Microstructural analysis of robot laser and induction hardened specimens with fractal geometry

Matej Babič
Ph.D. Researcher
Slovenia
babicster@gmail.com

***Abstract*—Mathematics and computer science are very useful in many other sciences. We use the mathematical method of fractal geometry in engineering, and specifically in laser techniques. Moreover, with fractal geometry we analysed the complexity of robot laser hardened specimens. We analysed specimens hardened with different robot laser cell parameters, namely the two parameters of speed v ∊ [2, 5] mm/s and temperature T ∊ [1000, 1400] °C. Robot laser surface-hardening heat treatment is complementary to conventional flame or inductive hardening. A high-power laser beam is used to heat the metal surface rapidly and selectively to produce hardened case depths of up to 1.5 mm, with the hardness of the martensitic microstructure providing improved properties such as wear resistance and increased strength. Induction hardening is a form of heat treatment in which a metal part is heated by induction heating and then hardening. Fractal patterns are observed in computational mechanics of elastic-plastic transitions. Fractal dimensions were calculated using image processing of SEM micrographs in combination with the implementation of a box-counting algorithm using ImageJ software. Also, fractal dimensions were used to describe the hardness of the hardened specimens. We found a relationship between fractal dimension and hardness. We compared the fractal structure of robot laser hardened and induction hardened material of DIN standard 1.7225. We determined which method of hardening gave the best result, and compared the fractal structure and hardness graphically.**

Keywords— Robot, laser, inductive, hardening, fractal geometry

I. INTRODUCTION

In fractal geometry [1], the fractal dimension, *D*, [2-4] is a statistical quantity that gives an indication of how completely a fractal appears to fill space as one zooms down to finer and finer scales. A fractal surface consists of many complicated zigzag planes. Recently, the concept of the fractal dimension has been applied to the analysis of these surfaces. There are many specific definitions of fractal dimension. The most important theoretical fractal dimensions are the Rényi dimension, the Hausdorff dimension, and the packing dimension. In practice, the box-counting dimension and the correlation dimension are widely used, partly due to their ease of implementation. In a box-counting algorithm the number of boxes covering the point set is a power law function of the box size. The fractal dimension is estimated as the exponent of this power law. Although for some classical fractals all these dimensions do coincide, in general they are not equivalent. The fractal dimension means self-similarity in mathematics and its value has been used to estimate the irregularity of fractured surfaces in materials science. Fractals are a new branch of mathematics [5] and art. Perhaps this is the reason why most people recognize fractals only as pretty pictures useful as backgrounds on the computer screen or original postcard patterns. Most physical systems of nature and many human artefacts are not regular geometric shapes of the standard geometry derived from Euclid. Fractal geometry offers almost unlimited ways of describing, measuring, and predicting these natural phenomena. Fractal structures can be found in robot laser hardened [6-10] patterns too when they are observed by electron microscopy. This report deals with some 1.7225 hardened alloys tested at room temperature, and the correlation between the fractal dimension and fracture [11] strength has been studied.

Fig. 1: Robot laser cell for hardening

II. MATERIAL PREPARATION AND METHODS

A. *Material Preparation*

Our study was limited to tool steel of DIN standard 1.7225. The chemical composition of the material was 0.38 to 0.45% C, 0.4% maximum Si, 0.6–0.9% Mn, 0.025% maximum P, 0.035% maximum S, and 0.15–0.3% Mo [12]. The specimen test section was in a cylindrical form with dimensions of 25 × 10 mm. After hardening, we polished and etched all specimens. Detailed characterization of their microstructure before and after surface modifications was conducted using a JEOL JSM-7600F field emission scanning electron microscope (SEM). We used the program ImageJ (available from the National Institute of Health, USA) to analyse these pictures.

Fig. 2: Inductor for induction hardening

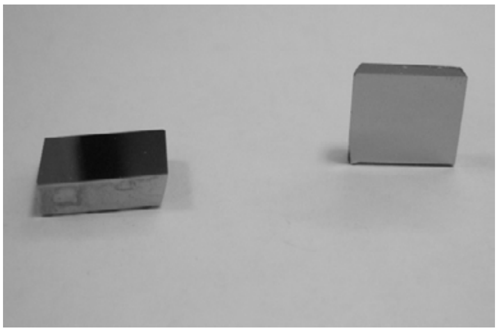

Fig. 3: Hardened specimens

Fig. 4: Etching and polishing of specimens

Step 5: SEM imaging

Figure 3 presents hardened material of DIN standard 1.7225. In Fig. 6 we can see the fractal structure of robot laser hardened specimens, and in Fig. 7 the fractal structure of inductive hardened specimens.

The microstructures of robot laser and induction hardened specimens of material of DIN standard 1.7225 were compared. The microstructure and fractures were observed by SEM.

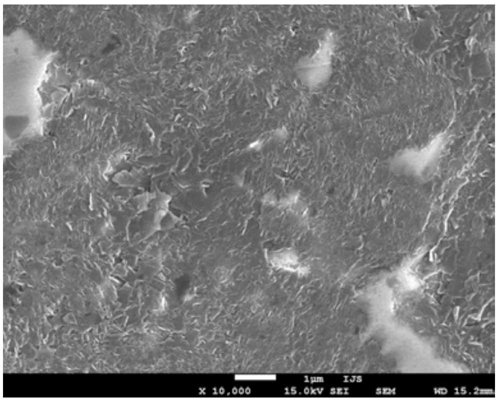

Fig. 6: Fractal structure of robot laser hardened 1.7225 specimens

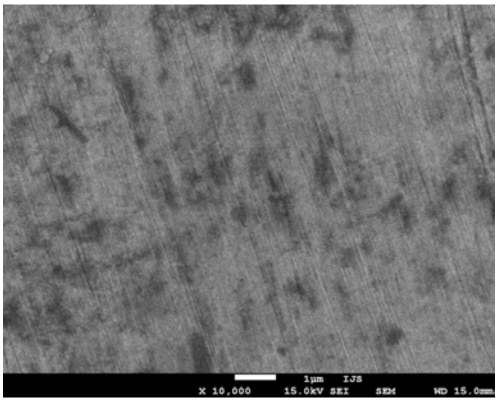

Fig 7: Fractal structure of induction hardened 1.7225 specimens

B. *Experimental Method*

The SEM pictures were converted into binary images (Fig. 8), from which we calculated the fractal dimension. The relationship between the fractal dimension D, volume V, and length L can be expressed as follows:

$V \sim L^D$ (1)

Fractal dimensions were determined using the box-counting method, which has been proven to have a higher calculation speed and greater accuracy by Dougan [13] and Shi [14].

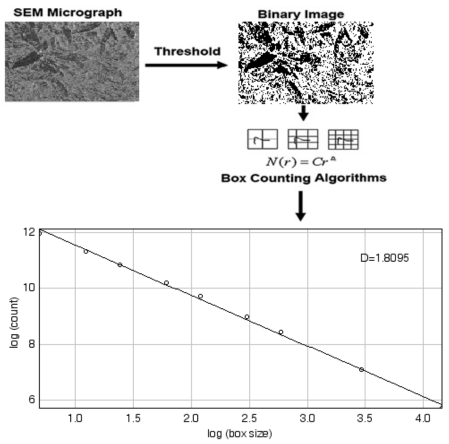

Fig. 8: Calculation of fractal dimensions with box-counting method

III. Results and Discussion

Figures 9 and 10 present the 3D fractal structures of the surfaces of the robot laser hardened and induction hardened specimens, respectively.

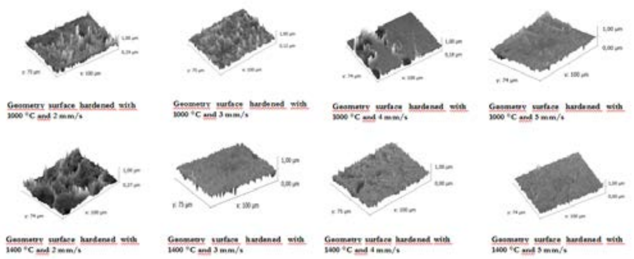

Fig. 9: Three-dimensional fractal structure of thegeometry surface of the robot laser hardened specimen

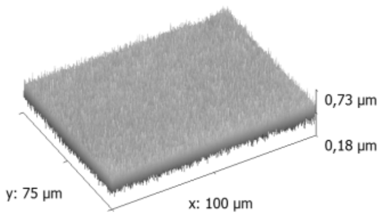

Fig. 10: Three-dimensional fractal structure of the surface of the induction hardened specimen

Fig. 11 and Fig. 12 present the relationship between fractal dimension and the hardness of specimens hardened at 1000 °C and 1400 °C at different speeds. Fig. 13 presents the relationship between fractal dimension and hardness of induction hardened specimen.

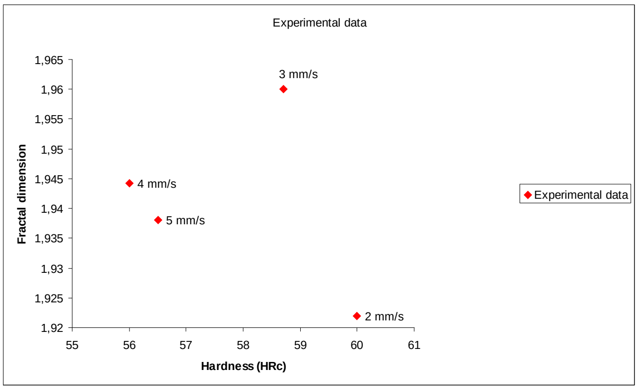

Fig. 11: Relationship between fractal dimension and hardness of specimens hardened at 1000 °C

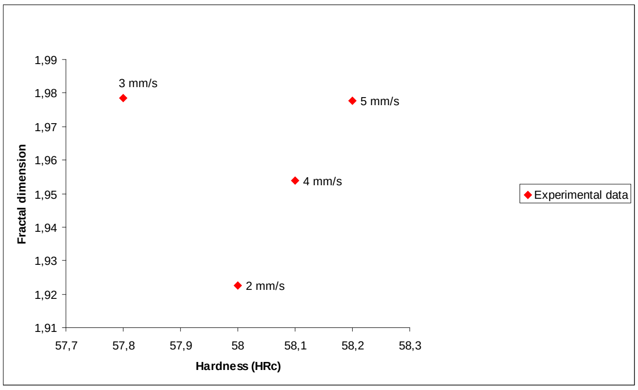

Fig. 12: Relationship between fractal dimension and hardness of specimens hardened at 1400 °C

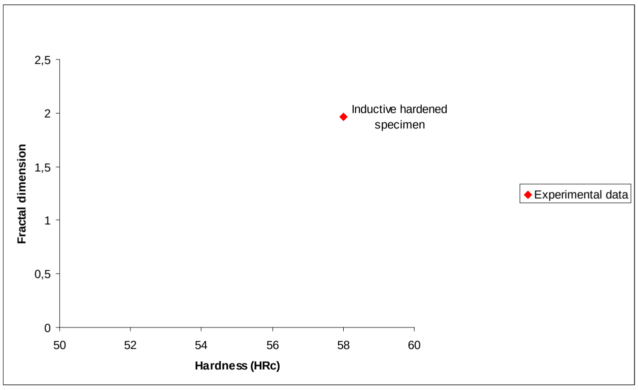

Fig. 13: Relationship between fractal dimension and hardness of induction hardened specimen

Fractal geometry is becoming increasingly popular in materials science to describe complex objects. With fractal geometry, we analysed how the parameters of the robot laser cell affect the hardness of hardened specimens. The fractal dimension of the robot laser hardened specimens also increases if we increase the temperature from 1000 to 1400 °C. If we increase the temperature from 1000 to 1400 °C, we decrease the hardness of the robot laser hardened specimen at 2, 3 and 5 mm/s. The fractal analysis of a series of digitized surface microstructures from the robot laser surface modified specimens indicated that useful correlations can be derived between the fractal dimensions and the surface microstructural features such as hardness and grain size.

IV. Conclusion

Fractal structures are also found in robot laser hardened and induction hardened specimens when viewed under sufficient magnification.

The main findings can be summarized as follows:

-A fractal structure exists in the robot laser and induction hardened specimens.

- We used the box-counting method to calculate the fractal dimension of robot laser hardened specimens for different parameters.

-With the fractal dimension we can describe the complexity of hardened specimens.

-We have identified the optimal fractal dimension of the different parameters of robot laser hardened tool steel.

-The fractal dimension varies between 1 and 2.

- This finding is important if we know that certain mixed alloys perform poorly because they have different melting temperatures; however, such alloys have much higher hardness and better technical characteristics. By varying different parameters (temperature and speed), the robot laser cells produce different fractal patterns with different fractal dimensions.

The relationship between porosity and the parameters of robot laser cells may be better understood through exploration of the fractal dimensions of the microstructure.

Laser parameters include power, energy density, focal distance, energy density in the focus, focal position, the shape of the laser flash, flash frequency, temperature, and speed of hardening. We want to calculate fractal dimensions for different materials and to find the relationships between these materials and these parameters of robot laser cells. We are interested in calculating the fractal dimension in:

- two-beam laser robot hardening (where the laser beam is divided into two parts),

- areas of overlap (where the laser beam covers the already hardened area),

- robot laser hardening at different angles (the angles change depending on the x and y axes).

References

[1] B. B. Mandelbrot, The fractal geometry of nature. New York: WH Freeman, 1982, p. 93.

[2] J.M. Barbaroux, F. Germinet, and S. Tcheremchantsev, Fractal dimensions and the phenomenon of intermittency in quantum dynamics, Duke Math. J. 110 (2001), 161–193.

[3] J.-M. Barbaroux, F. Germinet, and S. Tcheremchantsev, Generalized fractal dimensions: equivalences and basic properties, J. Math. Pures Appl. 80 (2001), 977–1012.

[4] M. Babič. Fractal dimension of the robotically laser hardening tool steel. In: M. Robnik and d. Korošak (eds.), 9th Symposium of Physicists, University of Maribor, Hotel Piramid, Maribor, 9–11 December 2010. Book of Abstracts. Maribor: CAMTP, 2010.

[5] M. Abramowitz and I. Stegun, Handbook of Mathematical Functions with Formulas, Graphs, and Mathematical Tables, Dover, New York, 1965.

[6] J. Grum, P. Žerovnik, and R. Šturm: measurement and analysis of residual stresses after laser hardening and laser surface melt hardening on flat specimens; *Proceedings of the Conference "Quenching '96"*, Ohio, Cleveland, 1996.

[7] M. Babič, M. Milfelner, and S. Stepišnik, Laser hardening metals. In: T. Perme, D. Švetak, and J. Balič (eds.), IRT Industrial Forum, Portoroz, 7–8 June 2010. Source of knowledge and experience for the profession: Proceedings of the Forum. Skofljica: Profidtp, 2010.

[8] Babič, M., Muhič, T. 2010, Fractal structure of the robot laser hardened materials. In: 18th Conference on Materials and Technology, 15th–17th November 2010, Portoroz, Slovenia. Program and abstracts book. [Ljubljana: Institute of Metals and Technology,], p. 73. (In Slovene)

[9] Babič, M. 2010, Fractal dimension of the robot laser hardening tool steel. V: ROBNIK, Marko (ur.), KOROŠAK, Dean (ur.). 9th Symposium of Physicists at the University of Maribor, Hotel Pyramid, Maribor, 9, 10 and 11 December, 2010. Book of Abstracts. London: CAMTP, [2] F. (In Slovene)

[10] Babič, M. 2010, Optimal parameters of a robot cell for laser hardening of metals at different angles. 19. Proceedings of the International Electrotechnical and Computer Conference ERK 2010, Portoroz, Slovenia, 20–22 September 2010, (Zbornik. Electrical and Computer Conference ERK .). Ljubljana: Slovenian section of the IEEE. (In Slovene).

[11] C. C. Barton, Fractal analysis of scaling and spatial clustering of fractures. In: C. C. Barton and P. R. La Pointe (eds.), Fractals in the Earth Sciences. Plenum Press. New York, 1995, pp. 141–178.

[12] http://www.splav.kharkov.com/steelgrade/mat_start_eu.php?name_id=335.

[13] L. T. Dougan, P. S. Addison, Estimating the cut-off in fractal scaling of fractured concrete, Cement and Concrete Research 31 (2001) 1043–1048.

[14] Y. Shi, X. P. Lou, S. H. Quan, Fractal dimension computation methods for gas diffusion layer of PEM fuel cells, Journal of Wuhan University of Technology 29 (2005) 79–82 (in Chinese).