

A Comprehensive Review of the Hole-Drilling Method for Residual Stress Measurement: Principles, Challenges, and Modern Advancements

Xiaobei Jin, Zhanpeng Li, Genming Liu

Tianjin University of Technology and Education, Tianjin 300222, China

ABSTRACT

The hole-drilling method is a widely used semi-destructive technique for determining residual stresses in engineering components. This paper provides a comprehensive review of the method's evolution, fundamental principles, and modern advancements based on an analysis of key literature. The review begins by outlining the traditional application for measuring uniform surface stresses and traces its development into the incremental hole-drilling technique, which allows for the determination of residual stress variation with depth. Central to this evolution is the use of calibration coefficients, which correlate measured strain relaxation to the underlying stress state. This paper synthesizes the various analytical and computational approaches for deriving these coefficients, highlighting the pivotal role of the Finite Element Method (FEM) in modern practice. A significant portion of the review is dedicated to a critical examination of the method's inherent challenges and sources of error, which include plasticity effects at high stress levels, the influence of component thickness (particularly in thin sheets), stress biaxiality, and discrepancies between ideal and real hole geometries. The literature reveals a consistent trend towards developing sophisticated correction procedures, often integrating FEM simulations with experimental data from both traditional strain gauges and advanced optical techniques like Digital Image Correlation (DIC). Persistent challenges include the lack of standardized procedures for thin components and highly plastic conditions. Future research directions point towards the development of integrated, multi-parameter correction models, further standardization, and the fusion of numerical simulations with full-field optical measurements to enhance the accuracy and expand the applicability of this vital measurement technique.

KEYWORDS

Residual Stress; Hole-Drilling Method; Incremental Hole-Drilling; Finite Element Method (FEM); Calibration Coefficients; Plasticity Correction.

1. INTRODUCTION

Residual stresses are self-equilibrating stresses that exist within a material in the absence of external loads. They are an inevitable consequence of manufacturing processes such as welding, casting, machining, and surface treatments like shot peening. These stresses can significantly impact a component's structural integrity, fatigue life, and susceptibility to stress corrosion cracking. Depending on their nature (tensile or compressive), they can be either detrimental or beneficial[1]. Consequently, the accurate measurement of residual stresses is of paramount importance in mechanical and structural engineering for quality control, failure analysis, and life assessment[2].

Among the various techniques available, the hole-drilling strain-gauge method, standardized by ASTM E837[3], is one of the most widely used and practical semi-destructive methods. Its

fundamental principle is straightforward: a small blind hole is drilled into the material, which relieves the residual stresses in the immediate vicinity. This stress relief causes a localized deformation (strain relaxation) on the surface, which is measured by a specialized strain-gauge rosette bonded to the surface around the drilling location. By relating the measured strains to the relieved stresses through pre-determined calibration coefficients, the original residual stress state can be calculated[4].

The traditional hole-drilling method, as established by Rendler and Vigness (1966)[5], involves drilling a hole to a depth approximately equal to its diameter to determine the average residual stress over that depth. However, many manufacturing processes induce non-uniform stress fields that vary significantly with depth. To address this, the incremental hole-drilling method was developed, where the hole is drilled in small, discrete steps, and strain readings are taken after each increment. This allows for the determination of a residual stress profile as a function of depth.

While powerful, the incremental method introduces significant complexities. The strain relaxation measured at each step is not only due to the stress in the current layer being removed but is also influenced by the change in hole geometry and the stresses relieved in all previous layers. This has led to the development of several calculation procedures, most notably the Integral Method proposed by Schajer (1988)[6], which has become the theoretical foundation for modern analysis. The accuracy of these calculations hinges entirely on the calibration coefficients used.

This paper synthesizes the findings from a broad range of literature to provide a comprehensive review of the hole-drilling method. It will cover the evolution of the technique from basic principles to advanced applications, with a particular focus on the critical challenges identified in the literature, including plasticity effects, thin component analysis, and stress biaxiality. Finally, it will review the modern Finite Element Method (FEM) based solutions proposed to overcome these challenges and outline future research directions.

2. LITERATURE REVIEW OF HOLE-DRILLING METHODOLOGIES

The hole-drilling method has evolved from a relatively simple experimental procedure to a sophisticated analytical technique supported by extensive numerical simulation. This section reviews its development, key calculation procedures, and the role of modern computational and measurement tools.

2.1. Fundamental Principles and the Incremental Method

The foundational work by Rendler and Vigness (1966)[7] established the relationship between the two principal stresses (σ_{\max} , σ_{\min}) and the relieved strain (ϵ_{α}) at an angle α relative to the maximum principal stress direction, through two calibration constants, A and B. The traditional approach, measuring average stress, was soon extended to depth profiling. This gave rise to the incremental hole-drilling method, where multiple strain readings are taken as the hole is progressively deepened.

Several calculation procedures were developed to deconvolve the stress profile from these incremental strain readings. As reviewed by Schajer (1988), early techniques like the Incremental Strain Method and the Average Stress Method had significant theoretical shortcomings, as they failed to properly account for the cumulative effects of stress relief from previous increments. The most robust and theoretically sound approach is the Integral Method. This method treats the total measured strain at a given depth as the integral sum of the effects of stresses relieved from all preceding layers. This requires a matrix of calibration coefficients (often denoted \bar{a}_{ij} and b_{ij}) that relate the strain measured after the i -th increment to the stress present in the j -th increment[7]. To further clarify the differences in performance, applicability, and theoretical basis among the three mainstream calculation procedures mentioned above, their key characteristics are systematically compared in Table 1.

Table 1. Comparison of calculation procedures in the hole-drilling method

Method	Principle	Advantages	Limitations
Incremental Strain Method	Uses incremental strain readings at each drilling step to estimate stress	Simple, easy to implement	Large errors due to cumulative strain effects
Average Stress Method	Calculates average stress within drilled depth	Provides a quick overall stress estimate	Cannot capture stress variation with depth
Integral Method (Schajer, 1988)	Considers total measured strain as integral effect of all relieved layers	Theoretically sound, widely adopted	Requires calibration coefficients (complex)

2.2. The Role of Finite Element Method (FEM) in Modern Calibration

Experimentally determining the full matrix of calibration coefficients is prohibitively complex. The widespread availability of computational power has made the Finite Element Method (FEM) the standard tool for calculating these coefficients. As demonstrated by Flaman and Manning (1985)[8] and detailed extensively in subsequent research, FEM can accurately simulate the hole-drilling process and determine the calibration coefficients for a wide range of geometries, materials, and strain gauge types. This has been a crucial enabler for the accuracy and versatility of the modern incremental method. Recent studies, such as that by Blödorn et al. (2017)[9], have used FEM to investigate the effect of the real blind hole geometry, including chamfers and fillet radii at the bottom of the hole, which are not considered in the idealized models but significantly affect the initial drilling steps..

2.3. Advanced Optical Measurement Techniques

Table 2. Comparison of strain measurement techniques for hole-drilling

Technique	Advantages	Limitations	Application Scenarios
Strain Gauge (ASTM E837 standard)	Widely available, standardized	Limited to local points, adhesive bonding needed	Industrial routine measurement
Digital Image Correlation (DIC)	Full-field strain/displacement, non-contact	Sensitive to noise, requires high-quality imaging	Research, validation studies
ESPI	High sensitivity, suitable for thin components	Expensive setup, vibration sensitive	Thin sheet analysis, advanced labs

While strain gauge rosettes are the standard, optical methods provide full-field displacement and strain data, offering richer information. Babaeian and Mohammadimehr (2021) [10] compared results from the traditional strain gauge method with those from Digital Image Correlation (DIC), a non-contact optical technique. They uniquely employed Mohr's circle for a more intuitive comparison and investigated the effect of elapsed time after drilling, finding that the closest results between the two methods occurred approximately 5 minutes after drilling, suggesting that immediate strain readings may not always be optimal. Similarly, Schuster et al. (2017)[12] utilized Electronic Speckle Pattern Interferometry (ESPI) to analyze the combined effects of plasticity and component thickness[13]. To better distinguish the performance characteristics, applicable scopes, and inherent trade-offs of the three strain measurement techniques introduced above for the hole-drilling method, their key information is comprehensively compared in Table 2.

3. CHALLENGES AND OPEN ISSUES

Despite its widespread use, the accuracy of the hole-drilling method is contingent upon several assumptions that are often violated in practical applications. The literature extensively documents these challenges.

3.1. Plasticity Effects at High Stresses

The standard hole-drilling theory is based on linear elasticity. However, when residual stresses are high (typically exceeding 50-60% of the material's yield strength), the stress concentration at the edge of the drilled hole can induce local plastic deformation. This plastic yielding leads to additional strain relief that is not accounted for in the elastic theory, resulting in a significant overestimation of the measured residual stress. This issue is a major focus of recent research, with studies by Schuster et al. (2017)[14], Li et al. (2024)[15], and others demonstrating that this effect can lead to errors exceeding 20%[16].

3.2. Thin Component Effects

ASTM standard E837 is primarily designed for "thick" components, where the plate thickness is significantly larger than the hole diameter. When applied to thin sheets, two problems arise. First, the stress field is no longer semi-infinite, which alters the calibration coefficients. Second, the removal of material causes a local loss of stiffness, inducing localized bending that superimposes onto the strain relief from the residual stress. Zhang et al. (2016)[17] showed numerically and experimentally that mismatch between calibration coefficients and plate thickness can result in errors of more than 10%. Schuster et al. (2017)[18] further demonstrated that this bending effect amplifies the plasticity effects, making the analysis of thin, highly-stressed components particularly challenging[19].

3.3. Stress Biaxiality

Calibration of the strain release coefficients is often performed under simple uniaxial tension for convenience. However, real-world residual stress fields, particularly in welds, are almost always biaxial. Li et al. (2024) [20] demonstrated that using uniaxially calibrated coefficients to measure a biaxial stress field can lead to significant errors (approaching 11% in their study of T-joints)[21]. This is because the stress biaxiality ratio affects the stress concentration at the hole edge and, consequently, the onset and extent of plastic deformation, which in turn alters the strain release behavior.

3.4. Real Hole Geometry and Drilling-Induced Errors

The theoretical models assume a perfect, cylindrical, flat-bottomed hole. In practice, the drilling process itself can introduce errors. High-speed air turbines with dental end mills, as investigated by Blödorn et al. (2017)[22], often create a chamfer at the bottom of the hole, which particularly affects the accuracy of the first few measurement increments. Furthermore, the drilling process itself, if not carefully controlled, can induce its own machining stresses, although this is largely mitigated by using high-speed, low-feed drilling techniques (Niku-Lari et al., 1985)[23].

4. FUTURE DIRECTIONS

The extensive research into the challenges of the hole-drilling method also points toward clear directions for future work aimed at enhancing its accuracy and broadening its applicability.

- **Development of Integrated Correction Models:** The literature shows that plasticity, thickness, and biaxiality are coupled effects. For instance, thinness can amplify plasticity. Therefore, future research should move beyond correcting for these factors individually and

focus on developing comprehensive, multi-parameter correction frameworks. Li et al. (2024)[24] have made progress in this area by proposing a rapid evaluation method that considers both stress level (plasticity) and biaxial stress ratio, using a distortion energy factor as a key parameter[25].

- **Standardization for Thin Components and High Stresses:** A significant gap identified in the literature is the lack of standardized procedures and tabulated calibration coefficients for thin components (e.g., thickness < 1.5 times the hole diameter) and for stress states in the plastic regime. Future work should focus on extensive FEM simulations and experimental validation to develop robust, standardized correction methodologies that could be incorporated into future revisions of standards like ASTM E837.
- **Fusion of Optical Methods and Numerical Simulation:** The use of full-field optical methods like DIC and ESPI provides a wealth of data that is not fully exploited by traditional evaluation methods. Future work should focus on more tightly integrating these full-field measurements with FEM. For example, the measured full-field displacement data could be used as input for inverse FEM models to directly solve for the residual stress profile, bypassing the need for traditional calibration coefficients altogether.
- **Application to Advanced Materials:** While most research has focused on isotropic metals, the application of the hole-drilling method to anisotropic materials (e.g., textured rolled sheets, as studied by Schuster et al.[26]) and composites (Babaeian & Mohammadimehr, 2021[27]) is an emerging field. This requires the development of highly specific calibration coefficients that account for the directional nature of the material's elastic and plastic properties[28].

5. CONCLUSION

The hole-drilling method has evolved from a simple technique for measuring average surface stress into a sophisticated and powerful tool for depth-profiling non-uniform residual stress fields. This review has synthesized the critical literature, highlighting that the modern incremental method, underpinned by the Integral Method and enabled by Finite Element Method (FEM) for the calculation of calibration coefficients, stands as the state-of-the-art..

However, the accuracy of the method is highly sensitive to conditions that deviate from idealized assumptions. Key challenges, thoroughly documented in the reviewed literature, include plastic deformation at high stress levels, localized bending effects in thin components, and the influence of stress biaxiality. These factors can lead to significant measurement errors, often resulting in an overestimation of the actual residual stress. The research community has responded by developing a range of correction strategies, predominantly leveraging FEM to create more accurate calibration coefficients tailored to specific geometries, materials, and stress states.

The path forward lies in the development of more comprehensive and integrated correction models that can simultaneously account for these coupled effects. The fusion of advanced optical measurement techniques with numerical simulations, along with a concerted effort to standardize procedures for thin and highly-stressed materials, will continue to enhance the accuracy, reliability, and scope of the hole-drilling method, solidifying its role as an indispensable tool in mechanical and structural engineering.

CONFLICTS OF INTEREST

The authors declare that they have no conflict of interest.

ACKNOWLEDGMENTS

This is the place to fill in information about funds, sponsors, etc. that need to be thanked.

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