A Software System to Accurately Calculate Parts Temperature for Hot Stamping

P. X. He[1], D. F. Zheng[1], L. Y. Shi[1], R. L. Wang[1], J. P. Lin[2,3](✉), Z. H. Zhao[2,3], and Y. K. Gu[2,3]

[1] Jinan Aotto Automation Co., Ltd., Jinan, Shandong, China
he_puxuan@aotto.cn
[2] School of Mechanical Engineering, Tongji University, Shanghai 201804, China
jplin58@tongji.edu.cn
[3] Shanghai Key Laboratory for A&D of Metallic Functional Material, Tongji University, Shanghai 200092, China

Abstract. Infrared thermal imaging system is a key component in hot stamping and is commonly used to collect parts temperature during the part production process. However, due to the inappropriate setting of the emissivity, the output produced via such system usually lack accuracy and consistency. A ± 150 °C temperature measurement error was observed at several hot-stamping lines. In this paper, a new infrared software system is proposed to calculate parts temperature by utilizing a mathematical model behind the scenes. The system factorizes 3D model of the part, position of the thermal camera and parameters of the environment to calculating the directional emissivity, which is further used to compensate the output obtained from the thermal camera. Compared to traditional thermal systems, the proposed software system achieved 83% increase in accuracy (±25 °C vs ±150 °C in measurement error). Nonetheless, usage of such software system will be discussed. For example, double sheet detection for hot stamping line have been implemented by setting the threshold of part temperature and dispatch warnings to PLCs via ProfiNet or Ethercat protocol. In combined with IIot and machine learning techniques, quality prediction system for hot stamping have also been built.

Keywords: Infrared thermal imaging system · Temperature · Emissivity · Hot stamping

1 Introduction

Hot stamping systems have been widely used in automobile production industry, over 15 hot stamping lines have been delivered by Aotto last year. The temperatures of sheet before closing the mold and after opening the mold are key process parameters. For example, the sheet metal temperature before mold closing should be higher than Ar3 to avoid the deterioration of mechanical properties caused by the transformation from austenite to ferrite [1, 2]. Severe quality problems could raise if such requirements are not met. In the past, infrared thermal imaging system have been developed by Aotto to

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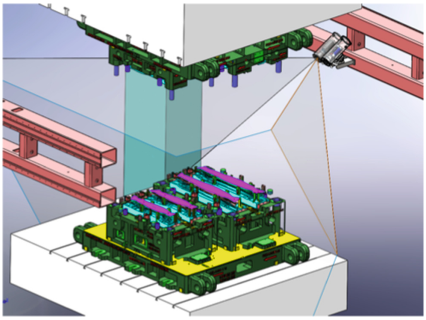

Fig. 1. Infrared thermal imager position.

measure temperature of sheet during forming process. A single constant emissivity was given to the thermal camera to measure the temperature. However, due to the complexity of hot-stamping line's layout (shown in Fig. 1) and part not being a flat surface, the observation angle has a huge impact on measured temperature. A ± 50 °C to ± 150 °C measurement error was observed at several hot stamping lines.

The emissivity is greatly affected by oxidation of the surface, the thickness of the sheet, the observation angle of thermal camera. To compensate errors and calculate the accurate emissivity, a lab environment was built to mimic the real industrial environment, a regression model was built to calculate the emissivity under different observation angle using lab results we generate from experiments. Furthermore, a software was design to extract observation angle at each point on the part surface in the field of view (FOV) of the infrared thermal. In combine with the observation angle matrix and the regression model, our software will output the emissivity matrix and by feeding the matrix into the thermal camera system, the actual sheet temperature will be calculated.

On top of such software component, a hot stamping software eco-system is built. Some key features include storing historical temperature and other key process parameters to trace the quality of product, sheet in-mold positioning verification and double-sheet detection to protect the mold and stamping machine from inappropriate positioning of sheet.

2 Directional Emissivity Modeling

2.1 Material Setup and Experimental Procedure

To simulate the process of hot stamping, a lab environment was built. Setup for our lab environment is shown in Fig. 2.

Calorimetry [3] method was used to calibrate the emissivity of the Optris PI640i thermal imagers. First, we placed the sample sheet in the muffle furnace oven and heated the sample at 750 °C for 5 min. This was to mimic the heating process of hot stamping. The sample sheet was then brought out of the furnace. We measure the current temperature of the sample using thermocouple. This process was to calibrate the emissivity for in-mold temperature. The sample was then cooled by high-speed nitrogen gas flow to 200 °C to 300 °C. Again, the thermocouple was used to measure the temperature. This process was

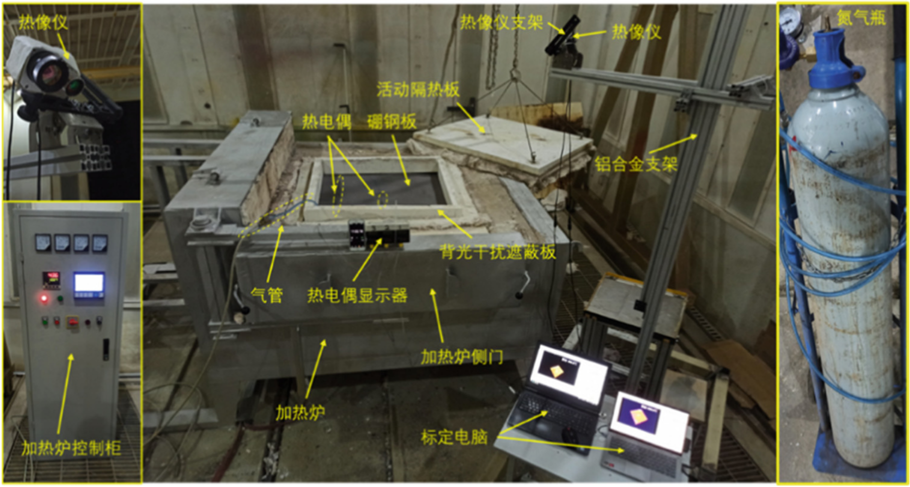

Fig. 2. Setup of our lab environment.

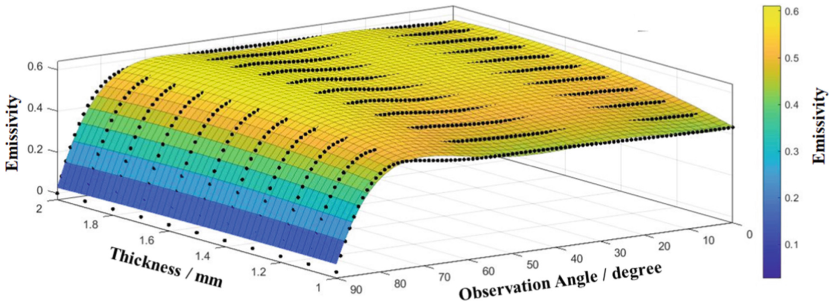

Fig. 3. Emissivity model by polynomial fitting.

to mimic the stamping process and calibrate the emissivity for out-mold temperature. The same process was repeated for same sample sheet but at different observation angle.

2.2 Emissivity Modeling

To calculate the emissivity at arbitrary angles, a polynomial regression function was introduced to fit the results we collection from experiments. The function takes observation angle and sheet thickness as input and output the emissivity. The plot of polynomial fitting function is shown in Fig. 3.

2.3 Extraction of Observation Angles and Calculation of Emissivity Matrix

Once we've had the regression model for emissivity calculation at various angles, it is necessary to extract the observation angle of each point on the sheet relative to the infrared thermal imager. We use the CAD model of the part as input. Firstly, we apply the gridding method to discretization the CAD model. Then the projection method was used to calculate the observation angle of thermal camera. After that, we can feed the angle matrix to the regression model and calculate the emissivity matrix.

3 Software Implementation

3.1 Program to Calculate the Emissivity Matrix

The program to calculate the observation angle was implemented using MATLAB. The program takes the CAD model which contains the part model and layout of part and thermal imager. It first applies the gridding method to get the surface mesh, calculates the normal vector of projection plane to the thermal imager. Then the projection plane can be calculated, and 3D model will be converted to 2D model. One thing to notice is that the number of mesh may not match the resolution of thermal imager, we must apply the interpolation method to get the observation angle matrix that matches the thermal imager resolution. Such MATLAB program will be compiled and integrated into our infrared thermal imaging system which is implemented in C#(winform). The C# software applies the angle matrix into the regression model and calculate the emissivity matrix. It then feed the emissivity matrix into the thermal imager sdk to get the final temperature matrix.

For different brands of infrared thermal imager, there are 2 major mechanisms to dynamically adjust the emissivity. IRay and HikVision thermal imager sdk provides public api to set emissivity for different areas of the image. However, there's usually an limitation on maximum number of areas (usually up to 10). We've been working with developers on iRay and HikVison team and they've provided us a private api which takes the emissivity matrix as input when calculating the temperature. For Flir infrared thermal imager, there's no public api to dynamically set the emissivity. However, a callback function can be provided to re-calculate the temperature with a new emissivity to compensate the temperature. We developed a function which loop through every individual pixel on the image to re-calculate the temperature.

3.2 Overall Architect of the Infrared Thermal Imaging System

Based on the program to calculate the emissivity matrix and compensated temperature, the infrared thermal imaging system as shown in Fig. 4 was built to store historical temperature and other process parameters, dispatch warnings if the temperature varies from process configuration, verify the in-mold sheet position, and detect double-sheet scenario.

The system mainly contains 4 layers of software/hardware components: the hardware layer, data collection layer, storage layer and application layer. The hardware layer usually contains PLCs, infrared thermal imager and industrial cameras which provide raw data for software systems. The data collection layer has 3 major components. The SCADA software which reads data from PLC and write commands to PLC. The infrared thermal image and industrial camera image collection system which collects image data from thermal imager and camera. The data gathered by this layer will be processed and store in storage layer. The time series data, for example part temperature and other

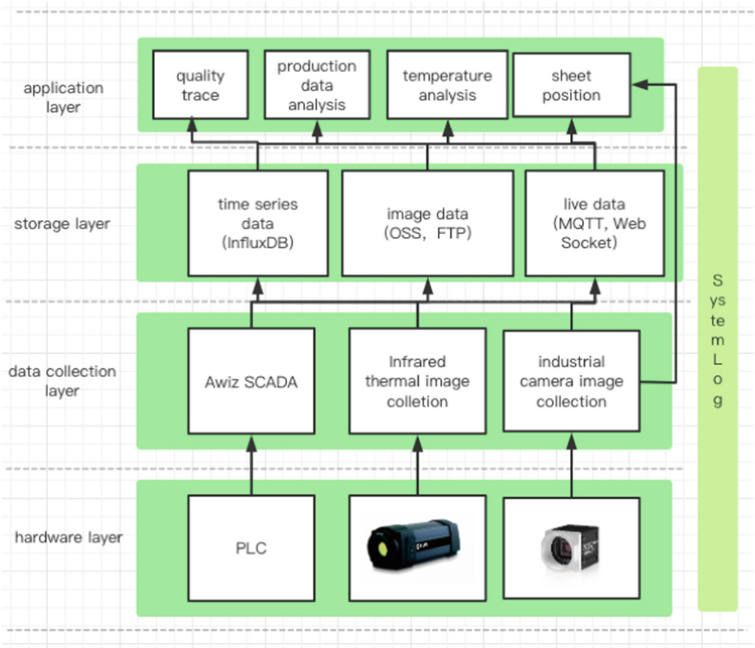

Fig. 4. Architect of the hot-stamping line software.

process data collected from PLC will be tagged with the unique barcode generated by the quality trace software and stored in the time series database. The thermal image and regular image will be stored in the local ftp server. Such data will also be forwarded to a law latency message queue (MQTT) for real-time usage. As part of data processing pipeline, the program to accurately calculate the part temperature will be integrated in this process. The application layer mainly contains software components which utilized temperature and other types of data. The quality trace system allows user to monitor the part temperature and trace the historical data to improve the settings of process parameters. The sheet position check system is also implemented to prevent damaging the die due to inappropriate positioning of sheet before the stamping process (Fig. 4).

3.3 Other Usages of Temperature Data on Hot-Stamping Line

Traditionally, there has been no convenient way to detect the double-sheet scenario for hot-stamping lines. However, we've discovered that such scenario has a major impact on in-mold sheet temperature. The in-mold temperature could drop to 600 °C compared to regular over 700 °C in-mold temperature. In combined with image, we gather from industrial camera which also indicates some obvious visual effects, we can accurately detect such scenario.

Once we have accurate historical part temperature, we could develop the quality prediction model using machine learning techniques. Our system can predict quality issues and will automatically raise warnings by analyzing the trend of temperatures.

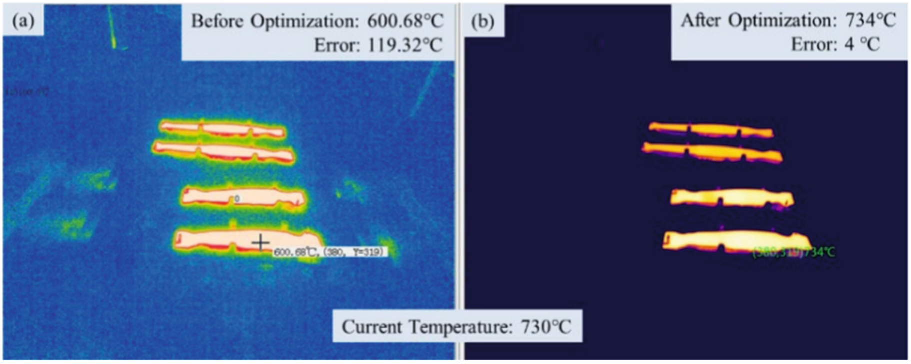

Fig. 5. Comparison of temperature measurement accuracy: (a) Before optimization, (b) After optimization.

4 Conclusion

The infrared thermal imager software has been deployed on one of our hot stamping line in Jiangxi to test the algorithm. The result we've observed has been quite positive so far. Figure 5 shows the comparison between the temperatures before and after the optimization. The screenshot on the left is the raw output we get from the thermal imager system which has an error of 119 °C. The screenshot on the right is the output from our thermal software which is only 4 °C higher than the actual temperature. We've repeated the same test on site for over a month and the error we observed has been constantly less than 20 °C.

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