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DIRECTED MEASUREMENTS AND HETEROGENEOUS STRUCTURES IN QUANTITATIVE FRACTOGRAPHY

Ervin E. Underwood

School of Materials Engineering
Georgia Institute of Technology
Atlanta, GA 30332-0245

ABSTRACT

Modern advances in the old problems of quantitative fractography have utilized the powerful relationships of stereology, including the special equations for directed measurements and the methods tailored to heterogeneous structures. The procedure that has evolved has broad, general application, and yet is amenable to simple, direct and efficient experimental methods. It is based on profilometry, using vertical sections, and requires directed measurements. Roughness parameters provide correction factors for measurements made on the flat SEM fractograph. These corrected values yield true magnitudes of features in the fracture surface. Quantitative descriptions of the fracture surface and its characteristics permit better correlations of fractographic features with mechanical properties and the formulation of better fracture mechanisms.

Key Words: directed measurements, heterogeneous structures, quantitative fractography, roughness parameters, vertical sections

INTRODUCTION

The historical developments leading to modern quantitative fractography have been amply surveyed in the recent literature (Coster and Chermant 1983, Exner and Fripan 1985, Underwood 1986a, 1987, 1987a, Wright and Karlsson 1983). The major experimental factor responsible for the current achievements is the widespread availability of the scanning electron microscope (SEM) and the SEM fractograph (Beachem 1969, Broek 1971, 1974, Pelloux 1965). However, direct, uncorrected measurements made on the SEM fractograph do not yield correct spatial magnitudes (Underwood 1986a). The single SEM image is in actuality a two-dimensional (reflected) projection, and lacks information in the z-direction. An additional degree of freedom, such as that provided by stereometry or profilometry, is necessary to complete the spatial analysis.

Fracture profiles have also been used extensively in qualitative studies of fracture surfaces (Broek 1971, 1974, Henry and Plateau). Sampling with profiles is essentially linear in nature as opposed to point sampling by stereophotogrammetry and area sampling by SEM. Profiles have been generated by sectioning at various angles to the fracture surface, with vertical sections (Shieh 1974, Pickens and Gurland 1976, Underwood and Chakrabortty 1981) being the most convenient experimentally. The major advantage accruing to vertical sections is that they are prepared in ordinary metallographic mounts. Moreover, serial sectioning is accomplished merely by grinding away part of the mount face (Cox and Low 1974, Van Stone and Cox 1976, Banerji and Underwood 1985, Gentier and Riss 1987). Any degree of complexity or overlap of the fracture profile is clearly delineated and available for direct measurements. Most importantly, planar sections in metallographic mounts reveal the underlying microstructure and its relationship to the fracture path (Underwood and Chakrabortty 1981).

The equations and procedures described here are simple and direct. Even so, care must be taken to conform to the requirements of the analysis. Equations pertaining to directed measurements (Underwood 1970, Saltykov 1974) must be used with measurements made in a specified direction in the vertical sections. These equations are related to the general stereological equations based on random sampling and measurement. However, the directed equations are not the same as the general equations, nor do they supersede them. Rather, they complement them and provide directional information rather than values averaged over all directions. Because of the commonality of direction of the vertical SEM beam, the vertical sections, and vertical projection of the fracture profiles, we must also define the roughness parameters R_L and R_S in terms of directed quantities.

Other methods have been employed to deal with projections. In several publications (Wright and Karlsson 1983, Baddeley et al. 1986, Gokhale and Underwood 1990, Wojnar and Dziadur 1987) the authors have used average projections obtained by integrating over all angles. This is not the same as projections made in one (perpendicular) direction. The integrated quantities serve a useful purpose for other applications (Underwood 1970, Baddeley et al. 1986, Kendall and Moran 1963) but do not give directional information. They should not be confused with the procedure defined here.

We proceed now to a consideration of the quantitative analytical relationships of fractography. The subject will be developed briefly from its stereological origins, with emphasis on the interrelationships between homogeneous and heterogeneous structures, and between random and directed measurements. Then roughness parameters and the parametric equations for estimating the true fracture surface area of any irregular surface are presented, followed by numerous references to the applications of these methods.

STEREOLOGICAL RELATIONSHIPS

The basic equations of stereology have been stated and derived in several treatises (Underwood 1970, Saltykov 1974, DeHoff and Rhines 1968, Weibel 1979-1980). These relationships are statistically-exact and assumption-free, in the sense that no crippling a priori assumptions of size or shape or angular orientation are required. Nor need the structure be "random"*, since if randomness of structure is not attained, then the measurements themselves can supply the missing element of randomness between test figure and structure.

In either case, the stereological equations are completely valid. Other than that, there are only the usual statistical requirements of adequate and proper sampling and a sufficient number of measurements to satisfy the needs of the investigation.

General Stereological Relationships

The general stereological equation for line length per unit area is

$$L_A = (\pi/2)\ P_L \tag{1}$$

where P_L equals the total number of intersections P of a test line (or grid of parallel lines) with the crack trace, averaged over all angles, and divided by the length of the test grid, L_T. L_A is defined as the ratio of the trace length L_t to the area of an arbitrarily chosen test area, A_T. This ratio is, of course, equal to the trace length per unit area.

Eq. (1) has been used for the analysis of crack traces. Similar equations are available for crack surfaces (Underwood and Chakrabortty 1981). The general stereological relationship for the area of surfaces of any configuration, provided sampling and measurements are performed randomly (Underwood 1970, Saltykov 1974), is

$$S_V = 2\ P_L \tag{2}$$

where S_V equals the surface area S_t per unit test volume V_T, and P_L is the intersection count as defined for Eq. (1). Although Eq. (2) is valid for any type of surface -- oriented, partially-oriented or random , no information regarding the actual surface configuration is forthcoming; only the magnitude. However, three-dimensional sampling of the crack surface by serial sectioning (Banerji and Underwood 1985) provides an indication of shape.

Combinations of the stereological equations are extremely useful. Eqs. (1) and (2) combine to form the general stereological equation

$$S_V = (4/\pi)\ L_A \tag{3}$$

which relates the crack surface area and the trace length.

Heterogeneous Structures

The above considerations are general in nature and apply to any type of microstructure. However, special care must be

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* By 'random structure' we refer to that hypothetical microstructural condition described as isotropic, uniform and random, in both angular and locational attributes. By 'random measurements', we mean measurements made with statistical uniformity over the entire specimen.

exercised when dealing with 'heterogeneous' as opposed to 'homogeneous' structures. For both types of structures, sampling should be done with 'statistical uniformity' over the entire specimen in order for the basic stereological equations to be valid. For heterogeneous structures, if the test areas are placed only at regions of high interest, there will be different, and incorrect, results.

Alternative approaches that permit localized sampling can be used with heterogeneous structures. These procedures are illustrated using a closed crack with its trace exposed in the plane of polish. It would appear, at first glance, that the ratio of trace length to test area is meaningless, because the choice of a larger or smaller test area (enclosing the same trace length) would give a different value of the ratio -- see Figure 1.

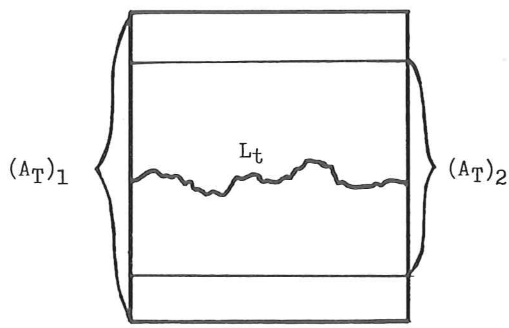

Fig. 1. Local sampling of heterogeneous structure. A crack trace in two test areas.

Of course this should not happen, since the value of L_A must be constant for a particular microstructure. The correct result depends on proper sampling. A single test area arbitrarily placed over a portion of the crack trace certainly does not constitute proper sampling. Rather, to use Eq. (1) directly, we should sample the entire specimen uniformly in order to obtain the correct value of L_A.

But this procedure, although correct, is not convenient for the purposes of our fractographic analysis. There are at least two ways to circumvent this apparent ambiguity with heterogeneous structures. One way is to utilize a ratio of lengths that, being dimensionless, is independent of the size of the test area. Consider an arbitrary test area placed over two lines L_t and L' as in Figure 2. If L_A is measured for each line according to Eq. (1), the test area terms will cancel out because they have the same magnitude. This follows according to

$$\frac{(L_A)_{trace}}{(L_A)_{proj}} = \frac{L_t / A_T}{L' / A_T} = \frac{L_t}{L'} \quad . \qquad (4)$$

Instead of ratios, we can solve for the absolute value of the microstructural feature. Equation (1) can be rewritten as

$$L_t = (\pi/2)\ P_L\ A_T \tag{5}$$

which enables the absolute value of L_t to be calculated since the value of A_T is known (an arbitrary constant). These two methods remove the ambiguity connected with local sampling of heterogeneous structures.

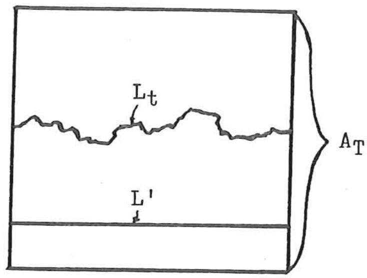

Fig. 2. Local sampling of heterogeneous structure. A crack trace and its projection in one test area.

The same considerations as discussed above with regard to the test area A_T also apply to Eq. (2) and the choice of test volume, V_T. For the heterogeneous structure composed of a single crack embedded in a surrounding matrix, sampling must be performed with statistical uniformity over the entire specimen volume in order to use Eq.(2) correctly. However, for a fractographic analysis, we wish to use 'local' sampling and an arbitrary test volume. This is possible if the test volume contains two surfaces, say S_t and A'. Then, application of Eq. (2) gives a ratio of areas as shown in Eq. (6).

$$\frac{(S_V)_{surf}}{(S_V)_{proj}} = \frac{S_t/V_T}{A'/V_T} = \frac{S_t}{A'} \ . \tag{6}$$

We see that the test volume term cancels out, regardless of its magnitude.

The absolute area of a fracture surface can also be obtained from Eq. (2) according to

$$S_t = 2\ P_L\ V_T \tag{7}$$

provided V_T can be assessed. If serial sectioning is employed, with n cuts a constant spacing Δ apart, we know that V_T equals $(n+1)\cdot\Delta\cdot A_T$. Substitution into Eq. (7) permits S_t to be calculated.

Directed Measurements

Directed measurements constitute an important complement to random measurements (Underwood 1970, Saltykov 1974). Sections are cut at selected locations and in preferred directions, and subsequent measurements in these planes may be taken in a specified direction. These procedures are frequently employed with structures having some degree of preferred orientation in particular directions or planes. The special equations for directed measurements may be useful in these cases.

Several such equations are available for lines in a plane, an example of which is a crack trace in the plane of polish (Underwood and Starke 1979, Underwood and Chakrabortty 1981). One relationship that involves projected quantities in a preferred direction is

$$(L_A)_{proj} = (P_L)_\perp \quad . \tag{8}$$

Here, $(L_A)_{proj}$ represents the ratio of projected length L' of the crack, along a chosen projection axis, to the area of the test region A_T. $(P_L)_\perp$ equals the number of intersections with the crack trace per unit length of a test grid placed perpendicular to the projection axis. Note that only one projection direction (vertical) is employed here. In order to avoid the ambiguity that occurs with heterogeneous structures, we can rearrange Eq. (8) to express the projected length in absolute terms, similar to that done above.

When dealing with directed measurements, the profile length can be projected either as an <u>apparent</u> projection or a <u>total</u> projection. Figure 3 illustrates the difference between the two types of projections. The apparent projected length L' of the crack trace between points A and B is simply the projected length A'B' on the projection axis, regardless of reentrancies or overlaps. On the other hand, the total projected length L" consists of the projection (in one direction), on the projection axis, of all segments of the curve, whether obscured or not.

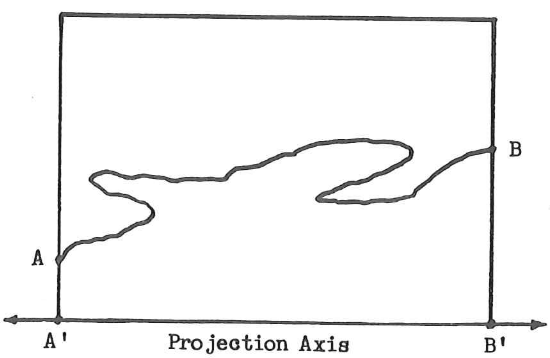

Fig. 3. Apparent projection A'B' on the projection axis of the crack trace AB

Directed measurements also give additional details about specific surface configurations (Underwood, 1970, Underwood and Chakrabortty 1981) For example, the projection equation for surfaces based on directed measurements is

$$(S_V)_{proj} = (P_L)_\perp \tag{9}$$

where $(S_V)_{proj}$ may be either the apparent or the total projection of the surface, projected perpendicular to the chosen projection plane, divided by the test volume. $(P_L)_\perp$ is analogous to the quantity described above in Eq. (8); here, however, the subscript $\perp$ refers to a projection line perpendicular to a projection plane (rather than a projection line). Figure 4 depicts the difference between apparent and total projections of surfaces and volume elements when projected in only one direction (Underwood 1970).

Equations (8) and (9) also combine to yield the important general projection equation based on directed measurements

$$(S_V)_{proj} = (L_A)_{proj} \; . \qquad (10)$$

This equality is valid for surfaces with or without overlap (Underwood 1990), and can be used with either the total or apparent projection.

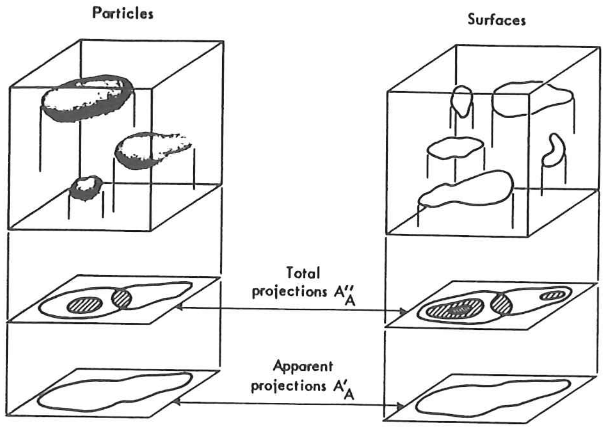

Fig. 4. Apparent and total projections of particles and surfaces (Underwood 1970)

When Equations (8), (9) and (10) are used with local measurements on heterogeneous structures, the values of $(L_A)_{proj}$ and $(S_V)_{proj}$ are dependent on the size of the test area or test volume. If the absolute values of the profile or surface projections are used instead of the customary stereological ratios, there is no ambiguity. The other procedure that circumvents this problem uses dimensionless ratios as described above.

Directed measurements are also employed to express the fractional length of an irregular planar curve, or fractional area of a partially-oriented surface, that is oriented in a particular direction (Underwood 1970, Saltykov 1974). Considering a fracture profile of length L_t, the fraction of oriented length is L_{or} / L_t, where L_{or} is the length of just those segments of the curve that lie in the selected orientation direction. A parameter that expresses the degree of orientation of such a partially-oriented line in a plane is $\Omega_{1,2}$, where the subscripts refer to lines, 1, in a plane, 2. The parameter is defined by

$$\Omega_{1,2} = \frac{(P_L)_\perp - (P_L)_\parallel}{(P_L)_\perp + 0.571(P_L)_\parallel} \qquad (11)$$

where $(P_L)_\perp$ and $(P_L)_\parallel$ are directed measurements made perpendicular $\perp$ and parallel $\parallel$ to the selected orientation axis. $\Omega_{1,2}$ can vary between the limits of 0 and 1, where 0 represents a completely random line (no oriented components) and 1 means a completely oriented line (a straight line parallel to the orientation axis). In between, the trace can have any degree of partial orientation and $0 < \Omega_{1,2} < 1$. Note that if the orientation axis is not selected properly, i.e., in the oriented direction of the trace, $\Omega_{1,2}$ will be negative (Wojnar et al. 1987), which is meaningless.

Parameters for the degree of orientation are also available for surfaces of various configurations (Underwood 1970, Saltykov 1974). Applications of these parameters have been described elsewhere (Underwood and Aloisio 1980, Underwood and Chakrabortty 1981), so will not be discussed here. Note that because these orientation parameters are dimensionless, they do not suffer a test area ambiguity when applied to heterogeneous structures.

ROUGHNESS PARAMETERS

Several types of roughness parameters have been proposed for profiles and surfaces (Pickens and Gurland 1976, El-Soudani 1978, Wright and Karlsson 1983, Underwood 1987). A major selection criterion for a roughness parameter lies in its suitability for characterizing irregular curves and surfaces. It is desirable that a roughness parameter expresses roughness well, relates readily to the physical situation, and equates simply to spatial quantities. Because profiles are easily obtained experimentally, it is natural that considerable attention has centered on their properties. The surface roughness parameters that have been proposed (Underwood 1987) are not as numerous, possibly because they are too difficult to evaluate experimentally.

Three roughness parameters have been identified that possess outstanding attributes for quantitative fractography. These are R_p, the profile configuration parameter; R_L, the (linear) profile roughness parameter; and R_S, the surface roughness parameter. Other useful parameters have been proposed for crack and microstructural characterization, and have been described in the literature (Shieh 1974, Pickens and Gurland 1976, Underwood and Starke 1979).

Profile Parameters.

The profile configuration parameter*, R_p, is essentially the ratio of average peak height to average peak spacing, $\overline{H}/\overline{W}$. As such, it is sensitive to variations in the roughness, or configuration, of an irregular planar curve. This parameter, and its applications, have been described in the literature (Underwood 1984, Underwood and Banerji 1987).

The profile roughness parameter (Pickens and Gurland 1976), R_L, is a ratio of lengths. It is defined as the true profile length divided by the apparent projected length

$$R_L = L_t \,/\, L' \tag{12}$$

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* Behrens EW. Personal communication 1977.

where the prime denotes the projected length of the profile, projected in a perpendicular direction to the selected projection axis. Since L' is a constant, R_L can vary between 1 and ∞, depending on the magnitude of L_t. Experimental values of R_L between 1.06 and 2.39 have been reported for a variety of materials (Underwood and Banerji 1987), corresponding to a range of R_S values between 1.5 and 2.5.

Both R_P and R_L are length ratios and thus dimensionless. Both require directed measurements for their evaluation. However, R_P is dependent on configuration, while R_L is defined basically in terms of length and not configuration. This latter point is not generally understood. An example of the primary dependence of R_L on length can be visualized with several profiles having the same length, but with different configurations and angular orientations (random or otherwise). They all have the same value of R_L. On the other hand, a group of profiles having the same angular frequency distribution but different lengths will all have different values of R_L.

Surface Parameters

A natural surface roughness parameter of great importance that parallels the profile roughness parameter is R_S (El-Soudani 1978, Underwood and Chakrabortty 1981, Wright and Karlsson 1983). It is defined as the true surface area S_t divided by the apparent projected area A', according to

$$R_S = S_t / A'. \tag{13}$$

Since A' is an arbitrary constant, S_t is obtained directly once R_S is known. Figure 5 illustrates the quantities involved in the surface roughness parameter and its interrelationships with R_L, the projection plane A', and a test plane A_T. Since the fracture surface is projected in a direction perpendicular to the projection plane, we are also concerned here with directed measurements. R_S is a ratio of areas, and thus is dimensionless.

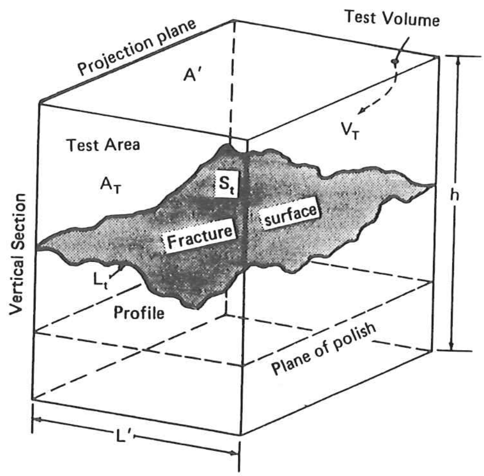

Fig. 5. Interrelationships of fracture surface to sections and projections.

It can vary between 1 and ∞, depending on the magnitude of the surface area. Moreover, R_S is defined primarily in terms of surface areas, and not the angular orientation of elements in the fracture surface. The rationale is similar to that presented above in discussing the length-based definition of R_L.

PARAMETRIC RELATIONSHIPS

Two roughness parameters, R_S and R_L have emerged as having basic significance in the quantitative study of fracture surfaces. However, R_S is difficult to evaluate, whereas R_L is experimentally accessible. Thus, a relationship between R_S and R_L is greatly to be desired. Both of these dimensionless ratios are closely related to stereological quantities. As defined, moreover, they both require directed measurements.

The relationship of R_L and R_S to their stereological counterparts L_A and S_V is simple and direct (Underwood 1987, Underwood and Banerji 1987). The equivalent equation to Eq. (3) in terms of roughness parameters is

$$R_S = (4/\pi)\ R_L\ . \tag{14}$$

This important equation is valid for any surface, if sampling is performed randomly. However, we would like to restrict the use of Eq. (14) to directed measurements only, because of the roughness parameters. Fortunately, directed measurements can be used with random surfaces, because a random surface should give the same value (statistically speaking) for measurements from any direction. Accordingly, for directed measurements perpendicular to the effective fracture surface plane, we can write (Underwood and Banerji 1987)

$$(R_S)_{ran} = (4/\pi)\ (R_L)_{\perp}\ . \tag{15}$$

This equation represents a straight line when plotted in (R_S, R_L)-coordinate space. It gives a practical maximum limiting curve, based on all known experimental values. Several attempts have been made to model fracture surfaces having specific configurations. Noteworthy are the stepped surface (Wright and Karlsson 1983), the vertical spike (Gokhale and Underwood 1990) and the deep fracture (Wojnar 1988) models. The first two models result in the equation

$$R_S = (\pi/2)[R_L - 1] + 1 \tag{16}$$

and the other is close to it. Moreover, in early work at Georgia Tech (Underwood 1980) with the computer simulated fracture surface (CSFS), triangular facets were elongated by a factor of up to 20X, giving a curve that lies slightly higher than that for Eq. (16). Thus it is apparent that by modelling a surface it is possible to exceed Eq. (15). However, an absolute maximum curve has not yet been demonstrated. At the present time, it appears that the CSFS curve is the best available upper limit curve for the (R_S,R_L)-diagram.

Other attempts to express R_S as a function of R_L have been published (El-Soudani 1978, Coster and Chermant 1983, Wright and Karlsson 1983, Cwajna et al. 1984, Gentier and Riss 1987, Wojnar

1988), but they do not compare too well (a 38 percent spread). Several of these attempts to establish a relationship between R_S and R_L suffer from the same defect; i.e., (R_S,R_L)-coordinates of (1,1) and $(2,\pi/2)$ are used as terminal points instead of (1,1) and (∞,∞) as required by the definitions of R_S and R_L. The values of $R_S = 2$ and $R_L = \pi/2$ are incorrect for quantitative fractography purposes, and are obtained from the general stereological equations for their ratios averaged over all orientations (Kendall and Moran 1963, Underwood 1970). What should be used instead are the directed equations for the unidirectional (perpendicular) projection of areas or lines.

To summarize, the upper limit in the R_S-R_L diagram is dependent on modelling, as portrayed by Eq. (16). The general fractographic equation, Eq. (14), is applicable to any surface, of any configuration (random, partially-oriented, overlapped, planar, etc.), provided sampling is random. R_S is a maximum for a given value of R_L; the coefficient has the maximum value of $4/\pi$. A value of R_S lower than the maximum can not be obtained from a random surface, of course, since the same (maximum) value is obtained whether a random surface is sampled randomly or with directed measurements. The only way one can get lower values of R_S (for a given value of R_L) is with nonrandom surfaces that are sampled by directed measurements. Intermediate values of R_S, between the limits of Eqs. (15) and (17), must derive from partially-oriented surfaces that are evaluated with directed measurements.

The minimum values of R_S, for any given values of $(R_L)_\perp$, can be visualized starting with a flat surface (at $R_S = 1$, $R_L = 1$) that is gradually crinkled to a greater extent at higher values of (R_S,R_L). A useful model for these minimum area surfaces is the corrugated ruled surface (Underwood 1989) whose elements are generated by the translation of a straight line parallel to itself. In terms of roughness parameters, we have

$$(R_S)_{ruled} = (R_L)_\perp \qquad (17)$$

where the sectioning plane is perpendicular to the elements of the ruled surface. When plotted in (R_S, R_L)-coordinate space, Eq. (17) is a straight line lying between (1,1) and (∞,∞) with a slope of 45°. Note that the coefficient in Eq. (17) has a minimum value of 1.

Other surface configurations are possible for the prototype minimum area surfaces. For example, the area of a flat surface could be incrementally increased by small hillocks or dimples. Sampling of such minimum area surfaces would have to be done over all angles, however, just to obtain a satisfactory estimate of S_t. The ruled surface makes a more convenient model inasmuch as only one vertical section is required. Moreover, R_S can be calculated directly once R_L is known.

A special case of Eq. (17) is the completely oriented surface with minimum surface area (a flat plane parallel to the projection plane). In terms of roughness parameters it is expressed by

$$(R_S)_{or} = (R_L)_{or} \qquad (18)$$

which has a value of unity when directed measurements are used as described above. The coordinates (1,1) plot as a point at the origin of (R_S, R_L)-coordinate axes.

Almost all the known experimental coordinate pairs of (R_S, R_L) (Underwood and Chakrabortty 1981, Wright and Karlsson 1983, Banerji and Underwood 1985, Exner and Fripan 1985, Sigl and Exner 1987, Drury and Underwood 1987, Underwood 1989) fall within the two limiting curves given by Eqs. (15) and (17), as shown in Figure 6. Note that most of the R_S values have been obtained from a modified form (Banerji and Underwood 1985) of the analysis by Scriven and Williams (1965), and not from any parametric equations.

Useful equations for the upper and lower limits have been described above. A more difficult problem is to devise a parametric equation for the partially-oriented surfaces between the two limits. Two linear parametric curves have been proposed as representative average curves through the limiting area in (R_S, R_L)-space.

Only one of the proposed average parametric equations lies completely within the upper and lower bounds (Underwood 1987). It is

$$R_S = (4/\pi)[(R_L)_\perp - 1] + 1 \qquad (19)$$

which represents a 'best' line through the bounded region. The derivation of this equation (Underwood and Banerji 1983, Underwood 1987) is based on broad, general stereological principles, so it has universal application to any nonplanar surface. Note that the relationship is linear, with (R_S, R_L)-termini at (1,1) and (∞,∞). An average value of R_S is calculated directly from the experimental profile roughness parameter, which leads to S_t according to Eq. (13).

Equation (19) appears in Figure 6 as the heavy central line between the limit curves. The data points fall satisfactorily around this median line, although there appears to be a trend for the points with lower values of R_L to lie nearer the upper limit.

Recently, a somewhat different parametric equation was derived (Gokhale and Underwood 1989) from the Scriven and Williams analysis (1965), giving

$$R_S = 1.16\ R_L\ . \qquad (20)$$

Although Eq. (20) is an approximation (the first term of a series) and does not lie completely within the upper and lower limits, the curve makes an excellent fit with the presently available experimental data.

R_S is expressed in terms of one parameter in Eq. (19). A two-parameter roughness equation for R_S that covers the entire region between the limiting curves has been proposed (Underwood 1986) (and used incorrectly (Wojnar 1988)). The correct two-parameter equation is

$$R_S = [(4/\pi) - (4/\pi - 1)\Omega_{1,2}]R_L. \qquad (21)$$

$\Omega_{1,2}$ is the Degree of Orientation from Eq. (11).

APPLICATIONS

The procedures and relationships provided above can be used to analyze actual fracture surfaces. For example, it has been found that corrections of more than 100 percent must be applied

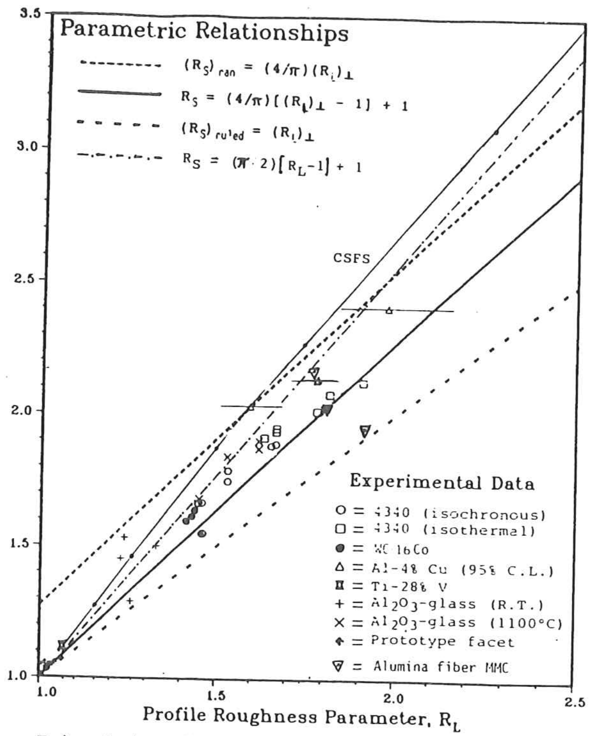

Fig. 6. (R_S, R_L)-plot of all known roughness data points and various limiting curves.

in some cases to the values obtained from uncorrected measurements of facets and dimples from SEM fractographs (Underwood 1986). Subtle effects can be detected by these quantitative methods, an example of which is the 500° C embrittlement temperature of 4340 steels revealed by roughness parameters (Banerji and Underwood 1984) and fractal dimensions (Underwood and Banerji 1987). In another application of roughness parameters, a modified fractal analysis of fracture profiles yields finite values of 'true' profile length and 'true' fracture surface area (Underwood and Banerji 1986).

Numerical results have been obtained for many typical fracture features. Among these may be listed facets (Underwood and Chakrabortty 1981), fatigue striations (Underwood 1984), crack traces (Underwood and Starke 1979, Underwood and Chakrabortty 1981), dimples (Underwood and Banerji 1985) and surface extrusions (Wang et al. 1982, Underwood 1983). Profile overlap parameters (Underwood 1990) are analyzed in detail, as are cells in foamed rubber (Underwood and Aloisio 1980), cavitation damage (Underwood 1984), composites (Drury and Underwood 1987) and anisotropy (Drury and Underwood 1987, Gokhale and Drury 1990). Upper-lower bounds to experimental (R_S,R_L) data plots are discussed (Underwood and Chakrabortty 1981), as well as parametric roughness equations (Underwood and Banerji 1983, Underwood 1987, Gokhale and Underwood 1989, Gokhale and Drury 1990). Serial sectioning (Underwood and Banerji 1983, Banerji and Underwood 1985) and profile angular distributions (Underwood and Chakrabortty 1981, Banerji and Underwood 1985, Gokhale and Drury 1990) are investigated. Important SEM correction equations (Underwood 1986a, Underwood and Banerji 1987) are provided in terms of roughness parameters. The parameters for degree of orientation (Underwood and Aloisio 1980, Underwood and Chakrabortty 1981) are applied to partially-oriented structures. Other applications based on these quantitative procedures can be devised as required.

SUMMARY

A general stereological treatment is presented here for the quantitative analysis of fracture surfaces. The experimental method of choice involves the use of profiles generated by vertical sections through the surface. It is shown how the important profile and surface roughness parameters, R_L and R_S, are related to basic quantities of stereology. The difference between directed and random measurements is stressed, as well as the precautions to observe when dealing with heterogeneous structures. Of basic importance are the parametric roughness equations that relate the surface and profile roughness parameters. The simple linear equation

$$R_S = (4/\pi)[(R_L)_\perp - 1] + 1$$

provides a good estimate of the surface roughness parameter, R_S, which contains the surface area. Knowing R_S and R_L permits the true spatial quantities to be calculated from measurements made on the flat SEM fractograph. Numerous applications of these methods to specific features in the fracture surface are listed.

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