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Thermal-sensing-assisted Process Monitoring of Surface Layer Development during Gas Carburizing

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Continuous thermal sensing provides valuable process information for intelligent heat-treatment systems. However, systematic investigations of the relationship between measurable thermal history and surface layer evolution during gas carburizing remain limited, restricting the application of thermal sensing to process monitoring and quality evaluation. In this study, a thermal-sensing-assisted evaluation framework was developed to investigate the relationship between measurable thermal history and surface layer development. Three K-type thermocouples were employed to continuously record furnace temperature histories during gas carburizing, providing time-resolved process information for comparison with the subsequent material response, while hardness characterization, diffusion-based estimation, and metallographic observations were integrated to evaluate surface layer evolution. The thermal sensing system exhibited stable and consistent temperature responses throughout the investigated temperature range, supporting its suitability for continuous process monitoring. Increasing the holding time promoted the progressive growth of the hardened layer, resulting in greater effective and metallographic case depths while maintaining nearly constant surface hardness. The metallographically determined case depths showed a growth trend similar to that of the Harris diffusion-based estimates. The proposed framework demonstrates that integrating thermal sensing with conventional materials characterization provides a practical approach for correlating measurable thermal history with surface layer evolution, offering an experimental basis for the future development of predictive virtual sensors in intelligent gas carburizing systems.

1. Introduction

Surface layer quality plays a critical role in the performance and service life of engineering components subjected to wear, fatigue, and contact loading. Among various surface hardening techniques, gas carburizing is one of the most widely adopted industrial processes because it effectively improves surface hardness and wear resistance while maintaining core toughness.[1–6] The final surface layer characteristics are primarily governed by the thermal history and carbon

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diffusion behavior during carburizing. Consequently, even small variations in thermal history may significantly affect carbon diffusion, case depth, and microstructural evolution, making continuous process monitoring essential for ensuring process consistency and product quality.

Recent advances in intelligent manufacturing have promoted the integration of sensing technologies into thermal processing systems for real-time process monitoring. Among various sensing approaches, thermal sensing offers a simple, low-cost, and continuous means of monitoring thermal history throughout heat-treatment processes.[7–11] Unlike conventional post-process characterization, such as hardness testing and metallographic observation, thermal sensing enables the continuous acquisition of process information without interrupting production. Establishing quantitative relationships between measurable thermal history and the resulting surface layer characteristics is therefore essential for developing sensing-assisted quality evaluation and future virtual sensing applications.

Previous studies have extensively investigated carbon diffusion, hardness evolution, and microstructural development during gas carburizing,[12–20] leading to significant advances in understanding carburizing mechanisms and diffusion-based modeling. However, most existing studies rely primarily on destructive post-process characterization to evaluate carburized layer development. Although thermal measurements are widely employed for furnace control, systematic investigations that integrate thermal sensing with hardness characterization, diffusion-based estimation, and metallographic verification for process-oriented evaluation remain limited. Consequently, the use of thermal sensing for process-oriented monitoring and quality assessment remains insufficiently explored.

In this study, a thermal-sensing-assisted evaluation framework is proposed to establish the relationship between measurable thermal history and surface layer evolution during gas carburizing. In the present study, we used continuously recorded furnace temperature histories as process information to be examined together with the subsequent material response, extending their use beyond furnace control and set-point verification. As illustrated in Fig. 1, continuous thermal sensing is integrated with hardness characterization, diffusion-based estimation, and metallographic observations to provide complementary information on process conditions and material response. Rather than relying solely on conventional postprocess characterization, the proposed framework correlates measurable thermal history with carburized layer development, providing a practical basis for process monitoring and the future development of predictive virtual sensors in intelligent heat-treatment systems.

2. Experimental Procedure

2.1. Materials

Commercial SAE 1022 low-carbon steel was selected as the model material for investigating surface layer evolution during thermal processing. Cylindrical specimens with dimensions of approximately 5.5 mm in diameter and 30 mm in length were prepared for all thermal processing experiments. SAE 1022 steel is widely used for carburized engineering components because of its good cold formability, excellent carburizing response, and broad industrial applications.[21–23] Its stable carburizing behavior makes it an appropriate material for evaluating the effects of

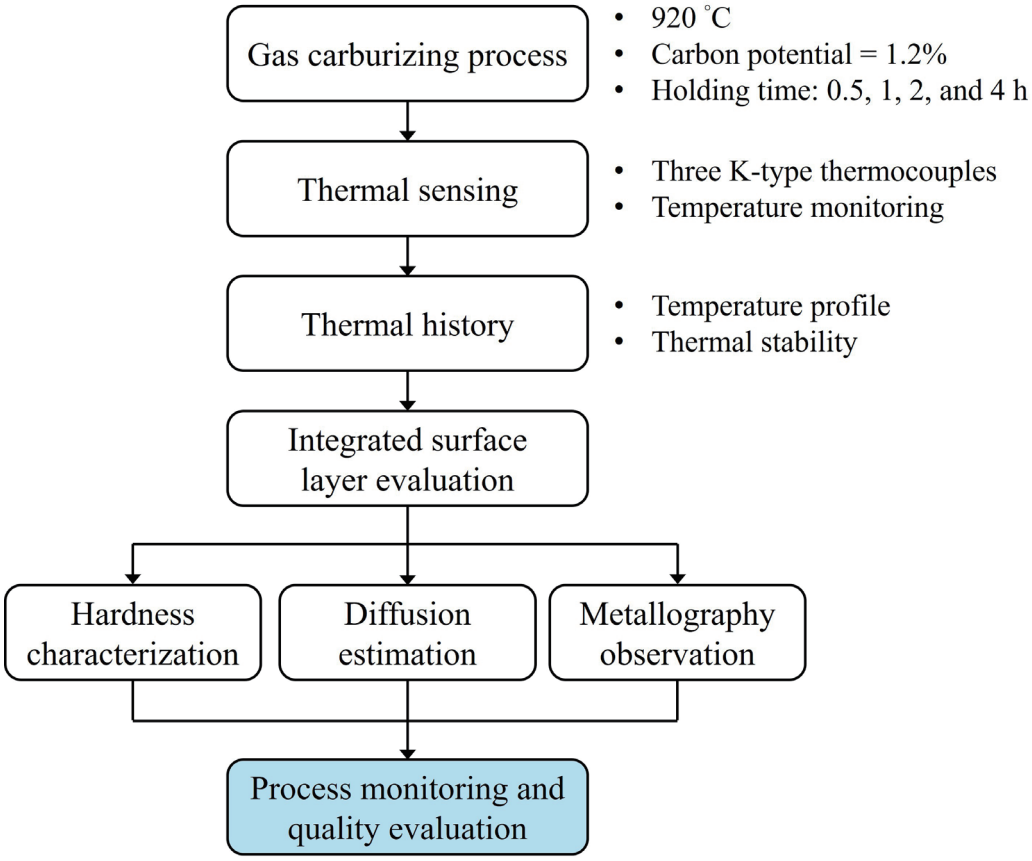


Fig. 1. (Color online) Schematic illustration of the proposed sensing-driven characterization workflow for surface layer evolution during gas carburizing. The workflow integrates thermal sensing, hardness characterization, diffusion-based estimation, and metallographic observations to establish the linkage between measurable thermal history and surface layer evolution, providing a practical basis for process monitoring and quality evaluation.

thermal processing conditions on surface layer development. The chemical composition of the investigated steel is summarized in Table 1.

2.2. Gas carburizing process

Gas carburizing experiments were carried out using a laboratory-scale gas carburizing furnace under a controlled carburizing atmosphere. The processing temperature was maintained at 920 °C, while the carbon potential was maintained at 1.2% throughout the treatment. To investigate the effect of holding time on surface layer development, specimens were carburized for 0.5, 1, 2, and 4 h. After carburizing, the specimens were directly quenched in oil and subsequently tempered at 200 °C for 1.5 h.

During the carburizing process, the furnace temperature and carbon potential were continuously monitored and recorded to ensure stable processing conditions. The recorded temperature data were subsequently used for comparison with hardness characterization, diffusion-based analysis, and metallographic observations according to the evaluation workflow illustrated in Fig. 1.

Table 1
Chemical composition of the as-received SAE 1022 steel (wt%).

C	Si	Mn	P	S
0.21	0.20	0.92	0.01	0.01

2.3. Thermal sensing system and performance verification

To ensure reliable temperature monitoring during gas carburizing, a thermal sensing system consisting of three K-type thermocouples (TC1–TC3) was employed. As illustrated in Fig. 2, the thermocouples were installed at different locations inside the gas carburizing furnace to continuously monitor the furnace temperature and verify temperature uniformity within the processing chamber.

Prior to the carburizing experiments, the performance of the sensing system was verified over the temperature range of 800–950 °C by comparing the measured temperatures with the preset furnace temperatures. The verification procedure was performed to evaluate the measurement consistency and stability of the thermal sensing system under representative processing conditions. To protect the thermocouples from the high-temperature carburizing atmosphere, the sensors were housed in high-purity ceramic protection tubes to enhance signal stability and reduce potential drift during continuous measurements. The results are presented in Fig. 3. Good agreement between the measured and preset temperatures supported the measurement consistency and stability of the thermal sensing system. The verified sensing system was subsequently employed for continuous temperature monitoring during the gas carburizing experiments, and the recorded temperature data served as the basis for the subsequent evaluation of surface layer evolution according to the workflow illustrated in Fig. 1.

2.4. Hardness characterization

Hardness characterization was performed after the complete carburizing, quenching, and tempering cycle. The specimens were sectioned perpendicular to the treated surface and prepared using standard metallographic grinding and polishing procedures. Vickers hardness measurements were subsequently performed from the treated surface toward the substrate interior to characterize the hardness distribution and surface layer development. Vickers hardness measurements were performed under a load of 300 gf with a dwell time of 10 s. At each nominal depth, five indentations were measured and averaged, and successive measurement depths were separated by 0.05 mm.

Hardness profiles were measured at regular depth intervals from the treated surface to the substrate interior. The effective case depth was defined as the distance from the treated surface to the location corresponding to a hardness value of 550 HV.[24–26] The metallographically determined case depth was measured separately by optical microscopy, as described in Sect. 2.5. The measured hardness profiles were subsequently compared with thermal sensing data and diffusion-based estimations for evaluating the relationship between thermal history and surface layer evolution.

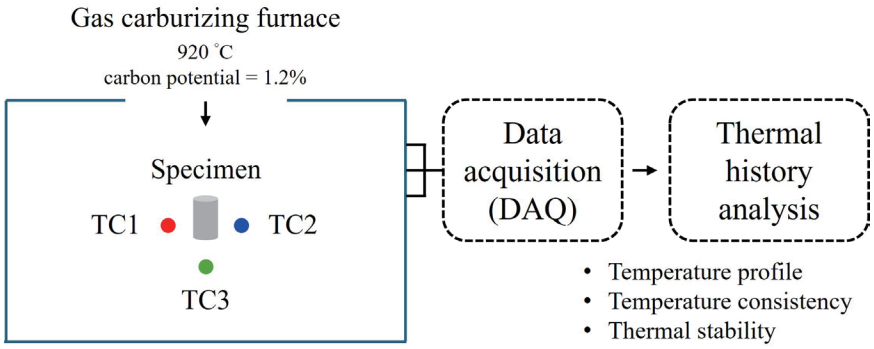


Fig. 2. (Color online) Schematic illustration of the thermal sensing system used for gas carburizing experiments. Three K-type thermocouples (TC1–TC3) were positioned around the specimen to continuously monitor furnace temperature. The acquired temperature data were transmitted to the data acquisition (DAQ) system for subsequent thermal history analysis.

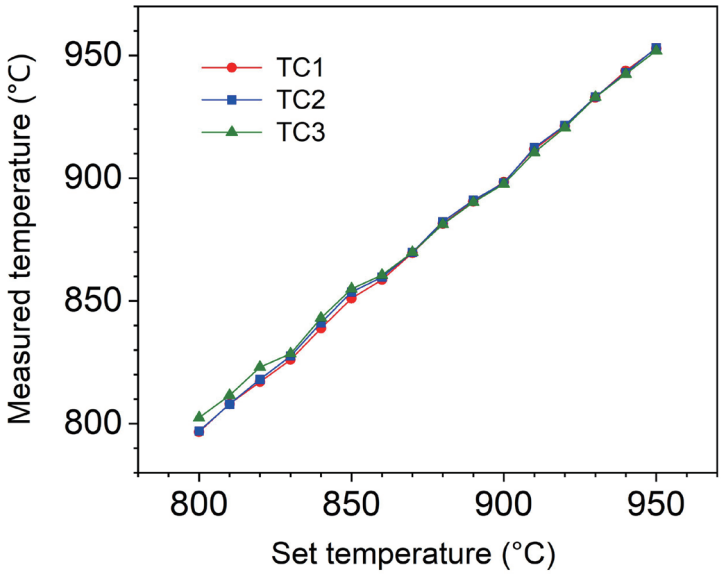


Fig. 3. (Color online) Performance verification results of the thermal sensing system. The measured temperatures recorded by TC1–TC3 show good agreement with the preset furnace temperatures over the range of 800–950 °C, supporting the measurement consistency and stability of the thermal sensing system prior to gas carburizing experiments.

2.5. Metallographic characterization

Metallographic characterization was performed after the complete gas carburizing, quenching, and tempering cycle to examine the morphology of the carburized layer. The specimens were sectioned perpendicular to the treated surface, mounted, ground, polished, and chemically etched using 3% Nital solution prior to microscopic observation.

Optical microscopy was employed to observe the carburized layer, the case/core boundary, and the corresponding microstructural features developed under different holding times. The metallographically determined case depth was measured normal to the treated surface, from the

surface to the optically identified transition between the near-surface and core microstructures. This microstructural criterion is distinct from the 550 HV criterion used to determine the effective case depth.

2.6. Diffusion-based estimation of case depth

The carburized case depth was estimated using the Harris equation, an empirical diffusion-based relationship commonly employed to predict case depth during gas carburizing:[27,28]

$$d = \frac{800\sqrt{t}}{10^{3700/(T+273)}}, \tag{1}$$

where d is the predicted case depth in millimeters, t is the carburizing time in hours, and T is the carburizing temperature in degrees Celsius. At the carburizing temperature of 920 °C employed in the present study, the temperature-dependent coefficient was calculated to be approximately 0.633 mm·h$^{-1/2}$, and the equation can therefore be expressed as $d = 0.633\sqrt{t}$. The calculated case depths were subsequently compared with the metallographically determined case depths to evaluate the consistency between diffusion-based estimation and surface layer development.

3. Results and Discussion

3.1. Thermal history analysis during gas carburizing

To establish the relationship between measurable thermal history and subsequent surface layer evolution, the thermal cycle employed in the present study is first illustrated in Fig. 4. As shown in Fig. 4, all specimens were subjected to the same gas carburizing schedule, including heating, carburizing at 920 °C, oil quenching, and tempering at 200 °C for 1.5 h. The only processing variable was the carburizing holding time (0.5, 1, 2, and 4 h), allowing the effect of thermal exposure duration on surface layer development to be systematically evaluated.

During gas carburizing, continuous temperature monitoring was performed using the verified K-type thermocouples described in Sect. 2.3. As demonstrated in Fig. 3, the measured temperatures obtained from the three thermocouples showed good agreement with the preset furnace temperatures throughout the verification range of 800–950 °C, confirming the measurement consistency and stability of the thermal sensing system. The recorded thermal history therefore characterizes the furnace thermal environment surrounding the specimens during carburizing. Continuous thermal sensing provides time-resolved information that can reveal heating transients, furnace temperature recovery, and fluctuations during the holding stage. In the present study, the recorded thermal histories were primarily used to assess the comparability and stability of the carburizing conditions among treatments, allowing holding duration to be examined as the main controlled variable associated with case-depth evolution. The sensing information thus provides a process-history reference for interpreting the subsequent hardness profiles and metallographic observations, extending its use beyond furnace set-point verification.

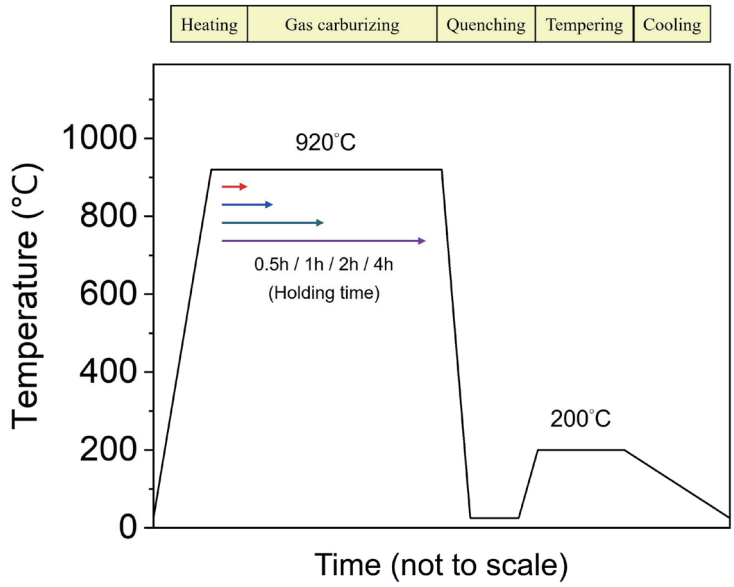


Fig. 4. (Color online) Schematic thermal cycle employed for the gas carburizing experiments.

Because the carburizing temperature and carbon potential were maintained at values of 920 °C and 1.2%, respectively, differences among the investigated conditions originated primarily from variations in holding time rather than fluctuations in processing temperature. Consequently, the measured thermal history provides a consistent process reference for subsequent comparison with hardness characterization, diffusion-based estimation, and metallographic observations. Accordingly, the measured thermal history constitutes the primary process information within the proposed framework, whereas hardness characterization, diffusion-based estimation, and metallographic observations provide complementary evidence for interpreting the corresponding material response.

3.2. Hardness characterization and surface layer development

To investigate how the measured thermal history is reflected in the resulting material response, hardness profiles were measured for specimens carburized with different holding times. The corresponding hardness distributions are presented in Fig. 5. Although the maximum surface hardness remained within a relatively narrow range under all processing conditions, the hardened layer progressively extended toward the substrate as the holding time increased, indicating the continuous development of the carburized layer with increasing thermal exposure.

According to the 550 HV criterion adopted in this study, the effective case depth increased systematically from approximately 0.30 mm after 0.5 h to around 0.80 mm after 4 h. In contrast, the maximum surface hardness remained nearly unchanged under all investigated processing conditions. These results indicate that increasing the holding time primarily promoted the inward growth of the hardened layer rather than further increasing the surface hardness. The observed hardness evolution is consistent with the diffusion-controlled nature of the carburizing

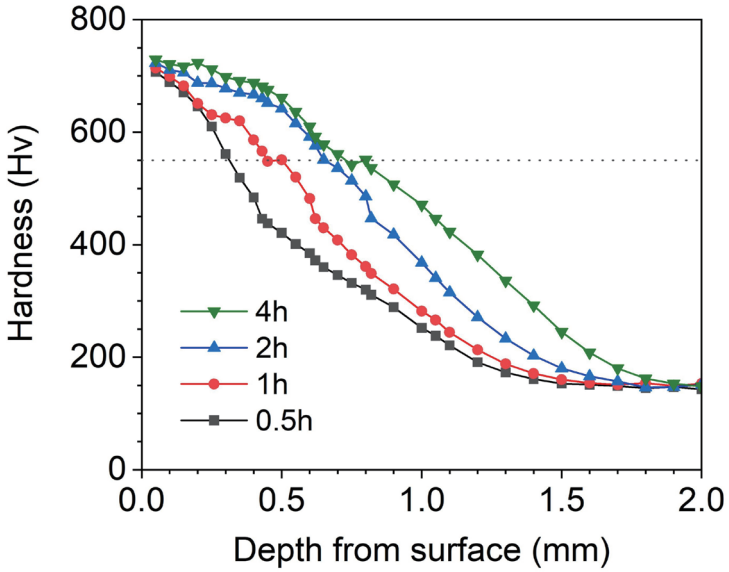


Fig. 5. (Color online) Hardness profiles of the specimens after gas carburizing with holding times of 0.5, 1, 2, and 4 h. Increasing holding time progressively extended the hardened region and increased the effective case depth while maintaining comparable surface hardness.

process. Since the carburizing temperature (920 °C) and carbon potential (1.2%) were maintained constant throughout the experiments, the surface carbon concentration likely approached a near-steady level under the fixed carbon potential, resulting in similar surface hardness regardless of holding time. Consequently, prolonged holding time mainly enhanced inward carbon diffusion, leading to the progressive expansion of the hardened region beneath the treated surface.

The hardness profiles further revealed that the hardness transition between the carburized layer and the substrate became increasingly gradual as the holding time increased. This broader transition region reflects the development of a continuous carbon concentration gradient and is characteristic of progressive carbon diffusion into the substrate during carburizing. These observations further confirm that, under constant processing conditions, holding time is the primary controlled variable governing the development of the carburized layer. More importantly, the hardness evolution exhibits a clear correspondence with the controlled thermal history established by continuous thermal sensing. Because the thermal conditions remained stable throughout processing and the holding time was the only processing variable, the measured thermal history can be directly associated with the progressive increase in effective case depth. The hardness characterization therefore provides experimental support for the process–response linkage between measurable thermal history and surface layer evolution. Within the present fixed-condition experimental design, the monitored thermal history, primarily represented by the holding duration under stable temperature and carbon potential, was consistently associated with the progressive increase in effective case depth.

3.3. Evolution of metallographic case depth and comparison with diffusion-based estimation

To further examine the relationship between the monitored thermal history and surface layer evolution, the metallographically determined case depths were compared with empirical estimates calculated using the Harris equation described in Sect. 2.6. The Harris equation is an empirical diffusion-based relationship used to estimate carburized case depth under constant carburizing conditions. As shown in Fig. 6(a), both the metallographically determined case depths and the Harris estimates increased with holding time, exhibiting similar layer-growth trends. The measured depths represent an optically identified microstructural transition, which does not necessarily coincide with the full extent of carbon enrichment or the return to core hardness.

Both the experimental measurements and the Harris estimates exhibited a consistent increase in case depth as the holding time increased from 0.5 to 4 h. Although the estimated values were generally slightly higher than the experimental measurements, the differences remained relatively small over the investigated processing conditions. The similar growth trends indicate that the diffusion-based model reasonably describes the overall trend of carburized layer development under the present gas carburizing conditions. The remaining deviations may be attributed to the empirical nature of the Harris relation, which does not explicitly account for carbon potential, alloy composition, surface reaction kinetics, or the experimental criterion used to determine metallographic case depth, together with practical uncertainties in experimental measurements. Quantitatively, the absolute percentage deviations of the Harris estimates relative to the metallographically determined case depths ranged from approximately 7.4 to 9.2%, with a mean absolute percentage deviation of 8.3%. The corresponding root-mean-square error was approximately 0.064 mm. These metrics were calculated using the unrounded Harris predictions, and the differences between the Harris estimates and the metallographically determined case depths were quantified under the investigated conditions. As further shown in Fig. 6(b), the metallographically determined case depth exhibited an approximately linear relationship with the square root of carburizing time, which is characteristic of diffusion-controlled case growth. An origin-constrained fit yielded an apparent case growth coefficient of approximately 0.59 $mm \cdot h^{-1/2}$, slightly lower than but comparable to the Harris coefficient of 0.63 $mm \cdot h^{-1/2}$. Given the limited number of holding-time conditions, this fitting result is interpreted only as evidence of consistency with diffusion-controlled case growth rather than as a general predictive model. The cylindrical specimen geometry should also be considered when applying the semi-infinite planar approximation underlying the Harris estimate. The specimen radius was approximately 2.75 mm, while the metallographically determined case depth after 4 h reached approximately 1.18 mm, corresponding to about 43% of the radius. The planar approximation therefore becomes less appropriate as the carburized layer develops, and cylindrical curvature and finite-size effects may contribute to the difference between the experimental and Harris case growth coefficients.

From the perspective of process monitoring, the similar growth trends provide a basis for interpreting the measured layer development under the recorded thermal conditions. Combined

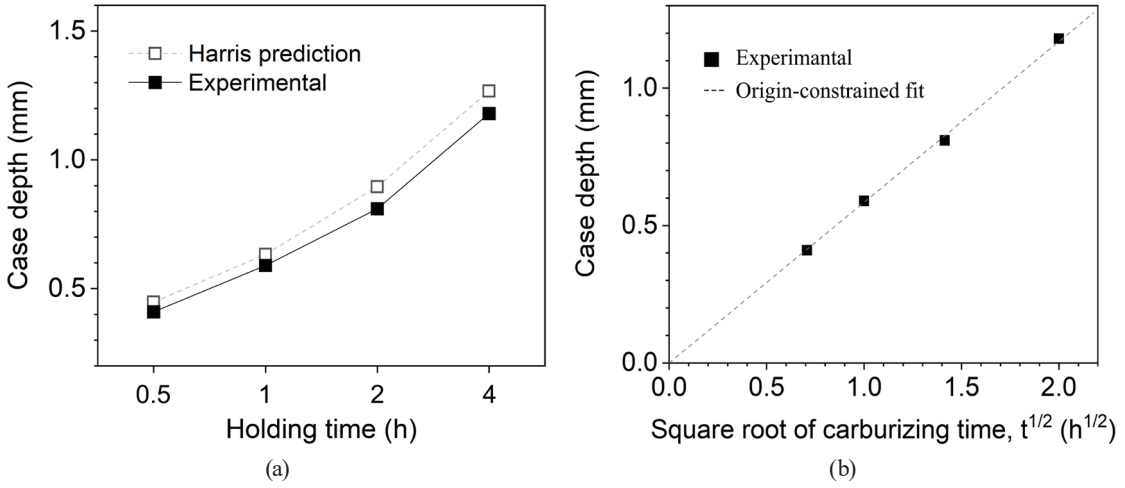


Fig. 6. (Color online) (a) Comparison of metallographically determined case depths and Harris estimates as a function of carburizing time. (b) Relationship between metallographically determined case depth and the square root of carburizing time. The approximately linear trend in (b) is consistent with diffusion-controlled carburized layer growth.

with the hardness characterization presented in Sect. 3.2, the diffusion-based estimation provides a reasonable approximation of carburized layer growth under the investigated conditions. These results demonstrate that integrating continuous thermal sensing with diffusion-based estimation and conventional materials characterization offers a practical approach for correlating measurable process information with carburized layer evolution.

3.4. Metallographic observations of surface layer evolution

Metallographic observations were performed to further verify the surface layer evolution identified from the hardness characterization and diffusion-based estimation. Representative optical micrographs of specimens carburized for 2 and 4 h are presented in Fig. 7. Distinct differences between the carburized layer and the substrate were clearly observed, confirming the progressive inward growth of the hardened layer during gas carburizing.

Following quenching and tempering, the surface region exhibited a hardened microstructure, whereas the substrate retained the characteristic microstructure of the base material. Increasing the holding time from 2 to 4 h produced a notable increase in the thickness of the carburized layer, which is in good agreement with the progressive increase in effective case depth obtained from hardness characterization and the total case depth estimated using the Harris relation. These observations provide direct experimental evidence that prolonged thermal exposure promotes the continued carbon diffusion and progressive inward growth of the carburized layer. The increase in metallographically determined case depth with holding time is consistent with the inward extension of the hardness profiles. These complementary observations support the progressive development of the carburized layer under the investigated processing conditions.

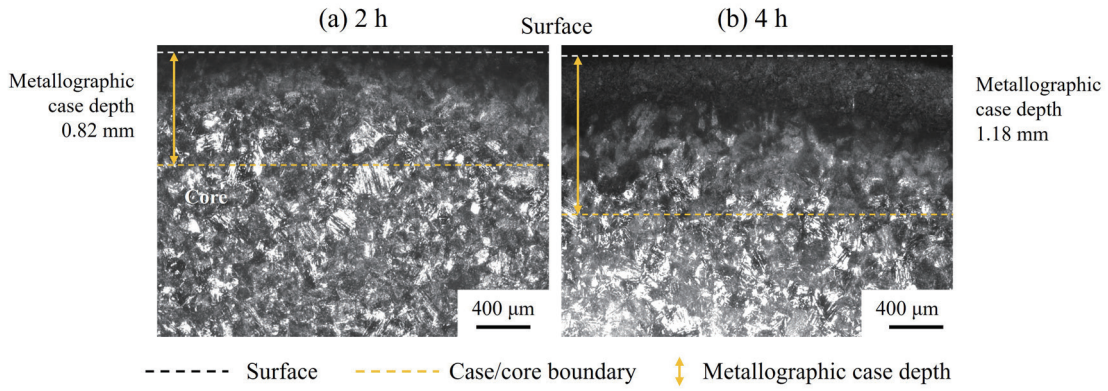


Fig. 7. (Color online) Representative optical micrographs of specimens processed for (a) 2 and (b) 4 h. The surface, case/core boundary, and metallographic case depth are indicated.

3.5. Discussion of the thermal-sensing-assisted evaluation framework

In the present study, the proposed thermal-sensing-assisted evaluation framework integrates continuous thermal sensing with complementary materials characterization to establish the relationship between measurable process information and surface layer evolution during gas carburizing. Rather than functioning as independent analytical techniques, hardness characterization, diffusion-based estimation, and metallographic observations collectively validate the material response associated with the monitored thermal history. This integrated approach extends the role of thermal sensing beyond conventional furnace temperature monitoring by providing a systematic basis for interpreting material evolution during heat treatment.

The relationship established in this study is physically supported by the diffusion-controlled nature of gas carburizing. Under constant carburizing temperature and carbon potential, increasing the holding time primarily increases the accumulated thermal exposure experienced by the material, thereby promoting inward carbon diffusion without significantly altering the surface carbon concentration. Consequently, the monitored thermal history is reflected by the progressive increase in case depth, whereas the nearly constant surface hardness suggests that the near-surface carbon condition approached a quasi-steady state. This physically consistent relationship explains why continuous thermal sensing can provide meaningful process information for evaluating surface layer evolution.

From an engineering perspective, the proposed framework provides a practical approach for process-oriented quality evaluation in industrial gas carburizing. Continuous thermal sensing enables the thermal history to be monitored throughout the heat-treatment cycle without interrupting production, while hardness characterization, diffusion-based estimation, and metallographic observations enable the complementary verification of the corresponding material response. By integrating process information with conventional materials characterization, the proposed framework establishes a practical linkage between thermal history and surface layer development, thereby supporting the more reliable evaluation of

carburizing quality. The potential implementation of this framework in future intelligent gas carburizing systems is conceptually illustrated in Fig. 8. As illustrated in Fig. 8, the proposed framework can be organized into three functional layers, namely, the sensor layer, analytics layer, and application layer. In a future implementation, the real-time thermal data acquired from the sensor layer would be transformed into thermal history and subsequently processed through feature extraction and a diffusion-based model within the analytics layer. The resulting virtual sensing framework can support the future prediction of key surface layer characteristics, including hardness profile, case depth, and surface quality, without relying solely on conventional post-process characterization. Figure 8 presents a conceptual roadmap that builds on the sensing-assisted evaluation framework demonstrated in this study, linking recorded thermal histories with post-process material characterization. These results provide an experimental foundation for future virtual sensing, with the implementation and validation of machine-learning-based predictive models forming the next stage of development.

Note that the present framework was established under fixed carburizing conditions, including a constant processing temperature and carbon potential, with holding time as the only processing variable. Changes in temperature alter carbon diffusivity and consequently the case growth coefficient, whereas changes in carbon potential modify the surface carbon boundary condition and the resulting carbon concentration profile. Although the Harris relation includes temperature dependence, the simplified expression used in this study does not explicitly account for carbon potential. The quantitative relationship established at 920 °C and a carbon potential of 1.2% provides a reference for extending the framework to other processing conditions through additional experiments that account for temperature and carbon-potential effects. Future studies may incorporate additional thermal descriptors, such as accumulated thermal exposure, heating characteristics, and thermal stability, together with carbon-potential histories and experiments over a broader range of processing conditions. These datasets can support the use of advanced data analysis or machine learning techniques to establish predictive models for case depth and microstructural evolution. Such developments will further advance the conceptual architecture illustrated in Fig. 8 toward intelligent heat-treatment systems capable of real-time process monitoring and the virtual sensing of surface layer characteristics, thereby enabling more efficient process control and quality evaluation.

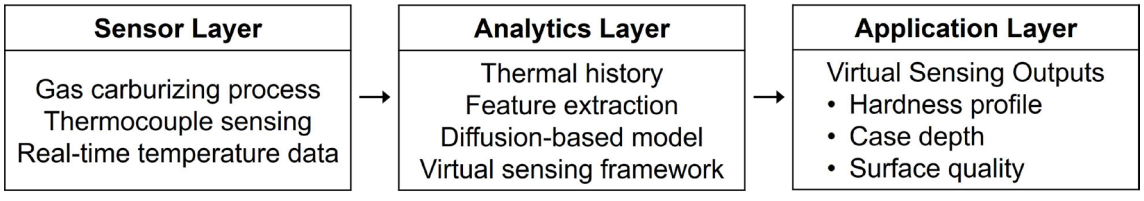


Fig. 8. Conceptual three-layer architecture illustrating the potential future implementation of the proposed thermal-sensing-assisted evaluation framework. Real-time temperature data acquired in the sensor layer are transformed into process information in the analytics layer, providing a conceptual basis for the future virtual sensing of key surface layer characteristics in the application layer.

4. Conclusion

A thermal-sensing-assisted evaluation framework was developed to investigate surface layer evolution during gas carburizing by integrating continuous thermal sensing with hardness characterization, diffusion-based estimation, and metallographic observations. Stable thermal conditions enabled the effect of holding time on surface layer development to be systematically evaluated. The hardness profiles revealed a progressive increase in effective case depth with holding time while maintaining nearly constant surface hardness, reflecting the diffusion-controlled growth of the carburized layer. The metallographically determined case depths showed a growth trend similar to that of the Harris diffusion-based estimates. An origin-constrained analysis yielded an apparent case growth coefficient of approximately 0.59 mm·h$^{-1/2}$, which was comparable to the Harris coefficient of 0.63 mm·h$^{-1/2}$, further supporting diffusion-controlled case growth. Overall, the proposed framework establishes a practical relationship between measurable thermal history and surface layer evolution by integrating continuous thermal sensing with complementary materials characterization, demonstrating the use of recorded furnace thermal histories as process information for interpreting subsequent material responses. These findings provide an experimental basis for process monitoring and the future development of predictive virtual sensors under a broader range of carburizing conditions.

Acknowledgments

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