Defense Technical Information Center Compilation Part Notice

ADP010906

TITLE: Self-Affine Scaling Studies of Fractography

DISTRIBUTION: Approved for public release, distribution unlimited

This paper is part of the following report:

TITLE: Paradigms of Complexity. Fractals and Structures in the Sciences

To order the complete compilation report, use: ADA392358

The component part is provided here to allow users access to individually authored sections of proceedings, annals, symposia, ect. However, the component should be considered within the context of the overall compilation report and not as a stand-alone technical report.

The following component part numbers comprise the compilation report:
ADP010895 thru ADP010929

SELF-AFFINE SCALING STUDIES ON FRACTOGRAPHY

J. M. LI, L. LU AND M. O. LAI

Department of Mechanical and Production Engineering
National University of Singapore
10 Kent Ridge Crescent, Singapore 119260
E-mail: mpeluli@leonis.nus.edu.sg

Applying variation-correlation method to images of fractography obtained from the scanning electron microscope (SEM), it has been found that there exists a fractal characteristic length within which the fractured surfaces are fractal. Investigation shows that the fractal characteristic length can represent the statistical maximum size of texture of the SEM image. Multi-magnification fractal analysis has shown that fractography cannot be described by a single fractal dimension but rather a series of fractal dimensions. Fractal study on the fractured surfaces of gray iron with different grain size has shown that there exists a positive relationship between tensile strength and fractal dimension. However, no essential relationship between impact toughness and fractal dimension for HP26Cr35Ni alloy could be obtained. Fractal dimension is sensitive to changes of mechanical properties caused by geometric factors such as grain size and is suitable to quantitatively describe the irregularity of fractography. For a given fracture mode, fractal dimension is not universal.

1 Introduction

Fracture phenomenon is one of the most intriguing areas in material science and engineering because it is associated with the life and safety of engineering parts. There is a lot of information related to fracture mechanism in fractography. Fractal based studies on fractography become important because of the problem of variance of conventional quantitative parameters with scales. During the last twenty years, many fractal-based methods for quantitative analysis on fractography have been developed. The methods can be categorized into the following three classes: (a) slit island analysis [1]; (b) profile analysis [1-5]; and (c) 3-dimensional (3D) surface analysis [6-8]. Among them, 3D surface analysis is the most interesting. The fractal characteristics of fracture surfaces and the relationship between fractal parameters and mechanical properties have been investigated using these methods. Some results justify that fractal dimension can be a measure of the toughness of a material [1, 9, 10]. On the other hand, some results have shown the existence of a universal value of fractal dimension for a given fracture mode. It has been conjectured that the value of fractal parameter α (α=3-D where D is fractal dimension) is 0.8 for ductile fracture [11] and 0.87 for brittle fracture [3]. These values imply that there is no correlation between fractal dimension and toughness because a universal value denies any dependence of fracture features on a specific toughness. In this paper, a new 3D surface model based on variation profile analysis has been introduced. Using this model, the fractal characteristics of different fracture modes and the correlation between fractal dimension and mechanical properties have been studied.

2 Experimental Procedures

A typical ductile fracture of microvoid coalescence was obtained by tensile testing a specimen of Assab 760 medium carbon steel. A transgranular cleavage mode was obtained by fracturing a Charpy V-notch specimen of the same steel after immersing it in the liquid-nitrogen for 60 minutes. Fracture of a pure Al_2O_3 ceramic specimen appeared to be brittle intergranular mode. To analyze the influence of geometric and non-geometric factors on fractal dimension of fractography, specimen A of gray iron was modified with 0.4%wt 75SiFe inoculation, while specimen B, with 0.3%wt FeSiCuMo metal stream inoculation to improve the graphite-eutectic microstructures. Tensile strength σ_b was obtained by tensile testing the various materials. A series of specimens of HP26Cr35Ni alloy with the size 4x4x35(mm) were taken from same regions of solidification. Thermal shocks before mechanical testing were carried out 0, 5, 10, 15 and 20 times. In the thermal shock, the specimens were heated to 1100°C for 10 minutes followed by water-quenching. After the thermal shock, impact toughness was obtained by impact testing without Charpy V-notch. The nominal compositions of these materials are listed in Table 1. All fracture surfaces were imaged by SEM followed by digitizing.

Table 1. Composition of materials investigated in wt%.

Materials	C	Si	Mn	P	S	Cr	Ni	Fe
760 steel	0.5	0.25	0.5					Bal.
Gray iron	3.0	0.12	0.7	<0.3	<0.05			Bal.
HP26Cr35Ni	0.55	2.5	2.0	<0.04	<0.04	26	35	Bal.

3 Variation-Correlation Method

The variation method has been introduced by Dubuc *et al* [4]. In this method, an ε-oscillation for the height function $h(x)$ of a profile, $v(x, \varepsilon)$, is defined as follows:

$$v(x,\varepsilon) = h_{\max}(x) - h_{\min}(x), \qquad |x - x_0| < \varepsilon, \tag{1}$$

The integral $V(\varepsilon)$ may be defined as:

$$V(\varepsilon) = \int v(x,\varepsilon)dx. \tag{2}$$

$V(\varepsilon)$ is termed the ε-variation. The limit of $V(\varepsilon)$ is zero for $\varepsilon \to 0$ due to continuity of the function h(x). The rate at which $V(\varepsilon)$ scales when $\varepsilon \to 0$ is:

$$V(\varepsilon) \propto \varepsilon^{2-D}, \tag{3}$$

which provides a method to calculate the fractal dimension D. The variation method can be interpreted as a numerical technique of box counting [4]. It has been demonstrated to be more accurate than any other techniques for fractal analysis of self-affine curves [4,5].

Based on variation method, a variation-correlation model for 3D surface has been developed [8]. In this model, it is assumed that $H(x,y)$ is a dimensionless field-like variable of a surface which may denote distribution of height or angle. If $H_{max}(x,y,\varepsilon)$ and $H_{min}(x,y,\varepsilon)$ are the local maximum and minimum of $H(x,y)$ in an ε-neighborhood respectively, a variation-correlation function $V_{cor}(\varepsilon)$ is defined as follows

$$V_{cor}(\varepsilon) = < [H_{\max}(x,y,\varepsilon) - H_{\min}(x,y,\varepsilon)]^2 > \tag{4}$$

The symbol <...> refers to two consecutive averaging operations. If the variation-correlation function $V_{cor}(\varepsilon)$ of the variable $H(x,y)$ on a surface obeys a power law in some significant range of scales $\varepsilon_{min} \leq \varepsilon \leq \varepsilon_{max}$, i.e.,

$$V_{cor}(\varepsilon) \propto \varepsilon^{2\alpha} \tag{5}$$

where the fractal parameter $\alpha = 3\text{-}D_{cor}$, the variation-correlation is called fractal variation-correlation function.

4 Results and Discussion

4.1 Fractal Characterization of Different Fracture Modes

The typical fracture modes of microvoid coalescence, transgranular cleavage and brittle intergranular fracture are shown in Fig.1 (a), (b) and (c). Fig.1 (d), which gives the V_{cor}-ε curves of these fracture surfaces, shows that the variation-correlation appears as lateral growth only within the range $\varepsilon < \varepsilon_{max}$. When $\varepsilon > \varepsilon_{max}$, the V_{cor}-ε curves appear to reach plateau value. These observations imply that the following short- and long-range relationships of variation-correlation versus scale are true

$$V_{cor}(\varepsilon) \propto \begin{cases} \varepsilon^{2\alpha} & \varepsilon << \varepsilon_{max} \\ V_{max}^2 & \varepsilon >> \varepsilon_{max} \end{cases} \tag{6}$$

From Eq.(6), the log-log plot of V_{cor} versus ε should be a straight line in the short-range of scales, of which the slope is different from that in the long-range of scales. To estimate ε_{max}, a linear measure M_F is introduced as follows

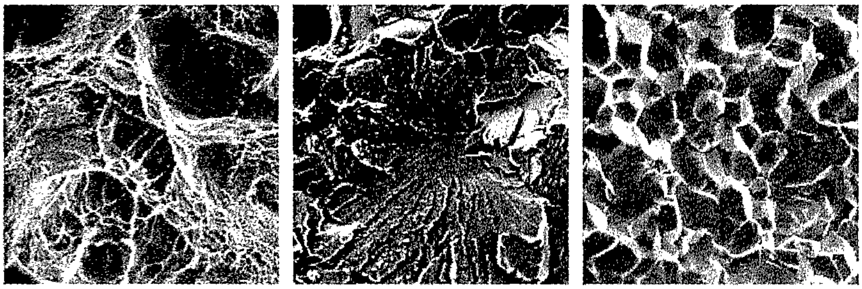
$$M_F = \frac{1-\delta}{1+\delta} \tag{7}$$

where δ is the degree of disperse expressing the fluctuation of the set of points (x_i, y_i) from the fit line. δ is defined as

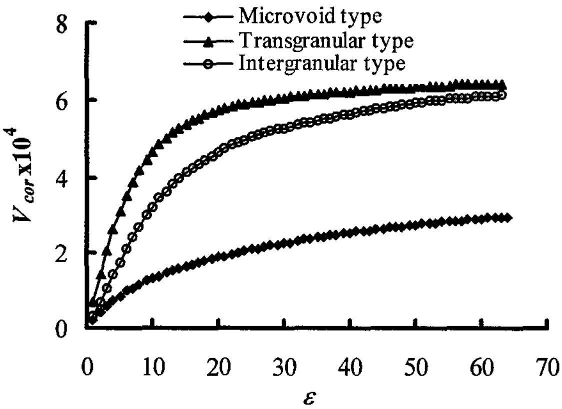
$$\delta = \sqrt{\frac{\beta - \rho^2}{\beta}}$$

where

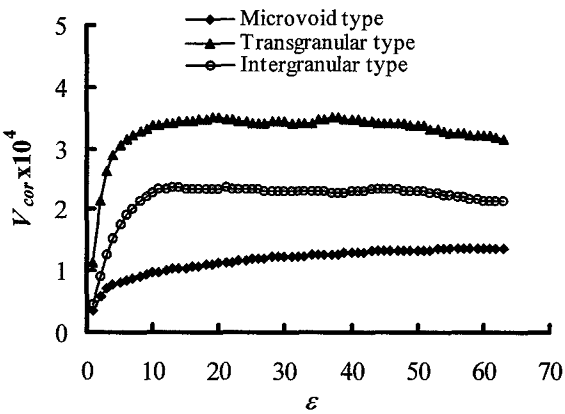
$$\rho = \frac{\sum_{i=1}^{N}(x_i - \bar{x})(y_i - \bar{y})}{\sum_{i=1}^{N}(x_i - \bar{x})^2} \qquad \beta = \frac{\sum_{i=1}^{N}(y_i - \bar{y})^2}{\sum_{i=1}^{N}(x_i - \bar{x})^2}$$



(a) (b) (c)



(d)



(e)

Fig.1. SEM fractography and fractal characteristics. (a) Microvoid fracture; (b) Transgranular cleavage fracture; (c) Brittle intergranular fracture; (d) Variation-correlation versus scale curve based on variation-correlation analysis; (e) Height-correlation versus scale curve base on height-height correlation analysis. The resolution of the images is 68.75μm/200pixels.

The value of M_F falls in the range between 0 and 1. When M_F tends to 1, the distribution of the points (x_i, y_i) is perfectly linear. When M_F tends to 0, the distribution becomes non-linear. Table 2 shows the values of D and ε_{max} estimated with M_F=0.7, while the correlation coefficient r of log-log plot is over 0.98, indicating M_F is a better linear measure than r.

Table 2. The estimation of fractal parameters and the maximum size d_{max} of the basic micro-morphology element on the fractography

Fractography	Variation-correlation				Height-height correlation				D_{max}
	D_{cor}	ε_{max}	r	M_F	$D_{h\text{-}h}$	ε_{max}	r	M_F	
Microvoid type	2.58	64	0.984	0.7	2.68	5	0.982	0.7	75
Transgranular type	2.54	17	0.983	0.7	2.58	5	0.972	0.7	31
Intergranular type	2.44	26	0.983	0.7	2.33	10	0.982	0.7	35

The above results confirm that there exists a characteristic length ε_{max} so that the log-log plot of variation-correlation is linear within ε_{max} for the fractography of a real material. Different from an ideal self-affine profile, for example, Weierstrass-Mandelbrot curve whose V_{cor} appears as lateral growth at all possible scales, the morphologies of fracture of real materials are constituted by those basic micro-morphology elements such as dimples, cleavage facets or boundary facets. The basic micro-morphology elements are affine at a limited scale, to form the texture of SEM images. Assuming that V_{max} is the expected value of maximum variation of the texture at all possible scales, V_{max} is bounded within a scale range ($\varepsilon < \varepsilon_{max}$) because of the affinity and periodicity of the fractography textures. Therefore, this characteristic length is associated with the statistical maximum size of the fractography textures. When the measuring scale ε is greater than ε_{max}, the largest and smallest values on the fractography are always included, resulting in $V_{cor}(\varepsilon)=V^2_{max}$.

From the data shown in Table 2, the value of D_{cor} for ductile fracture is the largest, while for brittle intergranular fracture, is the smallest. The results are well in agreement with the irregularity of these fracture surfaces. Fig.1 shows some small dimples are located inside the larger ones. The fractured surface experiences a large amount of ductile deformation and hence dimples at different scales are formed. Such fracture surface has multi-scaling similar structures leading to large ε_{max}, within which variation-correlation follows a lateral growth with the increasing scale. It must be noted that a large ε_{max} does not necessarily mean multi-scaling similar structures, because it is a parameter related to the maximum size of the surface texture. For the brittle intergranular fracture, the fractography is constituted by smooth boundary facets, resulting in a decrease in D_{cor}. The irregularity of the transgranular cleavage fracture is medium in spite of the rather rugged surface because of the smoothness of the surface of each grain.

For the sake of comparison, the curves of height correlation versus scale using height-

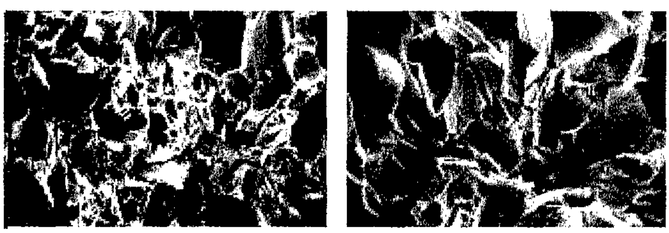
height correlation analysis [12-15] are also shown in Fig.1 (e). The height-height correlation function $C(\varepsilon)$ is defined as

$$C(\varepsilon) = < h(\varepsilon) - h(0) >$$

where $h(0)$ is the height of reference point and $h(\varepsilon)$, the height of the points with ε distance from the reference point. The estimated values of the fractal parameters are shown in Table 2. Fractal dimensions from height–height correlation appear the same tendency as those from variation-correlation in characterizing the irregularity of the fracture surfaces. However, the characteristic length ε_{max} in the height-height correlation analysis represents the correlation length [12-15] but not the size of texture. Consequently, the fractal characteristic length ε_{max} in variation-correlation analysis is a more suitable parameter in quantitative fractography because its estimated value is able to represent the maximum size $d_{\max}$ of the basic micro-morphology elements. Consider a simple case of brittle intergranular fractography, which simply consists of uniform morphology elements with maximum diameter $d_{\max}$. In variation-correlation analysis, when $d_{\max}/2 \leq \varepsilon < d_{\max}$, some estimated values of variation in statistical measurement have already reached the value of $V_{\max}$. When $\varepsilon \geq d_{\max}$, all the estimated values of variation are $V_{\max}$. Therefore, when $\varepsilon \geq d_{\max}/2$, the linearity of the log-log plot becomes worse so that the estimated value of ε_{max} falls into $[d_{\max}/2, d_{\max}]$ while its fluctuation depends on the given value of M_F. The results in Table 2 hence verify the validity of the analysis. Therefore, the fractal characteristic length can be employed as a statistical measure of the maximum size of texture of fracture surfaces.

4.2 Relationship between fractal dimension and mechanical properties

Fig.2 shows the SEM fractography and the multi-magnification fractal curves for the gray iron. Specimen A has been modified by FeSiCuMo metal stream inoculation. Thus, microstructures of the matrix and graphite structures were improved, leading to an increase in tensile strength σ_b (σ_b=314MPa for sample A and 255MPa for sample B). The elongation for gray iron is almost zero. The size of graphite and graphite-eutectic cells is a



(a) (b)

Fig.2. SEM fractography of samples A and B of gray iron. (a) SEM fractography of sample A; (b) SEM fractography of sample B. The resolution of the images is 421μm/160pixels.

very important geometric factor. Small grains will lead to multi-scaling fractal structures of the material and the fracture surface becomes more complicated. The cleavage facets of specimen A, which is associated with grain size, are smaller than those of specimen B, leading to the more complicated fractured surface as shown in Fig.2 (a). This implies that the fractal dimensions of specimen A is larger than that of specimen B. Fig.3 is the curve of fractal dimension versus SEM magnification, which verifies this analysis. Fig.3 shows that the fractography cannot be described by a single but rather a series of fractal dimensions. It also reveals that the fractography is not ideally self-affine at all scales of SEM. The transgranular cleavage fracture, for example, shows cleavage facets as dominant morphology at low magnification and river patterns as dominant morphology at high magnification, implying that fractal dimension for a given mode is not universal.

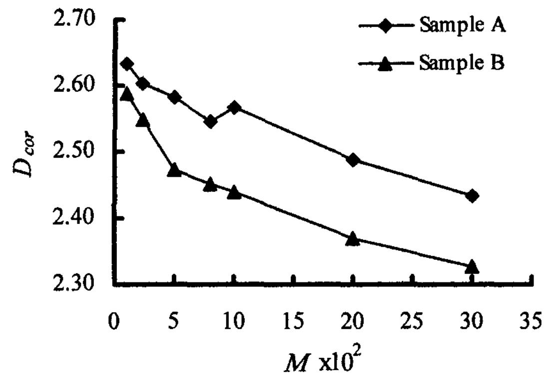
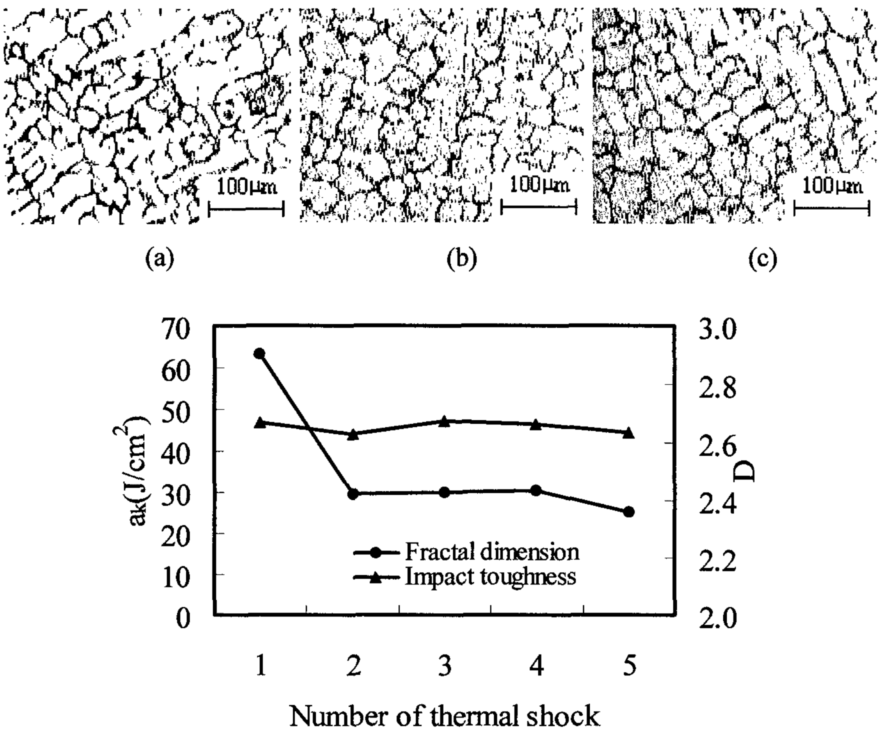


Fig.3. Fractal dimension D_{cor}-magnification M curves of samples A and B.

Fig.4 shows the austenitic dendrite structures of HP26Cr35Ni alloy. Because the specimens were taken from the same region of solidification, the distribution and size of austenitic dendrites of all the specimens are the same even though they have been subjected to different thermal shocks. Their impact toughness, however, is different from each other due to the formation of micro-cracks during the thermal shock treatment. Fractal measurements in Fig.4 (d) show that there is no significant difference in the fractal dimensions of the specimens under different thermal shocks. Therefore, there is no direct correlation between fractal dimension and toughness when the change in toughness is caused by non-geometric factors.

The present experiment has shown that fractal dimensions of fractography at SEM scales are not a single value but rather a series of values for a given fracture mode. This is because of the different dominant patterns of fractography in different range of magnifications. It can be deduced that when the magnification is high enough, the fractal dimension will tend to 2 because the micro-morphology elements approximately become 2D surfaces. The irregular geometric structures of fracture surfaces can reflect the state of the energy absorbed by the fracture surface due to the formation of new surfaces. If the change in toughness is only result of the irregularity of the fracture surface, the fractal can be employed.



(d)

Fig.4. Microstructures, impact toughness and fractal dimension of HP26Cr35Ni alloy specimens subjected to thermal shock of different times. (a) The origin microstructure; (b) microstructure with 10 times of thermal shock; (d) microstructure with 20 times thermal shock; (d) changes in impact toughness and fractal dimension with number of thermal shock.

5 Conclusions

The variation-correlation of fracture surfaces imaged by SEM has been found to follow a power law only within a limited range of scale of $\varepsilon < \varepsilon_{max}$. Beyond this range, the variation-correlation tends to be a constant. The scaling properties can be expressed by

$$V_{cor}(\varepsilon) \propto \begin{cases} \varepsilon^{2\alpha} & \varepsilon << \varepsilon_{max} \\ V_{max}^2 & \varepsilon >> \varepsilon_{max} \end{cases}$$

Fractal dimension of fractography at SEM scales is not a single value but rather a series of values for a given fracture mode. There exists a positive correlation between fractal dimension and toughness of the materials when the change in toughness is caused by geometric factors. However, if the change in toughness is caused by non-geometric factors such as micro-cracks, there is no essential relationship between impact toughness and fractal dimension. For a given fracture mode, fractal dimension is not universal.

References

1. Mandelbrot B. B, Passoja D.E. and Paullay A.J., Fractal Character of Fracture Surfaces of Metals, Nature. 308(1984) pp.721-722.
2. Underwood E. E. and Banerji K., Invited Review Fractal in Fractography, Material Science and Engineering. 80(1986), pp.1-14.
3. Måløy K. J., Hansen A., Lhinrichsen E. and Roux S., Experimental Measurements of the Roughness of Brittle Cracks, Physics Review Letter. 68(1992), pp.213-215.
4. Dubuc B., Quinion J. F., Roques-Carmes C., Tricot C. and Zucker S.W., Evaluating the Fractal Dimension of Profiles, Physics Review. A39(1989), pp.1500-1512.
5. Miller S and Reifenberger R. J., Improved Method for Fractal Analysis Using Scanning Probe Microscopy, Journal o Vacuum Science and Technology. B10(1002), pp. 1203-1207.
6. Denley D. R., Practical Applications of Scanning Tunneling Microscopy, Ultramicroscopy. 33(1990), pp.83-92.
7. Friel J. J. and Pande C. S., A Direct Determination of Fractal Dimension of Fractal Surfaces Using Scanning Electron Microscopy and Stereoscopy, Journal of material Research. 8(1993), pp.100-104.
8. Li J. M., Lu L. Su Y. and Lai M. O., Fractal-Based Description for the Three-Dimensional Surface of Materials, Journal of Applied Physics. 86(1999), pp.2526-2532.
9. Mu Z. Q. and Long C. W., Studies on the Fractal Dimension and Fracture-Toughness of Steel, Journal of physics D: Applied Physics. 21(1988), pp.848-850.
10. Long C.W. and Mu Z. Q., Fractal Dimension Measured with Perimeter-Area Relation and Toughness of Materials, Physical Review. B38(1988), pp.11781-11784.
11. Bouchaud E., Lapasset G. and Planes J., Fractal Dimension of Fractured Surfaces: a Universal Value? Europhysics letters. 13(1990), pp.73-79.
12. Yang H. N., Wang G. C. and Lu T. M., Diffraction from Rough Surface and Dynamic Growth Fronts. Singapore: World Scientific, 1993.
13. Yang H. N., Wang G. C. and Lu T. M., Instability in Low-Temperature Molecular-Beam Epitaxy Growth of Si/Si(111), Physical Review Letters. 73(1994), pp.2348-2351.
14. Palasantzas G. and Krim K., Scanning Tunneling Microscopy Study of the thick Film Limit of Kinetic Roughening, Physical Review Letters. 73(1994), pp.3564-3567.
15. Krim J. and Palasantzas G., Experimental Observations of Self-Affine Scaling and Kinetic Roughening at Sub-micron Lengthscales, International Journal of Modern Physics. B9(1995), pp.599-632.