Characterization Analysis Software for Microstructures Based on an Internet Sharing Platform

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Abstract: Characterization analysis software for microstructures based on an Internet sharing platform has been developed which can display and evaluate 3D morphology data for microstructures. This software is mainly used for data analysis and database functions, and is capable of storing sample data and user data, 3D display, remote sharing, and real-time processing of sample data, and is compatible with multiple data formats. It implements evaluation algorithms for parameters such as step height, grating period, and degree of roughness, and supports basic operations such as rotation, filtering, and leveling. Four types of permissions have been defined for the software for different users, and design for data security is also applied to effectively reduce security risks.

Keywords: Surface morphology, database, internet sharing platform, step height, grating period.

1. Introduction

The surface morphology of microstructures is an important factor affecting device function and surface quality. The measurement, analysis, and evaluation of surface morphology play an important role in product quality control and failure analysis in the semiconductor and precision manufacturing fields, among others. Characterization analysis software for microstructures is an integral part of surface morphology measurement instruments as it directly affects the accuracy, reliability, ease, and practicality of measurement data [1, 2]. Eftekhari, *et al.* used the AFM images to analyze the surface morphology of annealed FTO/ZnS bilayer films [3]. Jakubowicz, *et al.* studied the micro-scale structural parameters of surfaces produced through Selective Laser Melting (SLM) under various configurations of 3D printing parameters [4]. Sadeghi, *et al.* researched the influence of ion implantation on corrosion resistance of the nickel over steel, the surface morphology was acquired by AFM [5]. All of them conducted the post-processing using MountainsMap software. Good evaluation software can easily process measurement data, carry out data visualization, and standardize the parameter evaluation process.

In terms of surface morphology evaluation software, Huazhong University of Science and Technology (HUST) made an early start by carrying out a great deal of research work which focused on method analysis and evaluation algorithms for surface morphology area, stylus scanning surface morphology measurement software, evaluation algorithms for the degree of surface roughness, and other related content and by conducting research HUST managed to achieve a series of results [6, 7]. Huaqiao University developed a surface morphology evaluation system for grinding tools based on VC++, which is used to comprehensively evaluate 2D and 3D characteristics of such tools [8, 9]. The University of Huddersfield in the UK joined Taylor Hobson (an English technology company) and the National Physical Laboratory (UK) to work on the practical transformation of software measurement standards and designed a standardized software system for software measurements of 2D surface morphology evaluation parameters [10]. The National Institute of Standards and Technology (NIST) in the US developed a network-based surface metrology algorithm testing system. The standard data and filtering algorithms this provides can be used to verify the accuracy of the software of scientific research institutions and instrument manufacturers [11].

At present, mainstream surface morphology analysis software mainly includes MountainsMap software from Digital Surf, TrueMap software developed by TrueGage, and the free open source software Gwyddion, etc. [12–14]. These software are quite comprehensive and offer good human-computer interactions, but both require the client to be installed locally. Unlike Gwyddion, the other two models mentioned above require the purchase of licenses and their prices are expensive. This article uses browser/server (B/S) architecture to develop characterization analysis software for microstructures based on an Internet sharing platform. The software boasts online analysis of measurement data and sample database functions. It is compatible with multiple data formats and can be used to upload measurement data as well as store, display, and evaluate functions for common parameters such as step height, grating period, and degree of surface roughness.

2. Software Architecture and Functional Design

The characterization analysis software for microstructures is based on an Internet sharing platform and mainly includes characterization analysis software, a sample database, and a user database. The characterization analysis software is mainly used for post-processing and analysis and evaluation of instrument measurement data, and the sample database is mainly used for measurement data storage, classification, and measurement case display. The user database is used to add and delete user data and modify user permissions. By building an Internet sharing platform, the remote storage, analysis, and display of measurement data can be achieved. An overview of the architecture of the characterization analysis software for microstructures is shown in Fig. 1.

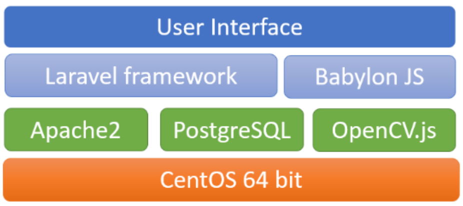


Fig. 1. Software architecture overview.

The first layer of the architecture deploys the 64-bit Community Enterprise Operating System (CentOS) operating system to build an enterprise-level Linux system environment on the cloud server while the second layer of the architecture features Apache2 Web server software, PostgreSQL object-relational database management system, and the OpenCV universal algorithm library. The third layer of the architecture adopts the Laravel development framework and Babylon JS framework, which are used for PHP Web development and Web3D rendering respectively. The fourth layer is the user interface which enables human-computer interactions.

The software is compatible with 3D data in a variety of storage formats, including .npz, .tdms, .txt, .sur, and .gwy, and can perform various operational calculations and filtering of measurement data. The software runs through a browser, which means there are less requirements for hardware. The user can log in to the software by opening the server address in browsers such as Google, Firefox, and Edge using 32-bit and

64-bit Windows XP, Windows 7, or Windows 10 to use all of the software's functions without any need to install the software separately with an installation package on a local computer. The structural principle and functions of the software are shown in Fig. 2.

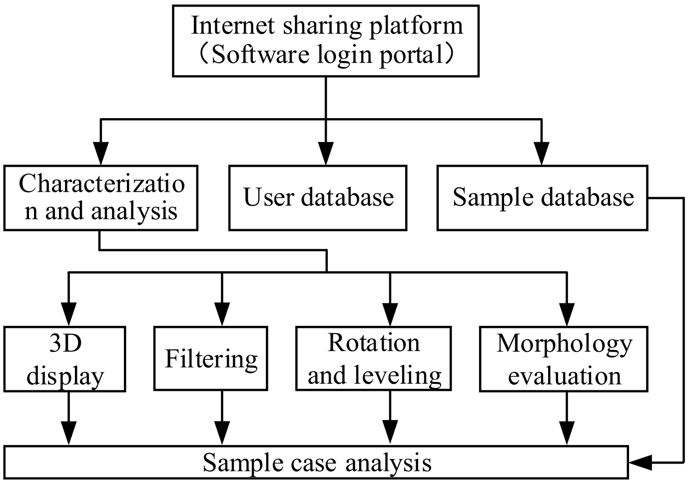


Fig. 2. Software structural principle and functions.

3. Data Analysis Tools

All of the data analysis tools of the software are implemented on the cloud and are used for 2D and 3D parameter analysis and evaluation. 2D data analysis tools mainly include the degree of line roughness (Ra , Rv , Rq , Rp , and Rt), step height (for one side and both sides), grating peroid, leveling, and filtering, etc. 3D data analysis tools mainly include sectional curves, average height, degree of roughness (Sa , Sq , Sp , Sv , and Sz), skew, flatness, binary threshold, filtering, rotation, mirroring, leveling, and 3D stitching, etc. In measurements of surface morphology, evaluation tools for steps, gratings, and degree of roughness are mainly used.

3.1. Step Evaluation Tool

Commonly used step height evaluation methods include histogram, bilateral fitting, and unilateral fitting methods. The histogram method utilizes digital image processing to express the *x*-axis as height and the *y*-axis as the frequency of occurrence of each height, and then calculates the step height based on the height difference between the two highest frequencies [15]. Ideally, the histogram for step height has only two peaks, but in actual measurement, the histogram will have multiple peaks, and the difference in frequency between peaks with similar heights is negligible. Therefore, there is a lot of room for error when using this method to evaluate step height.

The bilateral fitting method is the current standard method for step height evaluation as defined in the ISO5436-1: 2000 standard. This method can effectively eliminate the influence of step edge chamfers, burrs, and excessive areas on the side of the step, and offers high calculation accuracy. The least squares method is used to fit according to formula (1). When fitting, only the middle one-third of the upper surface of the step is taken, and one-third of the length of each side of the lower surface is taken for fitting, as shown in Fig. 3.

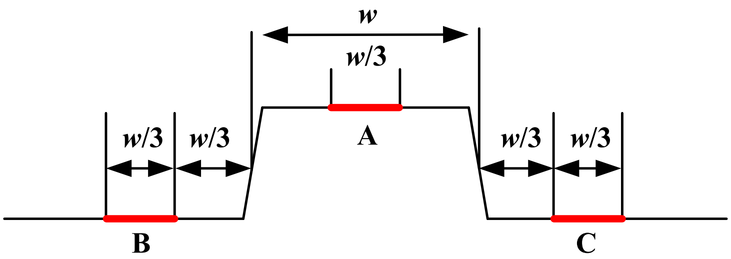


Fig. 3. Step height evaluation area.

The step height fitting formula is as follows:

$$H = \alpha X + \beta + \delta h \tag{1}$$

In the formula, H is the measured value vertically; X is the measured value horizontally; the parameters α, β, and h are determined by the fitting results. Take δ as +1 in area A and as -1 in areas B and C. The final calculated step height is 2 times h. The essence of this method is to regress the line segments located on different planes to the middle plane, use three line segments to form three regression equations, and then solve the equation for the three parameters.

The unilateral fitting method is generally used for the evaluation of steps on one side. Due to limitations in the CCD field of view of the optical method and limitations in the scanning range of other methods, the amount of data required by the bilateral fitting method cannot be collected for step structures with relatively large sizes. Therefore, straight line fitting can be performed on the upper and lower surface data points of the steps on one side to obtain the regression equations of the respective areas. The height of the measured step is obtained by calculating the difference in the *y*-axis of the central points of the respective fitting areas.

Fig. 4 shows the surface morphology data of the step standard sample obtained using a confocal microscope. The nominal height of the step standard sample is 1.8 μm. After arbitrarily intercepting a line, the step height is evaluated, and the step height calculation result is 1.789 μm.

(a) 3D morphology of steps

(b) Cross-sectional line

Fig. 4. Step height sample.

3.2. Grid Evaluation Tool

For 1D and 2D grid standard templates, commonly used evaluation methods include the center of gravity method and the Fourier transform method. The center of gravity method filters out all features that meet the conditions through a certain threshold, calculates the position of the center of gravity, and then obtains the period of the structure through linear fitting. This method has high requirements on the integrity of the line and cleanliness of the surface. If there are impurities on the surface of the sample, this will cause the sample line to change, thereby causing the center of gravity to shift. In addition, ripples on the surface of the sample and burrs in the line signal also affect the evaluation results of the center of gravity method. The Fourier transform method calculates the grid cycle by measuring the spatial frequency of the sample surface morphology information in the frequency domain, and determines the grating period by finding the $f_{\max}$ frequency point with maximum amplitude in the frequency domain. The grating period is $1/f_{\max}$. This method was used to evaluate the grating data with a period of 3 μm, and the grating period that was calculated was 2.911 μm. Fig. 5 shows the measurement data of the evaluated grating.

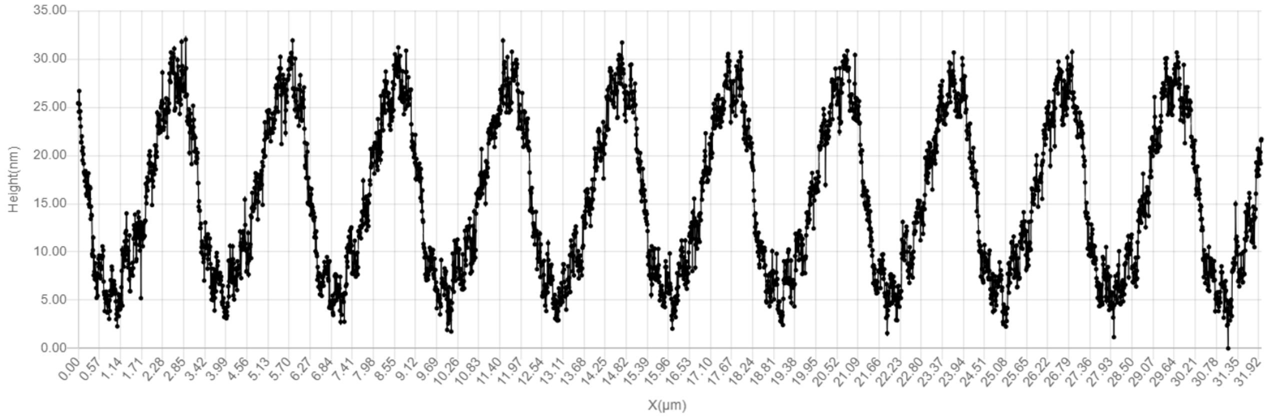


Fig. 5. 3μm period grating sample.

3.3. Roughness Evaluation Tool

At present, degree of surface roughness is mainly evaluated with parameters for 2D degree of surface roughness. The GB/T 3505-2009 standard follows the degree of roughness parameters and related concepts in the international ISO 4287-1997 standard. In the evaluation of 2D degree of roughness, it is first necessary to determine parameters such as the measurement direction, sampling length, and evaluation length, and then calculate the evaluation baseline and degree of surface roughness. Commonly used 2D degree of surface roughness parameters include line arithmetic mean deviation $R\text{a}$, line root mean square deviation $R\text{q}$, and other parameters. The formulas for calculating $R\text{a}$ and $R\text{q}$ are as follows:

$$Ra = \frac{1}{l_r}\int_0^{l_r} |z(x)|\, dx \tag{2}$$

$$Rq = \sqrt{\frac{1}{l_r}\int_0^{l_r} z^2(x)\, dx} \tag{3}$$

In the above formula, l_r is the sampling length and $z(x)$ is the distance from each point on the line to the evaluation baseline.

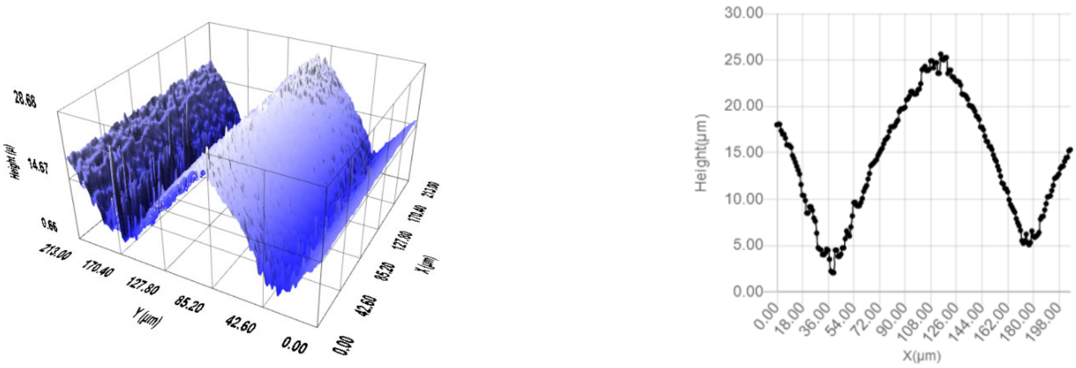
2D degree of surface roughness mainly represents the change in the sample surface line relative to the evaluation baseline, emphasizing the height information on a single line. The evaluation result is greatly affected by the selected line, and the information on a single line cannot reflect the entire surface, which means that the 2D degree of surface roughness evaluation method has certain limitations.

In 2006, the International Organization for Standardization released the ISO 25178-2006 standard, which provides an evaluation method for 3D degree of surface roughness. The 3D degree of surface roughness evaluation method breaks the limitations of the method for 2D degree of surface roughness evaluation and can accurately reflect the global information of the entire evaluated surface. Corresponding to $R\text{a}$ and $R\text{q}$ in the 2D degree of surface roughness evaluation method, the 3D degree of surface roughness evaluation method defines parameters such as surface arithmetic mean deviation $S\text{a}$ and surface root mean square deviation $S\text{q}$. The definitions of $S\text{a}$ and $S\text{q}$ are as shown in the following formulas.

$$Sa = \frac{1}{A}\iint_A |z(x,y)|dxdy = \frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}|z(i,j)| \tag{4}$$

$$Sq = \sqrt{\frac{1}{A}\iint_A z^2(x,y)dxdy} = \sqrt{\frac{1}{MN}\sum_{i=1}^{M}\sum_{j=1}^{N}z^2(i,j)} \tag{5}$$

In the formula, $z(x,y)$ is the distance between the 3D surface point and the evaluation datum plane; A is the area of the evaluation surface; M is the surface width in the direction x; N is the surface width in the direction y. The evaluation of 3D degree of surface roughness requires the establishment of an evaluation datum plane as the evaluation benchmark. When the measured surface is a flat surface, the datum surface should also be a flat surface; when the measured surface is a curved surface, the datum surface should be a curved surface with the same curvature. The spatial position of the datum can be determined by mathematical algorithms, with the least squares method being the most commonly used algorithm. This article uses the above 2D degree of surface roughness evaluation method to evaluate the roughness standard sample with a nominal Ra value of 6 μm. The calculated Ra value of the sample is 5.374 μm and the Rq value is 6.344 μm. Fig. 6 shows the degree of roughness sample and the intercepted line.



(a) 3D morphology of the roughness sample (b) Cross-sectional line

Fig. 6. Roughness sample.

A gold-plated sample was evaluated using the 3D degree of surface roughness evaluation method. The Sa value of the sample was 1.387nm, and the Sq value was 1.669nm. The 3D morphology of the sample is shown in Fig. 7.

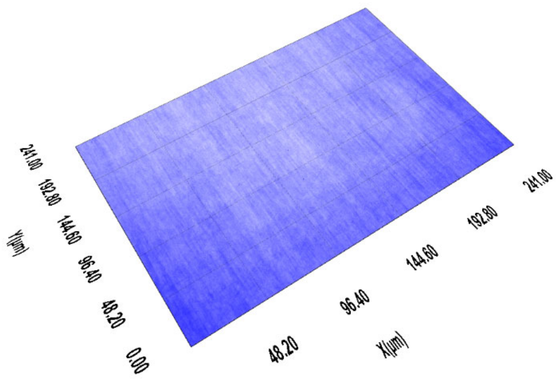


Fig. 7. Gold-plated sample.

4. Database Design

4.1. User Database

The user database is where user information is stored. It supports adding, modifying, and deleting of users, and can be used to search for users and export user lists. The software is designed with four database access user types and permissions, which includes ordinary users (L1), advanced users (L2), administrators (L3), and super administrators (L4). The four user types correspond to the four permissions respectively. L1 users can use data analysis functions and can upload, view, modify, and delete files for this account, and view and download files shared by other users. L2 users can use data analysis functions and can upload, view, modify, and delete files for this account, and view and down all files in the database. L3 users can use data analysis functions and can upload, view, modify, and delete files for this account, and view, download, and deletion of all files in the database. L4 users can use data analysis functions and can upload, view, modify, and delete files for this account and view, download, and deletion of all files in the database. It can also create, edit, and delete other users. Fig. 8 shows the user list.

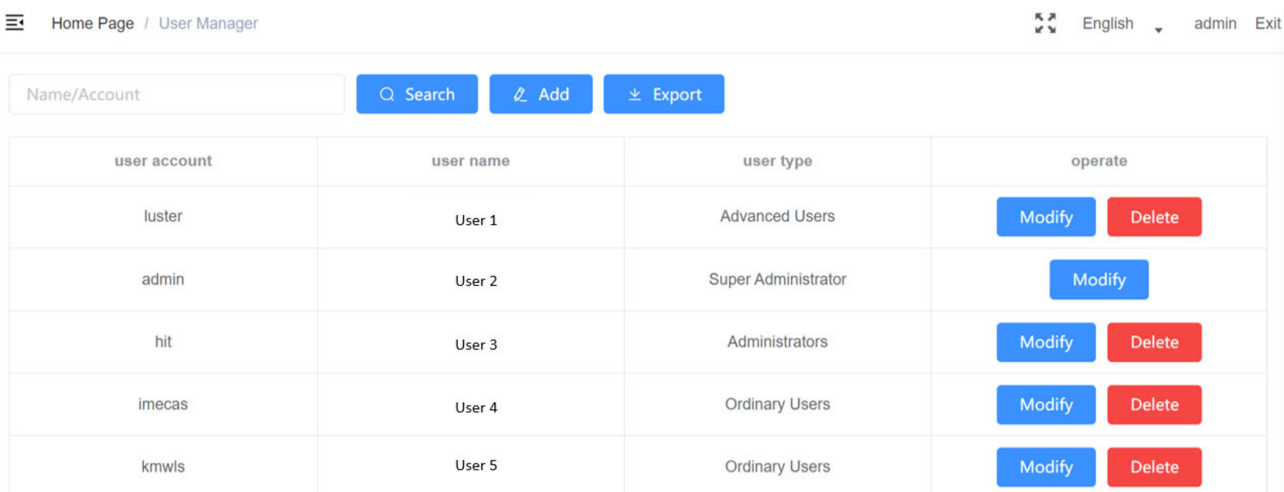


Fig. 8. User list.

4.2. Sample Database

The sample database is used to store and manage sample data, and implement functions such as adding, modifying, and deleting sample files. The database is designed with PostgreSQL 14.2, supports multiple data types, and allows users to customize the data type, index type, functions, triggers, and more to meet the needs of specific applications. The database supports 3D sample files in .npz, .tdms, .txt, .sur, and .gwy formats and 2D sample files in .txt and .dat formats. The sample title, introduction, sorting, imported unit, and display unit can be edited. After entering the sample database, the sample list is displayed as shown in Fig. 9. There are also some challenges in the data integration. The data in different formats are firstly converted into a unified intermediate format. Not all data formats can be easily converted to this intermediate format.

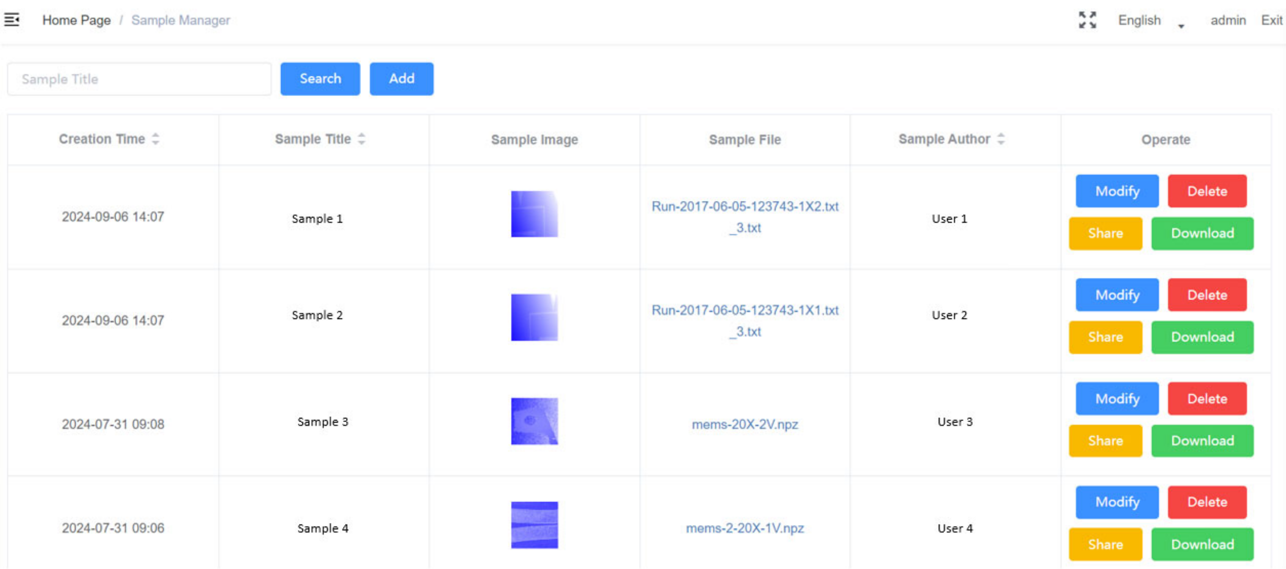


Fig. 9. Sample list.

4.3. Security Design

In terms of security and data integrity, PostgreSQL provides flexible authentication and authorization mechanisms and supports SSL encrypted transmission. An SSL certificate is necessary for any website that wants to protect user information. It encrypts the communication between the website and the user's browser, provides authentication, and prevent access to illegal websites set up by attackers. Even if the attacker obtains the user information, it cannot be read. In addition, it provides functions such as integrity constraints, triggers, and foreign keys to ensure data integrity and consistency. In addition to the security measures of the database management system itself, in terms of reliability the Alibaba Cloud servers are on duty 24 hours a day to effectively prevent hardware problems. The cloud server schedules snapshots every day so that if a system issue occurs, it can be quickly restored. The easiest and most effective way to secure a website application is to ensure all plug-ins and patches are updated to the latest version.

The login screen uses graphic code verification to prevent malicious access. Key information such as login passwords are encrypted and transmitted to ensure that no passwords appear in plaintext. For sensitive data, such as customer data, the data can be encrypted on the front end to ensure the data is encrypted during transmission and storage. Input validation is also performed on both front and back end to ensure that the data entered by the user conforms to expected format and type to avoid malicious input. During the development process, Apache Jmeter is used for concurrency stress testing and performance testing, and basic security testing such as SQL injection is performed on the system. If users need to further strengthen their security management, they can set up an IP whitelist to only allow access to users with specified IP addresses in order to minimize security risks.

5. Conclusion

In this article, the characterization and analysis software developed for microstructures based on an Internet sharing platform integrates measurement data analysis and evaluation and database functions. It adopts B/S architecture to store applications and data on the server, and uses the computing power of the server to perform data and logic analysis. The client (browser) sends requests through the web server and accepts html page data, which greatly reduces the difficulty of development and requirements for hardware. The software realizes seamless connection between the data analysis function and the database. Users can directly press the sample in the database to jump straight to the analysis page and perform calculations and evaluation of parameters for microstructures, such as conventional step height, grating period, degree of surface roughness, and more.

Compared to the existing microstructure analysis tools, the developed software has many advantages. The software is running on a cloud server and consuming less local hardware resources. No installation is required and users can only log in through a browser to use the software. Users can share the measurement data through the sample database. These are currently not available in most of commercial software. However, there is still much work to be done to improve software functionality. The analysis is not as powerful as commercial software and the user interface is not so friendly. In the following work, the software will be compatible with more data formats, expend more functional modules, and optimize display speed for large data volumes.

Conflict of Interest

The authors declare no conflict of interest.

Author Contributions

K. Sun: Software, Methodology, Investigation; J. Wei: Formal analysis, Data Curation; J. Wu: Conceptualization, Writing, and Supervision. All authors had approved the final version.

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