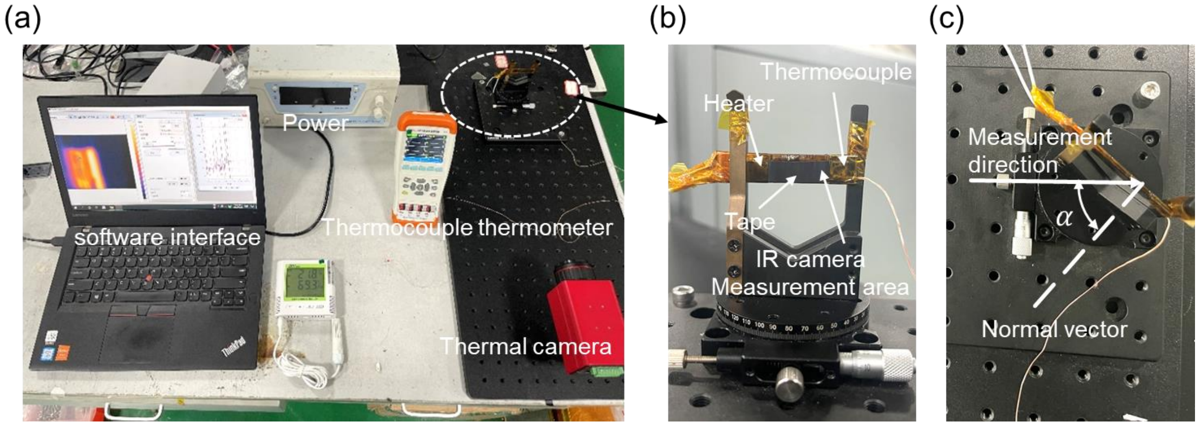

Figure 1: (a) Experimental apparatus for measuring emissivity of thermoplastic tapes at varying angles and temperatures; (b-c) Rotating stage for the emissivity measurement of thermoplastic tapes at varying angles and temperatures.

2.4 Thermographic measurement during the LAFP process

The temperature calibration was performed using a self-developed LAFP machine. A fibre laser system with a wavelength of 1080 nm (RFL-C1000, Wuhan Rekor Fibre Laser Technology Co.) was mounted with a fixed large nominal incident angle of 70° on the tooling surface. The laser shape was adjusted to a rectangular spot size of 15 mm×40 mm to cover the width of the tapes using a shaping device (GC15-30A, Gangchun Laser Technology Co.). An IR camera (618C-L29, FOTRIC infrared technology Co., 26 frames per second) was used to measure the temperature on the tape surface. The thermographic measurement was calibrated with the measured emissivity of prepreg tapes. The temperature measured by the IR camera was compared with the values measured by thermocouples.

3 RESULTS AND DISCUSSION

3.1 Effect of emissivity setting on thermographic measurement

The effect of emissivity setting on thermographic measurement for CF/PPS tapes was evaluated at varying temperatures using the experimental apparatus in Figure 1 (a). When the emissivity of tapes is overrated, the temperature measured by the infrared camera is lower than the actual temperature which is measured by thermocouples. Conversely, when the emissivity is underrated, the measured temperature is overrated. For example, if the actual temperature of the material is 161°C and the actual emissivity is 0.87, setting the emissivity to 1 on the infrared camera will result in a temperature output of 149 °C, while setting the emissivity to 0.15 will result in a temperature output of 493 °C. Moreover, the error in temperature measurement caused by variation in emissivity is larger at higher temperatures. For instance, at the temperature of 161°C, setting the emissivity to 0.7 results in a measured temperature of 186 °C, while setting it to 0.8 results in a measured temperature of 171 °C, resulting in a difference of 15 °C. However, at a temperature of 369 °C, setting the emissivity to 0.7 results in a measured temperature of 375 °C, while setting it to 0.8 results in a measured temperature of 412 °C, resulting in a difference of 37 °C. If the emissivity of tapes is set to 1, the measured temperature will be 12 °C lower than the actual temperature at 161 °C, and 47 °C lower than the actual temperature at 369 °C. These results indicate the thermographic measurement is more sensitive to the emissivity setting when the temperature of tapes is approaching the melting temperature.

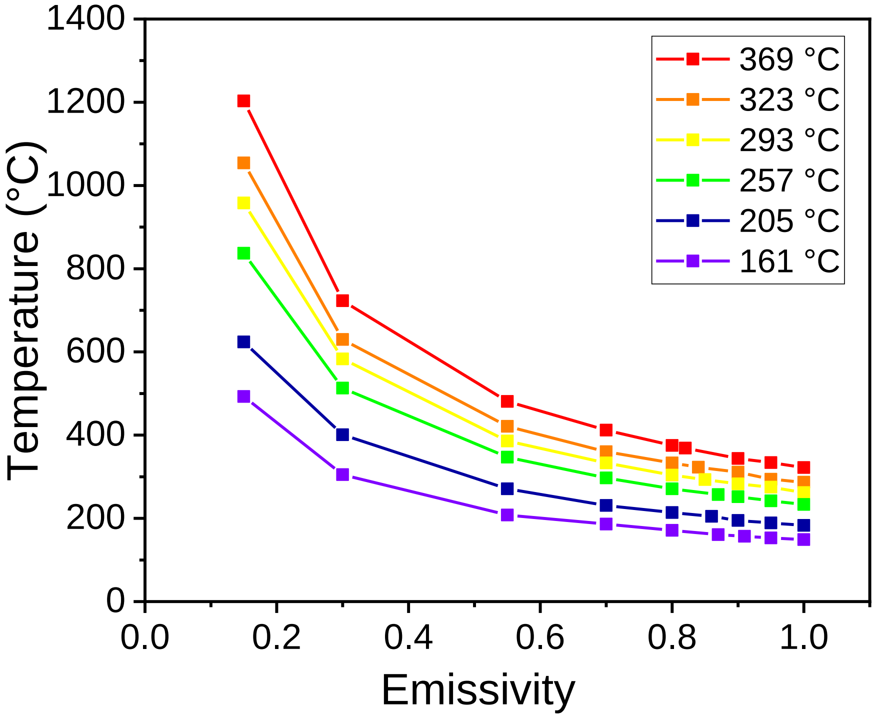

Figure 2: Effect of emissivity setting on thermographic measurement results.

3.2 Effect of surface roughness and measurement angle on emissivity

The surface roughness of both sides of prepreg tapes was measured by the KEYENCE VHX-1000C digital microscope and calculated by calculating the arithmetic average of profile height deviations from the mean line. Figure 3 (a-b) shows that the surface roughness of both sides of prepreg tapes is different. The roughness of the smooth surface of tapes is around 55% lower than that of the rough surface, as shown in Figure 3 (c).

(a) (b) (c)

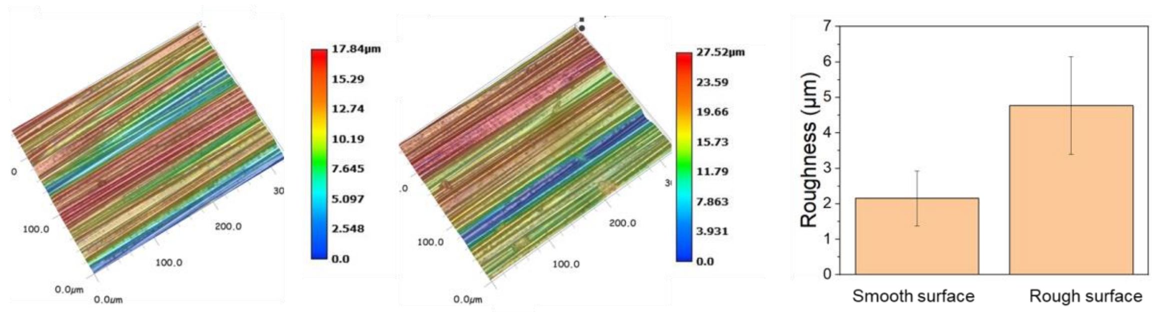

Figure 3: (a) Surface profile of smooth CF/PPS tape surface; (b) Surface profile of rough CF/PPS tape surface; (c) Roughness of the smooth and rough surface of CF/PPS tape.

Figure 4 shows the emissivity of prepreg tapes is lower on rough surfaces than on smooth surfaces below the melting temperature. When the temperature is approaching or above the melting temperature of 280 °C, the effect of surface roughness is becoming less significant. Figure 4 (a-b) shows that the emissivity of prepreg tapes remains constant below 60° and decreases with the increasing measurement angles from 60° to 80°.

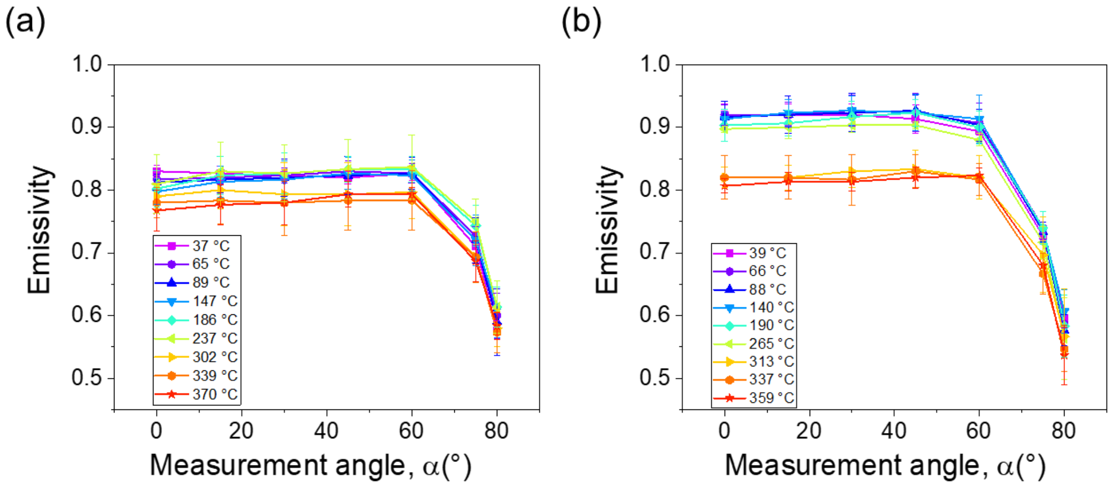

Figure 4: Effect of measurement angle on the emissivity of prepreg tapes with a smooth (a) and rough (b) surface at varying temperatures.

3.3 Effect of temperature on emissivity

Figure 5 shows the effect of temperature on the emissivity of prepreg tapes with rough and smooth surfaces at varying angles. Under the same measurement angles, the emissivity of prepreg tapes below the melting temperature of 280 °C is relatively constant and is higher than that above 280 °C. The results indicate that the emissivity is supposed to be updated during the thermographic measurement for the LAFP process since the emissivity is temperature-dependent.

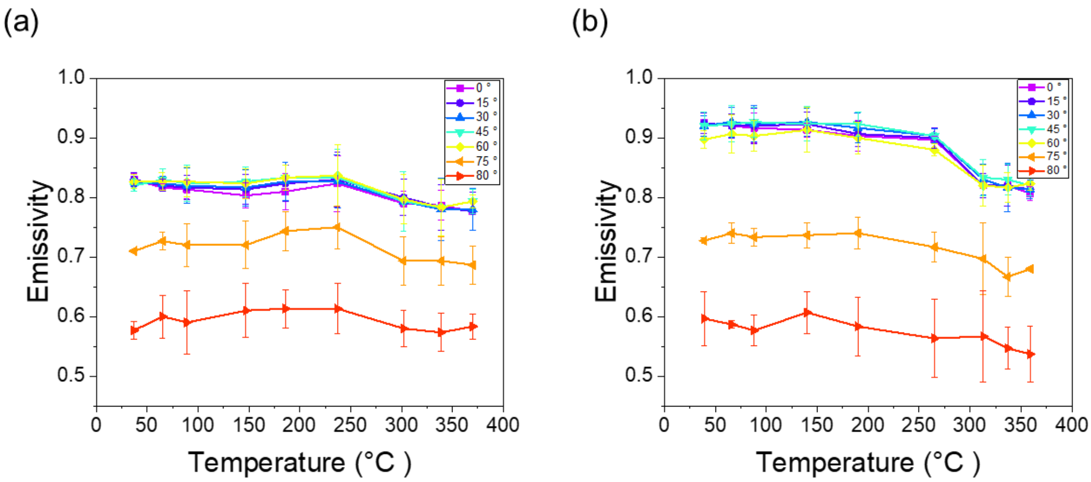

Figure 5: Effect of temperature on the emissivity of prepreg tapes with a smooth (a) and rough (b) surface at angles.

3.4 Temperature calibration and validation for the LAFP process

Based on the measured emissivity of tapes at varying temperatures and angles, temperature calibration and validation were performed on both sides of the tapes using self-developed LAFP equipment with an IR camera and thermocouples. For the smooth surface of the CF/PPS prepregs, the measurement angle of the infrared camera remained constant at 60°. The processing temperature of the CF/PPS tapes was approximately 260 °C. Therefore, the emissivity of the material was estimated to be approximately 0.82 based on the measured emissivity. After setting the emissivity, humidity and measurement distance on the IR camera software interface of the infrared camera and properly arranging the thermocouples, the CF/PPS prepregs were heated with the NIR laser during the LAFP process, as shown in Figure6 (a). The temperature was measured by the thermocouple and the infrared camera.

According to Figure 6 (b), the deviation between the temperature measured by the IR camera and that measured by the thermocouples is only 1%. For the rough surface of the CF/PPS prepregs, the deviation between the temperature measured by the IR camera and that measured by the thermocouples is below 2%, as shown in Figure 6 (c).

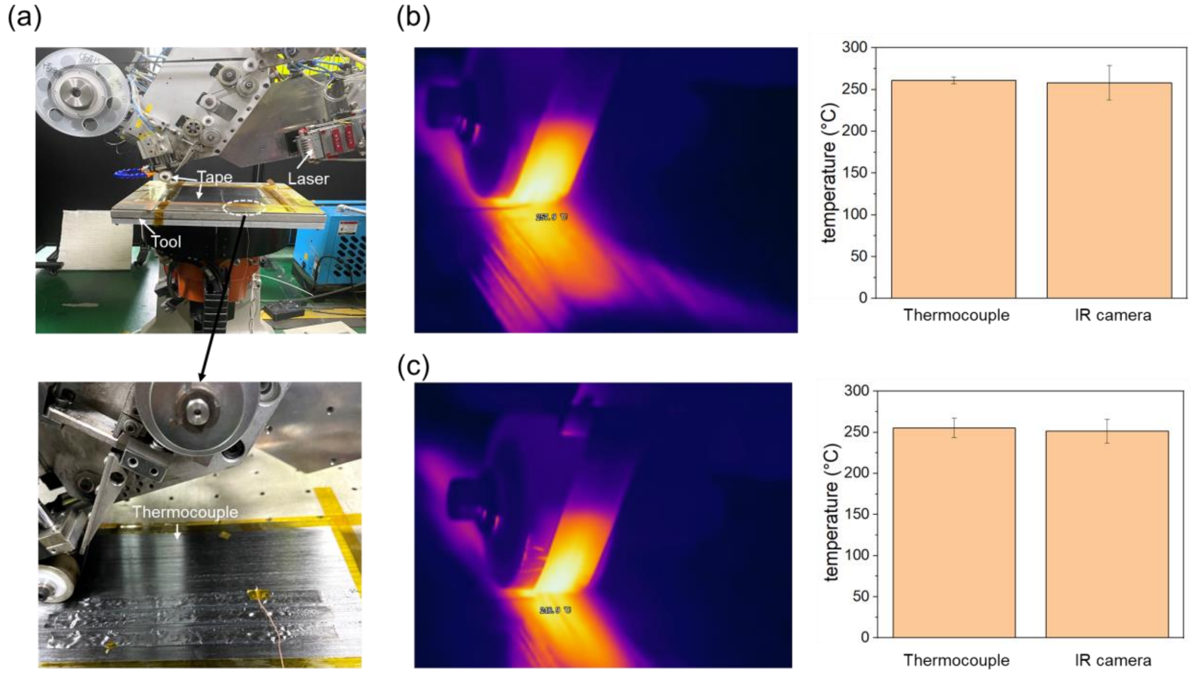

Figure 6: (a) LAFP machine and experimental setup for thermographic measurement and temperature calibration validation; (b) Thermographic results for the smooth surface of CF/PPS tapes; (c)

5 CONCLUSIONS

This study studies the effect of temperature and incident angle on the emissivity of CF/PPS prepreg tapes with smooth and rough surfaces. The results show that the error in temperature measurement caused by variation in emissivity is larger at higher temperatures, indicating the importance of emissivity setting for the thermographic measurement during the LAFP process. Furthermore, the emissivity of CF/PPS tapes at varying temperatures and incident angles was measured using thermocouples and thermographic measurements. The emissivity of prepreg tapes is lower on rough surfaces than on smooth surfaces below the melting temperature and becomes similar as the temperature is approaching or above the melting temperature of 280 °C. Moreover, the emissivity of prepreg tapes remains constant below 60° and decreases with the increasing measurement angles from 60° to 80°. Under the same measurement angles, the emissivity of prepreg tapes below 280 °C is relatively constant and is higher than that above 280 °C. Furthermore, the measured temperature-dependent and angular-dependent emissivity were utilized to calibrate thermographic measurements during the LAFP process. Compared to thermocouple measurements, a small error below 2% was achieved for thermographic measurements for both smooth and rough surfaces during the LAFP process. This work provides a valuable dataset for thermographic measurement for CF/PPS prepreg tapes during high-speed LAFP process.

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