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Communication

A Facile Method for the Evaluation of the Adhesion Strength of Strain Gauges

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Abstract: The adhesion of strain gauges (SGs) onto the underlying spring element plays an important role not only during the fabrication of the SG sensors but also for the final performance of the sensors. A novel and facile method for the evaluation of the adhesion strength of SGs is proposed, tested, and validated in this paper. In comparison with the traditional peel tester method, this method demonstrated both higher reliability and efficiency, especially from an industrial manufacturing point of view. The five-grade adhesion strength, with adhesion strength decreased from Grade 1 (G1) to Grade 5 (G5), results were corroborated by the classical pull-out adhesion testing method with satisfactory consistency and can be employed in the quick evaluation and monitoring of the adhesion strength. The easiness, convenience, and reliability of the method promises a great potential application in the industrial testing and manufacturing of SG sensors.

Keywords: adhesion strength; adhesive; strain gauge; sensor; pull-out adhesion testing method

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1. Introduction

Since the invention in 1938 by Simmons and Ruge and the first released commercial product in 1942 [1], strain gauges (SGs) have been extensively studied, firstly on their working mechanism and fabrication techniques and later on a variety of applications [2]. In addition to the common weighing and stress/strain analysis applications, more and more innovative applications in aerospace [3], automatic [4], civil engineering [5], and smart controlling [6] have been established owing to the high precision, excellent fatigue performance, and high environment and installing tolerance.

Sensors based on SGs are mainly composed of SGs and spring elements, and a layer of bonding adhesive (BA) is employed to bond the SGs onto the surface of the spring elements (Figure 1). Besides the intrinsic performance of the SGs and the spring elements [7], which have a great effect on the final sensor, the adhesion strength of the SGs on the spring elements played an important role in either the fabrication process or the final sensor performances of the as-prepared sensors. With a lack of good enough adhesion strength, the SGs might become loose or fall off the spring elements during the fabrication steps; without proper and consistent adhesion strength in and between the SG sensor, this would result in a fluctuated performance for the as-prepared sensors. Therefore, a high enough and consistent adhesion strength is one of the necessities for the preparation of qualified SG sensors, and the testing and monitoring of the adhesion strength pose the same importance.

Adhesion strength is defined as the maximum tensile strength applied directly perpendicular to the surface being tested and is generally measured using the traditional peel tester method [8], either quantitatively or qualitatively. However, these methods pose certain limitations. Peel testing presents challenges due to the bonding of the SG to the spring element component, making it difficult to design fixtures for effective peeling. Additionally, the inherent brittleness of the SG can lead to fracture during the peeling process, thereby compromising the accuracy of experimental results. Whether tested manually or by using the automatic test apparatus, tediousness is the primary impediment to preventing it from being widely used in the testing and monitoring of the parameter, especially in the industrial production line. Secondly, an assisting adhesive with a much higher adhesion strength between the SG and the tester than that between the SG and the spring element is sometimes hard to find, rendering the incapability of the method.

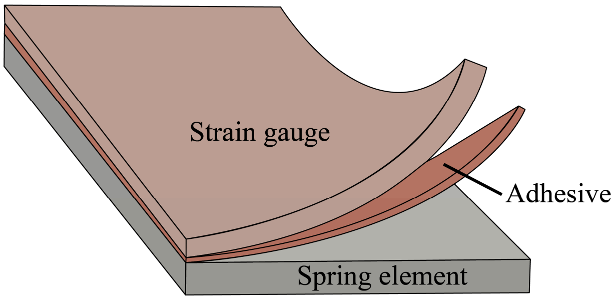


Figure 1. Schematic of an SG sensor.

Therefore, a novel and facile method for evaluating the adhesion strength of the SG onto the spring element is proposed, tested, and validated with operating steps and related technical details elaborated in the paper. The satisfactory reliability and validity of the method are finally corroborated by the pull-out adhesion testing method. This scenario is common in sensors designed to measure object deformation or stress, such as strain sensors, pressure sensors, and force sensors.

2. Evaluation Method

2.1. Methodology Proposal

The magnitude of peeling forces is mainly governed by the geometric configuration, compositional attributes of the thin film and substrate, and the cohesive characteristics at the interface [9]. Moreover, it is directly proportional to the geometric attributes of the interface. Consequently, the geometric interface after scraping the substrate affords the opportunity to establish a qualitative assessment of peel force magnitude. The specific methodology involves the execution of scraping operations on fully assembled SGs and employing the resultant deformation changes of the adhesive layer to evaluate the adhesion strength. This approach facilitates a comprehensive linkage between the interface's attributes and the magnitude of peeling forces, thereby providing a qualitative comprehension of adhesion strength. Subsequently, the scraping operations are carried out on the prepared SGs, and the shape changes in the SG post scraping serve as an indicator of the magnitude of the adhesion strength.

The specific implementation of the scraping process involves peeling the SG using a blade, starting from the opposite end to the solder pads end (Figure 2). The blade moves parallel to the adhesive layer until it reaches the location of the solder pads of the SG. During the scraping process, careful attention is given to the tilt angle of the blade's head, which should not exceed 30 degrees. Excessive tilt angles can result in increased damage to both the spring element and the SG, hindering the observation of curling changes in the SG. To mitigate the force resistance generated by the adhesive layer during peeling, a slight lateral movement of the blade's head is required to ensure the smooth progression of the blade. As manual scraping is utilized, there is no specific requirement for the lateral movement rate, which varies based on the adhesive's bonding strength. A higher bonding strength slows down the speed during manual scraping. Ultimately, the lateral movement rate of the tool head does not impact the final result. In summary, precision is demanded during the scraping procedure by keeping an eye on the blade's angle and lateral movements to ensure the accurate and damage-free testing of SGs.

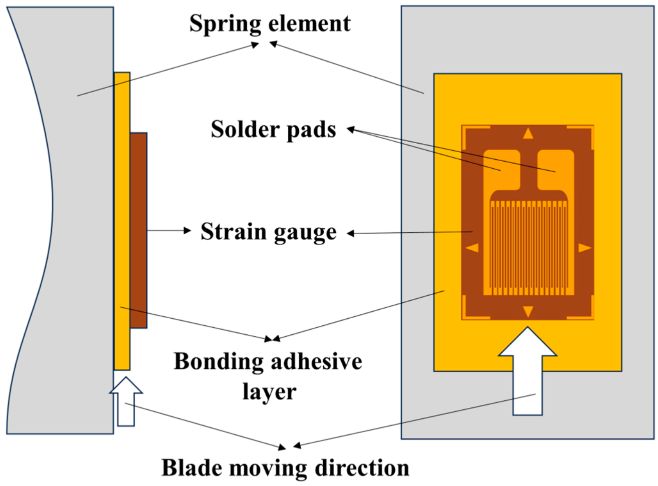


Figure 2. Illustration of blade moving direction and starting point location on the sensor.

As the blade moves forward, the SG separates from the spring element with some residual of the BA layer. Usually, this results in a curling SG with varied curl heights, which is defined as the vertical distance between the highest point on the SG and the surface of the spring element, as depicted in Figure 3. The bonding of the SG with adhesives of different strengths displays varying curl heights. Generally, the higher the adhesion strength, the more pronounced the curling of the SG, and the lower the curl height.

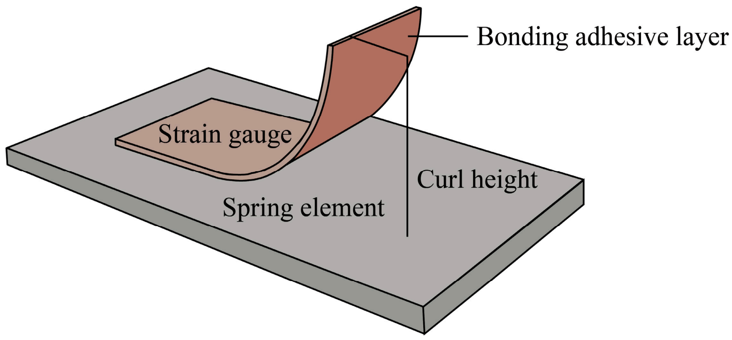


Figure 3. Schematic illustration of the curl height.

During the development process, selecting the appropriate BA is crucial as different application scenarios demand adhesives with varying performance characteristics. The performance of the BA may be affected by temperature variations, which are associated with thermal properties such as heat distortion temperature and thermal decomposition temperature. The development of the BA entails ensuring sufficient bonding strength initially and then maintaining a precise strain transmission performance. It is important to note that this testing method solely focuses on the bonding strength of the BA and does not take into account other performance indicators.

2.2. Evaluation Model

The adhesive typically used to bond SGs onto spring elements is a rigid BA, which ensures the strain generated by the spring element is faithfully transmitted to the SG. The model involves the interaction between the adhesive layer and the SG. When shear force is applied, the stiffness of the adhesive layer affects the bending and curling behavior of the strain gauge film. A stiffer adhesive layer leads to an increased bending and curling of the

SG, while a softer adhesive layer reduces these effects. According to the theory of elasticity, we can describe the bending force F_b acting on the SG using the following formula:

$$F_b = \frac{E_s \cdot t^3}{12 \cdot L^2} \tag{1}$$

Here, E_s represents the bending modulus of the SG, reflecting its ability to undergo elastic deformation under stress. t denotes the thickness of the SG, where a greater thickness offers a higher resistance to bending. L signifies the length of the SG, with longer lengths leading to a more uniform stress distribution during bending. The constant term *12* in the denominator represents the load distribution on the SG, akin to that of a simply supported beam. In this context, the midpoint of the beam experiences the maximum bending force, while the ends endure the minimum bending force.

The force exerted by the adhesive layer on the SG F_a can be described as:

$$F_a = k_a \cdot L \tag{2}$$

This equation delineates the tensile or compressive force exerted by the adhesive layer on the SG, with k_a denoting the stiffness of the adhesive layer, indicating its ability to undergo elastic deformation under stress. L represents the length of the SG on the adhesive layer's surface, delineating the range over which the adhesive layer impacts the SG. These equations amalgamate fundamental principles of material mechanics to depict the stress on the SG and the adhesive layer's influence on it. In practical applications, model parameters can be adjusted based on experimental data and simulation results to suit various real-world scenarios.

When there is bending between the SG and the adhesive layer, the adhesive layer applies tensile or compressive force on the SG to counteract the stress induced by bending. Thus, to maintain equilibrium, we can equate the bending force exerted on the SG to the force exerted by the adhesive layer on the SG. This facilitates the establishment of a balanced equation to elucidate this situation. Specifically, equating the two formulas and solving for the parameter L enables the representation of the adhesive layer's action range, ensuring equality between the bending force and the exerted force:

$$F_a = F_b \tag{3}$$

The disparity in stiffness between the SG and the bonding adhesive layer results in the bending and curling of the SG during scraping, with a higher stiffness of the bonding layer leading to a greater degree of curling.

Based on the degree of curling and the curl height of the SGs, five distinct evaluation grades are identified (Figure 4) and marked as Grade 1 (G1) to Grade 5 (G5), corresponding to the continuously decreasing adhesion strength of the BA. This grading system played a pivotal role in our study, enabling us to not only objectively quantify differences in adhesion strength among various Bas, but also to provide a clear methodology for comparing and classifying the performance of different samples.

It is important to note that these five evaluation grades represent different levels of BA adhesion strength. G1 signifies the highest adhesion strength, whereas G5 denotes the lowest adhesion strength. Through extensive scraping tests and the analysis of numerous samples, it was consistently observed that a progressive intensification of the degree of curling and a decrease in curl height in SGs occurred with increasing adhesion strength of the BA. This trend was consistently validated across different samples.

Although bonding strength no longer directly influences the degree of curling after removal, it can still indirectly affect it in certain situations. Even after the adhesive is removed, the bonding strength between two materials can impact their interaction. If the bonding between the materials is exceptionally strong, separating them during the removal of the SG may become more challenging. This could result in more SG residue remaining on the surface, increasing the surface unevenness and geometric changes, ultimately leading to a greater degree of curling. In other words, while bonding strength does not directly determine the degree of curling, it can affect the interaction between materials, thus indirectly influencing the degree of curling.

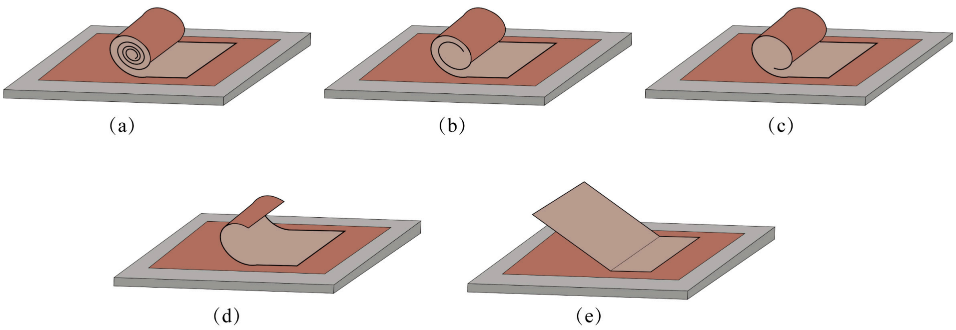


Figure 4. Adhesion strength: (**a**) G1 adhesion strength; (**b**) G2 adhesion strength; (**c**) G3 adhesion strength; (**d**) G4 adhesion strength; (**e**) G5 adhesion strength.

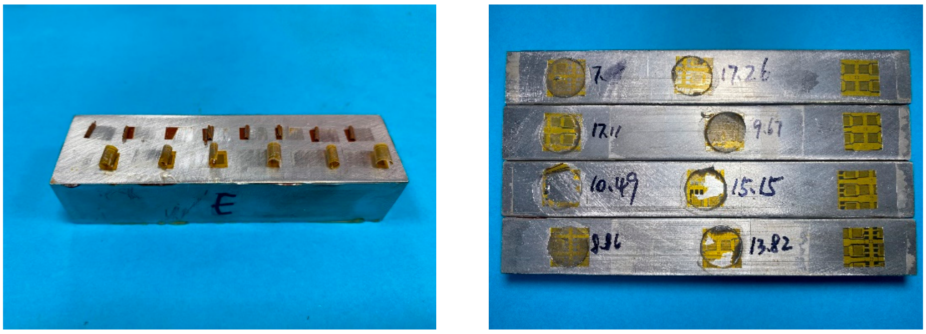
3. Experiment

Five different BAs with varying adhesion strength were selected based on the aforementioned grading system and were labelled as BA-1, BA-2, BA-3, BA-4, and BA-5, corresponding to adhesion strengths G1 to G5, respectively. The BA with the highest bonding strength is a commercial BA produced by Zhejiang Gaugewill Electronics Co., Ltd. (Quzhou, China), designated as model G308s. Other BAs used were developed during the research and develment process by Zhejiang Gaugewill Electronics Co., Ltd., offering varying bonding strengths. A metallic spring element material (Model LY12, Shanghai Yegri Steel Group Co., Ltd., Shanghai, China) was chosen as the substrate and underwent polishing and cleaning processes to ensure an impurity-free surface [10]. Subsequently, SGs (Model 350-3AA-T10, Zhejiang Gaugewill Electronics Co., Ltd.) were adhered to the surface of the metallic spring element following the standard procedure [11]. To avoid any adverse effects on the performance of the BA, all coupons were subjected to curing treatment based on their respective curing conditions, ensuring complete solidification of the BA. This meticulous process guarantees optimal performance and reliability of the BA in the experimental setup.

The adhesion strength assessment is commonly completed using the traditional peel tester method, yet it is essential to recognize that the applicability of this method is limited by factors such as the adhesive type, the joint material, and the material's flexibility [12]. However, due to the potential brittle nature of SGs, the traditional peel tester method is not suitable for their evaluation. Therefore, the pull-out adhesion testing method is adopted as an alternative method to assess the adhesion strength of SGs. The obtained mechanical curves were then compared to the adhesive grades proposed by our qualitative testing method to validate their accuracy and precision. The pull-out adhesion testing method was conducted on an automatic pull-out adhesion testing machine (Model BEVS2201, Guangzhou Shenghua Industrial Co., Ltd., Guangzhou, China). The tests were performed at room temperature with a pulling rate of 0.75 MPa/s.

4. Discussion

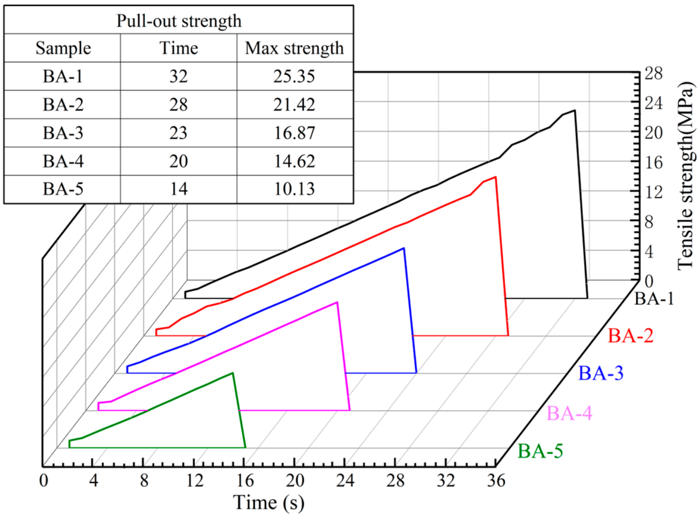
The image of the scraped SGs and the measurements of curling height and curling degree are shown in Figure 5a. Following the scraping process, the SGs exhibit varying degrees of curling due to differences in the BA. Deeper curling of the SGs corresponds to smaller curling heights. Figure 5b illustrates the adhesion of the SGs after tensile testing. However, the data obtained through this method are not accurate, as the SGs were not fully extracted. This outcome arises because the bonding strength of the adhesive used in the tensile test is lower than that of the BA used for bonding the SGs. Despite its limitations, this method can still evaluate the magnitude of bonding strength, thereby validating our assessment model.



(**a**) (**b**)

Figure 5. Shape of SG after scraping and drawing test: (**a**) Curl degree and curl height of SGs after scraper test; (**b**) SG after pull-out test.

By using the pull-out adhesion testing method, the quantitative adhesion strength of the SG is usually manifested. The pull-out adhesion testing method results shown in Figure 6 demonstrate a gradual decrease in the pull-out adhesion from BA-1 to BA-5. This indicates a continuous reduction in their adhesion strength, with BA-1 exhibiting the highest adhesion strength. The pull-out adhesion testing results agree well with the grades proposed in our method, in which G1, characterized by the deepest curling and the smallest curl height, has the strongest adhesion strength, while G5 has the weakest adhesion strength. The quantitative results from the pull-out tests provide specific numerical values for the adhesion strength between different grades, further confirming the accuracy and effectiveness of the qualitative evaluation method proposed for measuring the adhesion strength of the BA.



Pull-out strength		
Sample	Time	Max strength
BA-1	32	25.35
BA-2	28	21.42
BA-3	23	16.87
BA-4	20	14.62
BA-5	14	10.13

Figure 6. Quantitative results of different BAs obtained using the pull-out adhesion testing method.

With the increase in adhesion strength, the SGs after scraping will exhibit different grades. It should be noted that the degree of curling and curl height of SGs after scraping actually have various ways of changing. Although this testing method only selects the above five Grades for classification, in reality, there is still diversity within these five adhesion strength grades. In other words, the adhesion strength of the BA may fall between two grades as proposed, allowing for further subdivision into subgrades if needed. By adopting this approach, variations in the adhesion strength of the BA can be more precisely captured, thereby providing additional information and references for practical applications and research. This meticulous classification method contributes to a more comprehensive understanding of the differences between various levels of adhesion strength, offering more flexible options for further research and experimental design.

5. Conclusions

A facile method for the evaluation of the adhesion strength between the SG and underlying spring element was introduced in this paper. The 5 grades (G1 to G5) of adhesion strength identified from the method showed great consistency to the classical pull-out adhesion testing method, rendering it an easily used and reliable method in the monitoring and evaluation of the adhesion strength of SGs. It not only allows for qualitative evaluation of adhesion strength through visual observation but can also be completed within a relatively short timeframe, making it suitable for situations requiring rapid assessment. Despite these advantages, the method still has limitations, particularly when dealing with complex structures or special materials. This method showed great application promise during fabricating SG sensors, especially for monitoring and quick testing in a mass production line.

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