

Fractal Characterization of Shot-Peened Surfaces

By: Yoshiki Oshida¹, Tatsuyuki Seno², Tadashi Nishihara³, and Akitoshi Itoh⁴.

¹ Department of Dental Materials, Indiana University School of Dentistry, Indianapolis, Indiana U.S.A.

² Thermotech Division, Dowa Mining Co., Yokohama Japan

³ Department of Mechanical Engineering, Kokushikan University Faculty of Engineering, Tokyo Japan

⁴ Department of Mechanical Engineering, Gunma University Faculty of Engineering, Gunma Japan

Presented at the joint Europe-USA seminar on Shot Peening 29-30 Sept. 1992, Cincinnati, Ohio, USA - 14 Oct. 1992, Grenoble, France.

Abstract

There are several methods to determine the coverage of shot-peening; (1) direct methods (visual methods, the Straub method, the Peenscan method), (2) indirect method (the Valentine method), or (3) simply the percent coverage is estimated from the curve of Almen arc height against the duration of shot exposure.

In this study, a novel method is proposed. Shot-peened surfaces of quench-tempered steel were subject to the Fractal Dimension Analysis to determine the degree of the coverage. Using steel shots and controlling the impingement time, four levels of coverage were pre-determined; namely, 60%, 110%, 225%, and 450%. Surface roughnesses were measured on samples shot-peened with four different pre-determined coverages. The "box counting method" was employed on surface roughness profiles to determine the Fractal Dimension (D_f).

It was found that D_f decreased linearly from the as-machined condition up to the pre-determined coverage of 225%, and once D_f reached 1.22 ($\approx \log_4/\log_3$ in the Koch curve), it remains constant. Therefore, it is suggested that the optimum coverage value (i.e., about 200%) can be determined by monitoring changes in D_f parameter on shot-peened surfaces.

Keywords: Shot-peening, Coverage, Cr-Mo steel, Fractal dimension, Koch's curve, Richardson box counting method.

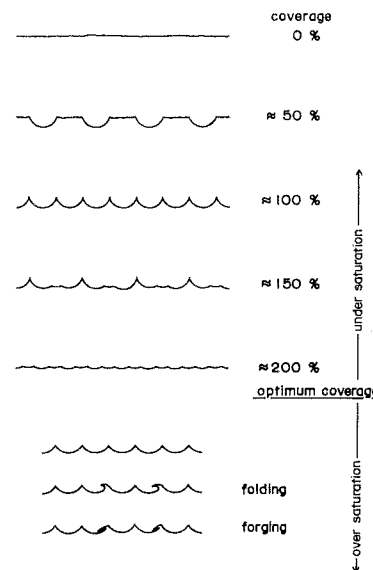
Introduction

Shot peening is a type of cold working by which compressive stresses are induced in surface layers of metallic parts by the impingement of shot stream. The major purpose of shot peening is to increase fatigue strength as well as fatigue life [1, 2]. The process has other useful applications, such as relieving tensile stresses that contribute to stress-corrosion cracking, forming and straightening of metal parts, testing the adhesion of silver plate on steel, reducing the coefficient of friction [3], and enhancing the surface wettability of biomedical prostheses [4].

To ensure to operate shot peening at its best beneficial and optimal conditions, a sufficient and necessary value of surface coverage is needed to be controlled and determined. Of

course, one cannot expect above effects at an under-coverage condition. If shot peening is operated at an over-coverage condition, a part of craters's peripheries of indents will be folded and forged by a succeeding shot stream, providing a potential crack initiation sites during a fatigue stressing. This might be due to partially localized work-hardened fragments of work piece (see Fig. 1).

Several methods are proposed to determine the optimum coverage; namely direct methods (visual and the Straub methods) and indirect methods (such as the Valentine method) [5]. Visual methods, not quantitative, are widely used and consist of visual inspection under an optical (10X) magnification of the peened surface. Another visual method is related to the replica method of the peened surfaces. The Straub method consists of tracing the images of the indented areas on translucent paper, and measuring the total area and the



the indented area with a planimeter. Percentage of coverage is expressed as the ratio of indented area to total area multiplied by 100. Peenscan method (MIL-S-13165-B Amendment 2) consists of painting a part before peening with a dye sensitive to ultraviolet light, inspecting the part under the ultraviolet light for any missed areas, and re-inspecting the part under ultraviolet light. Complete removal of the dye indicates 100% coverage of the part. The Valentine method consists of making a duplicate of the part from low-carbon steel, annealing the peened parts for several hours to promote recrystallization and grain growth, and relating peening coverage to the amount and continuity of grain growth, by metallo-graphic examination of cross sectional area [5]. Because of the difficulty in quantitatively measuring coverage by these methods, coverage is usually estimated from the curve of Almen arc height against the duration of shot exposure.

In this study, a novel method by using the Fractal dimension concept is proposed to determine the percentage coverage of shot-peened surfaces.

Fractal Dimension

We are accustomed to the Euclidian dimension (d) of 0, 1, 2, and 3, which respectively correspond to a dot, line, a surface, and three-dimensional objects. In reality, however, many geometrical shapes do not quite fit into one of these categories.

Fractals are a new geometric concept, whose primary object is to describe the great variety of natural structures that are irregular, rough or fragmented, having irregularities of various sizes that bear a special “scaling” relationship to one another [6]. Namely, it is “self similar” over a wide range of scale [7]. To accommodate such geometries, Mandelbrot introduced the ideal of intermediate Fractal dimension, $D_f (>d)$ [6, 7] such that $2 \leq D_f \leq 3$; the higher the D_f value, the rougher the surface; while for a line, $1 \leq D_f \leq 2$. Rough surfaces are also known to exhibit the feature of geometric self-similarity and self-affinity [6, 8, 9, 10, 11], by which similar appearances of the surface are seen under various degrees of magnification [12]. Since increasing amounts of detail in the roughness are observed at decreasing length scales the concept of slope and curvature, which inherently assume the smoothness of a surface, cannot be defined. Hence, it is necessary to characterize rough surfaces by intrinsic parameter which are independent of all scales of roughness [12]. This suggests that the Fractal dimension, which is invariant with length scales and is closely linked to the concept of geometric self-similarity, is an intrinsic property and should be used for surface characterization [12]. The D_f satisfies the properties of continuity, non-differentiability and self-affinity [12, 13].

There are several ways to define the Fractal dimension; e.g., slit island method [7], vertical section method [14], or box counting method [15]. It was reported that the D_f obtained by the slit island method provided the same value as the D_f obtained by the vertical section method after the Fourier analysis [14]. In this study, the box counting method was employed because this method has an easy access to a computerized data acquisition and processing.

One can find various applications of the fractal analysis in surface science and engineering fields. Surface sciences on a surface adsorption phenomena [16], sandstone porosity [17], fine particle profiles [18], or wettability [19] utilized the Fractal dimension. Fracture surface of ductile materials were extensively characterized by the D_f [7, 14, 20, 21, 22, 23, 24]. Surface fracture topology of brittle materials was also studied by the Fractal dimension [25]. Application of the Fractal analysis to the tribological phenomena can be found in various articles [26, 27, 28].

Fractal concept has been successfully employed to characterize metallographic features [29, 30, 31, 32]. One of the authors (TN) had employed the Richardson plot method to characterize the spark test patterns and to relate D_f to carbon contents in steels [29].

The rough surface and surface texture of various materials were analyzed by the Fractal dimension [8, 12, 33]. Majumdar et al., studying the machined stainless steel surface, found that the $D_f = 1.5$ and the power spectra indicated the power law of $1/\omega^2$, which corresponds to a Brownian process [12]. Furthermore, Chesters et al., using a contact diamond stylus profilometer to characterize the surface of stainless steel with various surface finishes, reported that $D_f = 1.3 \sim 1.9$ for as-machined condition, $1.1 \sim 1.2$ for electropolished surface and $1.2 \sim 1.7$ for chemically polished surfaces. It was also found that the higher R_a (arithmetic average roughness) and R_m (its largest single deviation, the higher D_f [8].

Test Materials and Procedures

1. Test Material

The test material was SCM 420 steel ($0.9 < Cr < 1.2$, $0.15 < Mo < 0.35$, $0.38 < C < 0.43$). The test piece has a dimension of 30 mm wide, 15 mm thick and 120 mm long. The test piece was carburized, water-quench and tempered. The hardness of the tempered martensite was $H_{RC} 61.0$.

2. Shot Peening

The used shot was SB-6PH (from Shintoh Brader Co.; $0.89\%C$, $0.80\%Si$, $0.82\%Mn$, $0.023\%P$, $0.026\%S$), tempered martensitic microstructures. The hardness of shot was $H_{RC} 59.8$ (ranging between 54.7 and 62.5). Shot size distribution was 0.9% in grid size of 0.85 mm, 74.3% in 0.710 mm, 24.3% in 0.600 mm and 0.5% in 0.500 mm all in weight, respectively. By controlling the impingement time and using a nozzle type machine, the four levels of coverage were pre-determined; namely, 60%, 110%, 225%, and 450%.

3. Surface Roughness Measurement

The surface roughness meter Model SP-11 with a probe (SE-3E, Kosaka Manuf.), was employed for measuring the surface roughness. This device has an accuracy of $\pm 3\%$ (in R_{max}). Referring to Fig. 2, it was observed that a diameter of the effective cone size of projected shots was 50 mm. The center line was marked after shot peening. Three additional lines were also marked, 5 mm, 10 mm, and 15 mm, from the center line. Roughnesses were measured on these four lines, which are perpendicular to the machining direction.

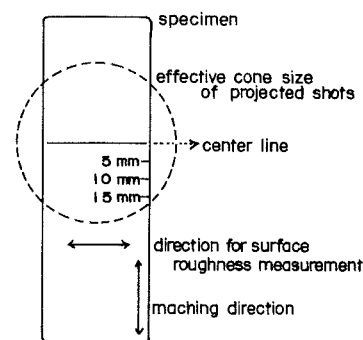


Fig. Locations for surface roughness measurements

4. Determination of the Fractal Dimension

According to the box counting method (a Richardson plot), the box size, r , can be related to the box number, $N(r)$, in a formula of $N(r) \propto r^D$. The slope of a log-log plot of r and $N(r)$ is the Fractal dimension, D_f , of the profile. In this study, four scales (r) were prepared; 1×1 mm, 3×3 mm, 5×5 mm, and 10×10 mm. Each scale was superimposed onto the obtained surface roughness profiles to count the boxes, $N(r)$.

Results and Discussions

Fig. 3 shows the roughness profile of as-machined surface prior to shot peening. The D_f was 1.38. As described previously, D_f of machined surface of stainless steel was reported 1.5 [12] and 1.3 ~ 1.9 [8]. Hence, the D_f 1.38 of Cr-Mo steel was in agreement with those reported D_f s for stainless steel.

Fig. 4 shows surface roughness profiles, obtained at the center line of Fig. 2, for four differently pre-determined coverages. Fig. 5 shows surface textures of shot-peened steel at the center line and two other locations away from the center line.

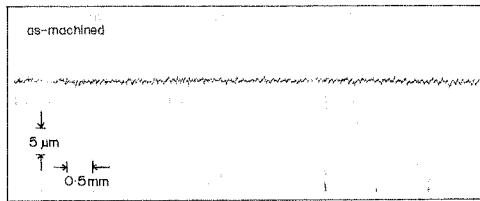


Fig. 3 Surface profile of as-machined condition

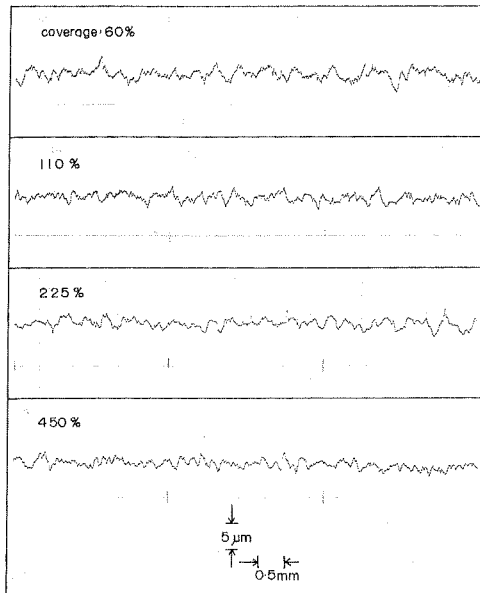


Fig. 4 Surface profiles shot-peened surfaces, measured at a center line in Fig. 2

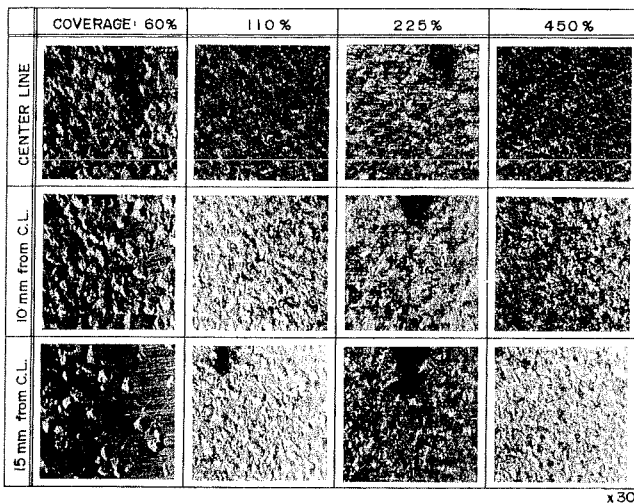


Fig. 5 Surface textures of shot-peened steel

Four different locations (see Fig. 2) exhibit different D_F s as expected, as seen in Fig. 6. As also found in Fig. 5, any locations except the center line were not completely shot-peened. Hence, D_F value obtained from the center line was decided to use to define the optimal coverage. As seen in Fig. 7, D_F value at the center line decreased continuously from the as-machined unpeened condition to the pre-determined coverage of 225%. It is believed that the 200% coverage is generally recommended in an engineering practice. Although D_F did not alter beyond the coverage of 200% as seen in Fig. 7, the 400% coverage is not practical, this is over-covered.

Of the most interest is that $D_F = 1.22$ obtained at the center line at coverage of 200%. This value is very close to $D = \log 4 / \log 3 (=1.2618)$ which is a basic Koch curve, dating back to 1904. It is, therefore, suggested the shape and its distribution of

used shots were uniform and shot peening itself was performed properly.

The surface roughness and its characteristic D_F are influenced by many factors including relative hardness of a workpiece and shots, type and shape of shots, energy level, etc. Hence, further studies are needed to complete this novel method for determination of the shot peening coverage.

Conclusion

The quench-tempered Cr-Mo steel was shot-peened. Shot peened surfaces were subjected to surface roughness measurements. Fractal dimension, D_F , was obtained by the box counting method on surface roughness profiles under various pre-determined coverages. Within limited number of data, the following conclusions can be made:

1. Fractal dimension, D_F , can serve as a novel indicator to determine the optimum coverage of shot peening operation.
2. For the Cr-Mo steel shot peened with equivalent hardness of steel shots, D_F decreased continuously from 1.38 for the as-machined unpeened surface to 1.22 for the coverage 200%.
3. The obtained D_F 1.22 was very close to the Koch's curve ($D = \log 4 / \log 3 = 1.26$), indicating uniformities of both used shots and coverage.

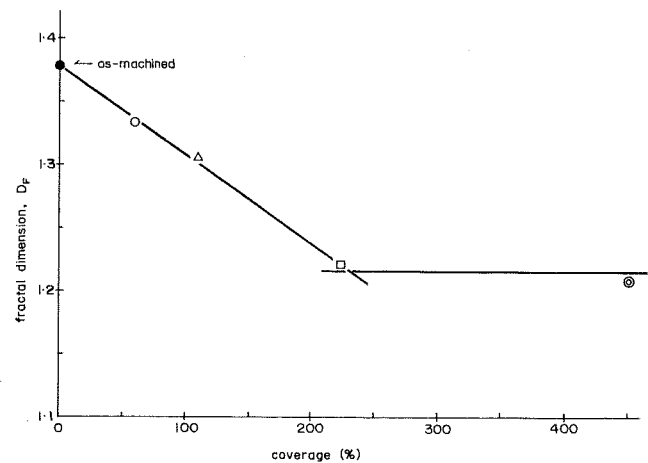


Fig. 7 Changes in D_F as a function of pre-determined coverage

Acknowledgments

The support by the Iketani Science and Technology Foundation (Grant No. 031052B) and by the IUPUI (Indiana University Purdue University at Indianapolis) Faculty Development (Grant No. 22-761-63) are gratefully acknowledged.

References

- [1] Oshida Y, Daly J: in *Surface Engineering* ed. by Meguid SA, Elsevier Applied Science, London, 404;1990.
- [2] Oshida Y, Daly J: *Proc. Int'l Conf. on Shot Peening (ICSP-4)*, 317;1990.

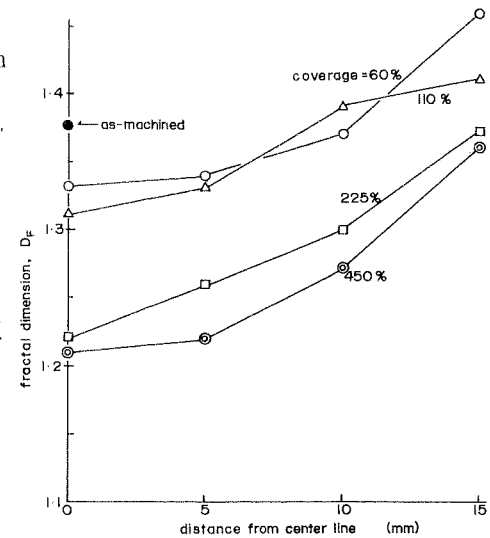


Fig. 6 Changes in D_F as a function of distance from the center line

- [3] Oshida Y, Sachdeva RCL, Miyazaki S: *Biomedical Materials and Engng*, in press; 1992.
 - [4] Oshida Y, Sachdeva RCL, Miyazaki S, Daly J: *Jour. of Materials Science: Materials in Medicine*, in press 1992.
 - [5] American Society for Metals: *Metals Handbook*, 5:138;1989.
 - [6] Mandelbrot BB: *The Fractal Geometry of Nature*, Freeman, NY 1983.
 - [7] Mandelbrot BB: Passoja DE, Paullay AJ: *Nature*, 308:721; 1987.
 - [8] Chesters S, Wen HY, Lundin M, Kasper G: *Applied Surface Sci.* 40:185;1989.
 - [9] Mayak PR: *Jour. Lubr. Technol.*, 93:398;1971.
 - [10] Sayles RS, Thjomas TR: *Nature*, 271:431;1978.
 - [11] Peitgen HO, Saupe D: *The Science of Fractal Images*, Springer N.Y.; 1988.
 - [12] Majumdar A, Tien CL: *Wear*, 136:313;1990.
 - [13] Berry MV, Lewis ZV: *Proc. R. Soc., London A*, 370:459;1980.
 - [14] Pande CS, Richards LE, Louat N, Dempsey BD, Schwoeble JA: *Acta Metall*, 35:633;1987.
 - [15] Richardson LF: *General Systems Yearbook*, 6:139;1961.
 - [16] Pfeifer P, Avnir D, Farin D: *Surf Sci.*, 126:569;1983.
 - [17] Katz AJ, Thompson AH: *Phys. Rev. Lett.*, 54:1325;1985.
 - [18] Kaye BH: *Powder Technol.*, 21:1;1978.
 - [19] Hazlett RD: *Jour. Colloid and Interface Sci.*, 137:527;1990.
 - [20] Hornbogen E: *Jour. Mater Sci.*, 21:3737;1986.
 - [21] Rosenfield AR: *Scripta Metall.*, 21:1359;1987.
 - [22] Coster M, Chermant JL: *Jour. Mater Sci.*, 14:509;1979.
 - [23] Underwood EE and Banerji K: *Mater Sci. Eng.*, 80:1;1986.
 - [24] Dauskardt RH, Hanbensak F, Ritche RO: *Acta Metall.*, 38:143;1986.
 - [25] Mecholsky JJ, Passoja DE, Fenberg-Ringel KS: *Jour. Am. Ceram. Soc.*, 72:60;1989.
 - [26] Ling FF: *Tribology Trans.*, 32:497;1989.
 - [27] Stupak PR, Donovan JA: *Jour. Mater Sci.*, 23:2230;1988.
 - [28] Majumdar A, Bhushan B: *Jour. of Tribology*, 112:205;1990.
 - [29] Nishihara T: *Heat Treatment* 29:99;1989.
 - [30] Hornbogen E: *Zeit. Metallkunde*, 78:622;1987.
 - [31] Hornbogen E: *Int'l Materials Rev.*, 34:277;1989.
 - [32] U-Schmidt H: *Prakt Met.*, 25:3;1988.
 - [33] Keller JM, Chen S. Crownover: *Computer Vision, Graphics, and Image Processing* 45:150;1989.
-