Review

A novel method for failure analysis based on three-dimensional analysis of fracture surfaces

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A B S T R A C T

The fractured surfaces include a lot of useful information that can help investigate the reasons that caused metal materials to break. For example, the details on the processes that lead to failure can be determined from these surfaces, making it useful to investigate their morphology. The principle of the fracture-surface topography analysis (FRASTA) was used in this research and some progresses have been made on quantitative reverse deduction of metal fracture surfaces. In FRASTA, the fracture surfaces are scanned by laser microscope and the elevation data is recorded for analysis. The crack-tip opening angle (CTOA) was firstly determined by the cross-sectional plots. Simple bar hypothesis was then proposed. As for the hypothesis, the fracture surfaces can be assumed to be composed of independent rectangular bars. After dividing the plastic deformation left on the fracture surfaces into such single bars, the original lengths of these bars were calculated and then the global strains of these bars during the course of failure were calculated, and finally the J-integral was calculated. Then, the relationship between J-integral and crack opening displacement (COD), and the relationship between J-integral and fracture surface average profile for plain strain were deduced. Furthermore, according to the relationship between true stress and true strain for the material, the normal stress on the cross section of each single bar was determined. Summing up all the loads on all bars provided the total applied load of the specimen. Some experiments have been performed and the proposed methods have been verified to some extent. At the same time, software, namely fracture surface analyst (FSA) was developed as per the proposed methods and was used for analysis successfully.

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1. Introduction

When fracture accidents take place in a structural component, there are only the broken parts left for investigation. Fracture surfaces of broken parts include a lot of useful information. They record details and sequences of process that caused the failure. It is necessary to research fracture surfaces thoroughly.

In order to investigate the reasons that caused the material to break, it is necessary to clarify the temperature, environment and load imposed on the material. But these records are often unavailable. For this reason, it is useful to extract messages from broken materials. To analyze fracture surfaces and deduce the reasons that caused the failure is a proposing way.
Fracture surfaces of broken parts (in failure analysis) and test specimens (in materials development) are routinely examined using an optical microscope and scanning electron microscope (SEM) to obtain qualitative information including crack initiation sites, the direction of crack propagation, and associated fracture mechanisms. While it is also possible to obtain limited quantitative information, such as fatigue-crack-growth rates based on the striation spacing by using conventional techniques, generally there is not sufficient information that can be used in quantitative fracture-mechanics analyses.

Fracture-surface topography analysis (FRSTA), developed by SRI International, is a procedure for reconstructing the process of crack extension in microscopic details by comparing the topographic features from conjugate areas of opposing fracture surfaces [1]. It overcomes the limitations of conventional techniques by quantifying and analyzing the topographies of conjugate fracture surfaces simultaneously to reconstruct a fracture event (via computer). The concept of analyzing conjugate fracture surfaces is based on accurately characterizing the micro-failure processes that result in final rupture. The FRSTA considers that as the crack extends, the material immediately beneath the newly formed fracture surfaces undergoes no further inelastic deformation.

FRSTA uses fractured-area-projection plots (FAPPs) and cross-sectional plots (XSPs) to present results [2]. FAPPs are taken perpendicular to the fracture plane and provide information on micro-crack-initiation sites and projected areas of micro/macro cracks. XSPs show sections perpendicular to the fracture surface and display the micro-cracks in profile, how two surfaces match each other, the amount of overlap (inelastic deformation) necessary before the fracture, and the amount of crack-face-opening displacement.

As shown in Fig. 1, the gray-scaled volumes are the upper and lower fracture surfaces, respectively. The white areas on the left in FAPPs and XSPs are considered to be the opening of fracture faces; the dark areas indicate the extent of plastic deformation before the fracture; and the white areas on the right indicate the compression of plastic deformation zone. Using the FRSTA technique, the details of the void nucleation and growth, the coalescence of the voids and cracks, and the crack propagation process can be clarified visually [3].

2. FRSTA’s applications

FRSTA applications involve the characterization of crack history and fracture mechanisms, and the determination of fracture parameters.

Failure analysis is the main field that FRSTA can be used. FRSTA was used to determine crack-initiation times and crack-growth rates from the post-test examination of AISI Type 304 stainless steel constant-extension-rate specimens fracture surfaces which were tested in different simulated, modified boiling water reactor service environments [2]. FRSTA clearly identified the difference in micro-fracture mechanism between two specimens tested in different environments. The details of voids nucleation and growth, the coalescence of voids and crack, and the crack propagation are clarified visually by using the FRSTA technique when studying the ductile fracture of Al-alloys 7075 and 2017 [3]. The results of FRSTA not only support the superiority of dynamic irradiation effect to the static irradiation effect on fatigue behavior but also provide good evidence for the mechanism of the dynamic irradiation effect based on the interaction between continuously induced defect clusters and mobile dislocations for the in-beam fatigue behavior research for 20% cold-worked 316 stainless steel [4]. The mechanism of subsurface crack initiation and propagation in high strength steel in a very high-cycle fatigue region was revealed by a computational simulation using FRSTA method for specimens of a high carbon chromium bearing steel with data obtained from rotary bending fatigue testing in air [5].

Besides the failure analysis, FRSTA can also be used for the development of the materials. The development of an advanced material that has high fracture toughness generally is a time-consuming, trial-and-error process. Materials development would be more efficient if detailed micro-fracture mechanisms could be understood from the first trial sample; i.e., in what part of the material a micro-crack started, how the growing crack interacted with various constituents, and what mechanism resists crack growth. FRSTA was used to determine how micro-fracture occurred in silicon-carbide (SiC) fiber-reinforced titanium-aluminum (Ti3Al) composite material and examine the fracture surfaces of two broken polyethylene specimens from the extruded and compression-molded material [6]. They demonstrated that FRSTA could portray...
micro-fracture mechanisms in a complex material and also could delineate the hidden effects of processing on the fracture behavior of materials. The results told that FRASTA was useful not only in material design, but also in process quality control. Another function of FRASTA is to determine the fracture parameters. FRASTA was used to obtain the information on the fracture toughness directly from a broken part [6]. The crack-arrest toughness assessed via FRASTA from conjugate fracture surfaces agreed very well with the values computed from dynamic measurement data. The possibility of deducing load spectrum parameters from fatigue failure surfaces is explored by applying innovative, three-dimensional topographic characterization and analysis techniques to failure surfaces in aluminum sheet [7]. FRASTA provided a way to quantify overloads. A procedure was sought for to estimate fatigue loading information from the characteristics of roughness of fracture surfaces [8]. The topography of fracture surfaces produced in compact tension specimens of a titanium alloy in load-shedding and monotonically increasing $\Delta K$ tests were analyzed with a fast Fourier transform. FRASTA helped determine the relationship between fracture surface roughness and fatigue load parameters.

3. Development of quantitative fracture surface analysis by FRASTA

The FRASTA technique can be widely used for failure analysis, materials development and determination of fracture parameters. However, the FRASTA application has previously focused on smaller size scales and localized behaviors [9]. At the same time, only a few fracture parameters were determined by FRASTA. Thus, the ability of FRASTA to extract quantitative information from fracture surface is greatly restricted. With the development of experimental equipment, laser microscope is used for fracture surface analysis. By this non-contact three-dimensional scanning system, the global fracture surfaces of larger size scale fracture surfaces can be examined and analyzed. Combined with the development of software, the fracture surfaces and the whole fracture process can be rebuilt and many fracture parameters can be determined during the course.

3.1. Experiments

A compact tension (CT) specimen of alloy steel was used as an instance to illustrate the progresses made in this area. The displacements at two different locations were measured using the double gauge method. That is, a clip gauge and a ring gauge were used to measure the opening displacements at the load-line and crack mouth, respectively, as shown in Fig. 2. During the test, the displacements and the corresponding loads at these two locations were recorded.

After the completion of the test, the conjugate fracture surfaces were examined by laser microscope as shown in Fig. 3 and the elevation data was recorded. The resolutions of the laser microscope along the X, Y, and Z directions are 50 $\mu$m, 50 $\mu$m and 1 $\mu$m respectively. The working ranges of the stage along the X and Y directions are both 15 cm. Fig. 4 shows the recorded fracture surface.

3.2. Process of FRASTA simulation

Fig. 5 displays the principle of matching the conjugate fracture surfaces. According to [2], the corresponding location of the upper and lower fracture surfaces should share common features because when crack takes place, plastic deformation will be left on the fracture surfaces and will not undergo further deformation. That is to say that the corresponding location on the conjugate surfaces can match each other well.

The process of using FRASTA to simulate the process of fracture is shown in Fig. 6. The upper fracture surface is first inverted along specimen thickness direction and mirrored to correlate the lower fracture surface; after being adjusted to the proper position, the conjugate surfaces are rotated and moved according to the recorded displacements at load-line and crack mouth respectively.

![Fig. 2. A clip gauge and a ring gauge were used to measure the displacements at load-line and crack mouth respectively.](image-url)
3.3. Calculation of some parameters

3.3.1. CTOA and others

A number of different criteria are used to predict crack growth. The crack opening angle is one of the most appealing. There are two definitions for the crack opening angle, crack-tip opening angle (CTOA) and the crack opening angle (COA) as shown in Fig. 7 [10]. The CTOA is the local slope of the crack face near the crack tip while the COA is the ratio of the crack opening displacement at the site of the initial crack tip to the current crack extension. It has been verified that, after an initial
transient period, stable crack growth occurs when the CTOA reaches a constant critical value \[11\]. This value is referred to as the critical CTOA. The critical CTOA fracture criterion is widely used to describe fracture behavior \[12,13\].

CTOA is generally defined as shown in Fig. 7 as the angle between the upper and lower crack surfaces \(r_m\) behind the crack-tip. To measure CTOA during testing is often inconvenient. In FRASTA, the elevation data of the conjugate fracture surfaces was obtained and the process of fracture was simulated as shown in Fig. 6, making it simple to calculate CTOA. By just locating the current crack-tip and two points \(r_m\) behind the crack-tip on the upper and lower fracture surfaces respectively, the value of CTOA can be determined.

It is worth noting that during the period of the crack's initial growth, i.e. when crack extension \(\Delta a < r_m\), the initial crack-tip is assumed to be the current crack-tip. This means that, when \(\Delta a < r_m\), CTOA = COA.

The variance of CTOA with crack extension is plotted in \[14\] as shown in Fig. 8. From the results it is clear that the CTOA becomes constant with the crack extension. Fig. 9 shows the variation of CTOA through specimen thickness. It found that the CTOA does not vary with position along the thickness direction.
Using this method, COA, crack opening displacement (COD) and crack-tip opening displacement (CTOD), which are inconvenient to obtain by traditional methods, can also be easily calculated.

3.3.2. J-integral

The $J$-integral is one of the most important parameters to assess the toughness and describe the extension of a crack body. Generally, the elastic compliance method is used to calculate the $J$-integral and construct the $J$–$R$ curve for CT specimens. In our previous work [15,16], a new method, which makes use of the elevation data of the conjugate fracture surfaces and is on the basis of FRASTA, was proposed to calculate $J$-integral.

According to the simple bar hypothesis proposed in our work, the fracture surfaces can be assumed to be composed of independent rectangular bars as shown in Fig. 10. In order to simplify the calculation, this paper supposes the plastic deformation is symmetrical about the fracture surface. The sizes of these bars in the directions of crack extension and specimen thickness are determined by the step lengths of the laser microscope. Thus, along the direction of crack extension, the amount of plastic deformation which is gray-scaled in Fig. 10 can be considered to be the elongation of the bar. Considering the simple tension test for rectangular specimens, during the course of the test, as the load increases from zero to the specimen’s failure, the strain varies from 0 to $\varepsilon_f$ and the stress varies from 0 to $\sigma_f$. As introduced in [17], the strain distribution along the bar can be written as some kind of power exponential function. Thus, for a fracture surface that is considered to be composed of such simple bars, the strain distribution of the strain component along the $z$ axis can be plotted as $F(z)$ as shown in Fig. 10, where $\varepsilon_y$ is the critical strain of yield and $\varepsilon_f$ is the critical strain of fracture. It is clear that $\varepsilon_y$ is the value at the end of the bar (on the boundary of the plastic field) and $\varepsilon_f$ is the value at the center of the bar (on the fracture surface). Both of them are material constants [18]. By integrating, we can get the elongation and the ratio of elongation to original length of the bar. By deduction, it is found that the ratio of elongation of the bar is also a constant. That means the size of the plastic field is in proportion to that of the plastic deformation.

At the same time, based on FRASTA principle, when the conjugate fracture surfaces are driven to the initial position (stated before the test started) after being broken, the overlap refers to the plastic deformation left on the specimen. As introduced above, we supposed that the plastic field was composed of independent rectangular bars with the original length of the bar $l$ and the elongation $\Delta l$. Because the ratio of elongation for some material can be determined by tension test and the elongation $\Delta l$ can be determined by FRASTA, $l$, which denotes the scale of plastic field, can also be determined.

According to the relationship between true stress and logarithmic strain of the material, the energy consumed for plastic deformation of a single bar under tension can be found by using integration,

$$u_j = \nu_j \int_{\varepsilon_y}^{\varepsilon_f} Ke^ne$$

(1)
where $v_{ij}$ is the volume of each bar, $K$ is a constant and $n$ is the work hardening exponent.

On the basis of the upper suppositions and by summing up the energy consumed by each individual bar which has been broken during the course of crack extension; we could obtain the total energy consumed for crack extension and the energy release rate, which is $J$-integral, can be represented as,

$$J = \frac{\Delta U}{B \Delta a} = \frac{U_n - U_{n-1}}{B(a_n - a_{n-1})}$$

(2)

where $U_{n-1}$ and $U_n$ are the dissipated plastic energy when crack extends to $a_{n-1}$ and $a_n$ respectively, and $B$ is the specimen width.

Finally, the paper plotted the $J$–$R$ curves constructed by using the method proposed and also by the elastic compliance method respectively as shown in Fig. 11. Comparison results showed that these two curves match each other well.

The new method proposed provides a new way to calculate the $J$-integral. Since it can be obtained from the fracture surfaces of the broken components, it is also convenient for widespread application.

### 3.4. Relationship between $J$-integral and fracture surface average profile

As introduced above, $J$-integral can be calculated from metal fracture surfaces. But, in practice, it is inconvenient to calculate the $J$-integral and plot the $J$–$R$ curve because the recorded fracture surface can be regarded to be composed of many accidented lines, and to simulate the process of fracture is to locate the conjugate lines on the upper and lower fracture surfaces precisely according to the displacements recorded at load-line and crack-mouth respectively during test. Slight deviation of location will make the results deviate from the theoretical value much. On the other hand, calculation of $J$-integral based on the simulation of crack extension using every pair of lines can only represent the state of some certain position while not the global fracture surfaces. With these means, using the average profile to represent the whole fracture surface was proposed in [16].
In [16], the relationship between $J$-integral and the fracture surface average profile was deduced as follows,

$$J_g = p.c.f. \left( \frac{1 + \frac{P}{n+1}}{K} \right) \delta_g$$

where $p.c.f.$ is the plastic constraint factor, $P$ is the ratio of elongation and $\delta_g$ is the average deformation which is left on fracture surfaces.

Comparison between the results by the new method and by the compliance method showed that what introduced could provide a proposing way to calculate $J$-integral from the average profiles of fracture surfaces conveniently.

### 3.5. Relationship between $J$-integral and COD

$J$-integral and crack opening displacement $\delta$ (COD) are important parameters for characterization of fracture in engineering materials. The relationship between $J$-integral and COD has been investigated for a long time and is generally represented as $J = m \sigma_y \delta$. In order to determine the value of $m$, extensive studies and experiments have been performed. But the final conclusion is unavailable.

In fact, the value of COD can be determined during simulation of crack extension by the fracture surface average profile as introduced in [18], that is, there is some relationship between COD and the fracture surface average profile. At the same time, because the relationship between $J$-integral and the fracture surface average profile was deduced in [16], both $J$-integral and COD are related to the fracture surface average profile. The relationship between $J$-integral and COD was deduced as,

$$J = p.c.f. K \left( \frac{1}{n+1} \right) \delta$$

A series of center-cracked tension (CCT) and double-edge notched (DEN) specimen experiments were performed, results in Fig. 12 shows that the proposed expression worked well.

### 3.6. Calculation of the applied loads on the specimen

To reveal the reasons that lead to the final failure, calculation of the applied loads during the course of failure is the most important. According to the simple bar hypothesis, the fracture surfaces can be assumed to be composed of independent
rectangular bars as shown in Fig. 10. The sizes of these bars in the directions of crack extension and specimen thickness are determined by the step lengths of the laser microscope. Thus, along the direction of crack extension, the amount of plastic deformation which is gray-scaled in Fig. 10 can be considered to be the elongation of the bar.

In order to calculate the load applied to the specimen during the course of failure, we should first determine the global strain of each bar during the course of failure. As shown in Fig. 13, the crack has extended from the “initial crack tip” to the “present crack tip”; that is, material behind the present crack tip (between the “initial crack tip” and the “present crack tip” in Fig. 13) has been fractured, and thus forces acting on the bars composing this part have been released. For the material in front of the “present crack tip”, it still bears a load. By adding the loads acting on these bars together, the applied load of the specimen can then be determined. As shown in Fig. 13, assuming the final elongation of the bar when the specimen fractures is \( \delta_y \), and dividing the elongation into two parts, \( \delta_y' \) and \( \delta_y'' \), where \( \delta_y' \) represents the elongation of the bar when the crack extends to the “present crack tip”, and \( \delta_y'' \) represents the residual elongation of the bar with the crack extending further from the “present crack tip” until the final failure. It should be noted that the dot-dashed lines in Fig. 13 are the initial fracture surfaces. The distance between them when the crack extends to the “present crack tip” represents the relative displacement of the conjugate fracture surfaces, which can be recorded by gauges.

As introduced above, \( \delta_y' \), \( \delta_y'' \) and \( \delta_y'' \) can be easily obtained by reconstructing the process of crack extension using FRASTA. Assuming that work hardening in the material obeys the Hollomon equation, the applied load on the specimen can be calculated as,

\[
F = p \times q \times K \times k \times \sum \varepsilon_i^a
\]

where \( p \) and \( q \) are the step lengths along the X and Y directions, \( \varepsilon_i \) is the average strain at \( x_i \) and the \( k \) is the number of bars with the same \( x \) coordinate.

The method was applied to fracture surfaces obtained from double-edge notched (DEN) specimens made of two kinds of metallic alloy, broken under low-cycle fatigue in [19]. Fig. 14 shows the maximum applied loads versus crack extension for specimen A and specimen B respectively. Results showed that the calculated maximum fatigue loads were almost equal to what recorded during testing, which are 47 and 30 kN respectively.

3.7. Development of FRASTA simulation software

The new method introduced above can accurately calculate the parameters of crack such as CTOA, \( J \)-integral and applied loads. But the process of calculation is generally very troublesome and time-consuming; at the same time, it is hard for those who do not have much experience in this field to do this work. In order to avoid this kind of complications and make the calculation more accurate, Fracture Surface Analyst (FSA) was developed in [20].

The software was developed under the operating system of Microsoft Windows with the platform of Microsoft Visual Basic. The procedure of functions that the software fulfilled was detailed in [20]. Fig. 15 shows the main interface of FSA.

A series CCT and DEN specimen experiments were performed in [20]. Elevation data of fracture surfaces was firstly processed by FSA to build the three-dimensional fracture surfaces. Then the process of fracture was simulated in accordance with what introduced above. During fracture process simulation, values of parameters such as CTOA, \( J \)-integral and applied loads were calculated and recorded. Finally, the variation of these parameters with the crack extension was plotted. From the Fig. 13. Two parts of the elongation of a single bar.
results of our previous work, it is found that FSA could accurately simulate the process of fracture for three types of specimen – CT, CCT and DEN and could accurately calculate the values of these parameters of crack. Thus, we consider that FSA can be widely used for fracture surface three-dimensional analysis.

4. Conclusions and future work

From what is presented in this paper, it is clear that the FRASTA simulation, which can record the elevation data of fracture surfaces and simulating the process of crack extension, can be used for failure analysis, materials development and
determination of some fracture parameters. FRASTA’s ability to reveal the entire sequence of evolving fracture events could be useful in areas including development of a life-prediction model, providing a physical correlation with acoustic-emission signals, and improving the efficiency of materials development. It provides a new way to analyze the global fracture surfaces and the whole process of fracture and can obtain much more quantitative information. It is possible to calculate some parameters of crack such as CTOA and $J$-integral. Based on the relationship between the plastic energy and the plastic deformation which can be determined by FRASTA, the loads that were imposed on the specimen during fracture can also be calculated. The method may provide a new way to help clarify the causes, such as over-load, variance of temperature, corrosion and so on that lead to fracture for metal materials without performing experiments while just from the broken parts. Thus, the ability of FRASTA to solve real-world problems will be greatly improved.

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