Defect Detection and Full Surface Characterization of High Curvature Cathode Filaments

Ding-rong YI[1], Cai-hong HUANG[1], Jing-fang XIE[2], Yu-ming CAI[2], Yong QIAN[3] and Ling-hua KONG[4,*]

[1]College of Mechanical Engineering and Automation, Huaqiao University, Xiamen 361021, China

[2]Minglang Instrument Sci. and Tech. (Xiamen) Co. Ltd., Jimei District, Xiamen, 361021, China

[3]Ningbo Five-Dimensional Inspection Co. Ltd. National Physics Science &Technology Park, No. 228 Jingu North Road. Yinzhou District, Ningbo City, Zhejiang Province, China

[4]School of Mechanical and Automative Engineering, Fujian University of Technology, Fuzhou 350118, China

*Corresponding author

Keywords: Cathode filament, Digital scan, Surface characterization, Defect detection, Online quality inspection, High-curvature surfaces, Optical occlusion, Line detector.

Abstract. Surface defects of cathode filaments of microwave magnetron would cause magnetron failure and scrapped microwave systems. Therefore, surface defects on cathode filaments must be carefully inspected. Conventionally, filaments are manually and visually inspected using their amplified images under an optical microscope. This is because automatic defect detection of cathode filaments is a challenging problem. The difficulty comings from its complex surface shape with multiple turns of high curvature spiral circles, which occlude each other. Such complex shape prevents capturing of sharp focusing images, which are essential for a computerized automatic detection algorithm. Further, the variable nature of production defects complicated the process of automatic defect detection task. To solve these problems, this paper proposes an automatic defect detection method to deal with issues related to complex shapes containing occlusions as well as high curvatures, particularly for the quality inspection of spiral shaped cathode filaments. The method includes a novel digital scanner, which sequentially brings all sections of the filament sides into sharp focusing of the optical imaging system. The method also employs multiple optical systems to imaging multi-sides of the spiral filament. The computational algorithm primarily uses line-detectors. In an evaluation experiment, the proposed method was used to automatically inspect over 14 million cathode filaments. Experimental results indicate that its false negative rate was 0.0065%, and its false positive rate was 6.83%. This indicates that the proposed method could successfully detect all kinds of surface defects at over 99.99% accuracy. It reduces the workload for manual inspection from 100% down to 93.17%, over an order of magnitude reduction. Further, the efficiency of the proposed method is 70 spiral filaments per minute, satisfying the requirements of online quality detection of existing manufacturing lines of filament cathodes.

Introduction

Cathode magnetron are widely used in both military applications[1,2] as well as household microwaves[3,4]. The core of a cathode magnetron is the cathode filament, which is typically made of thorium tungsten or barium-tungsten alloy. When excited at a high voltage, the cathode filament of a magnetron cathode within a microwave oven would generate Tera Hertz frequency microwaves causing water molecules to move, vibrate, and bump into other food molecules at high frequencies. In this way, the filament inside a cathode converts electromagnetic energy into heat, which is quickly absorbed by the food. Therefore, the filament within a cathode magnetron is the core component of a microwave oven. Though the chemical composition of the cathode filament determines the escape power, emission stability, and lifespan of a microwave oven. However, when the chemical composition is optimized and fixed, the manufacturing quality of the cathode filament determines the level of noise, stability, efficiency, and lifetime of a microwave oven[3]. Thanks to its rich resources in rare earth raw materials of tungsten and thorium, over three quarters of worldwide microwave oven used filament cathodes are made in China. The manufacturing of filament coils includes multiple processes. The first step is to pull the molten thorium tungsten material into a long-wire. Secondly, bend and wound the long-wire into a spiral tube. Thirdly, cut the spiral tube into individual cathode filaments. Fourthly, packaging the filament coils into trays. Then the fifth or the last step is quality inspection under an optical microscopic instrument (Fig. 1). The typical length of a filament coil is about 12mm, with outer-circle diameter of about 4mm. The coil contains about 10 spiral sections or winding circles with pitch size between two adjacent circles is about 1.2mm. Since the filaments are cut out of a long-winded tube line, their both ends may either have a normal round- or defected sharp-shaped cutting cross-section, depending on the cutting tool.

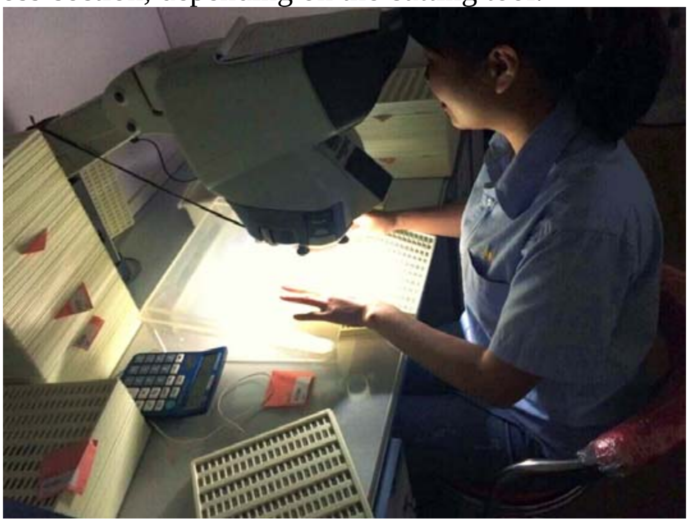


Figure 1. Conventional surface quality inspection procedure of filament cathode under an optical microscopic instrument

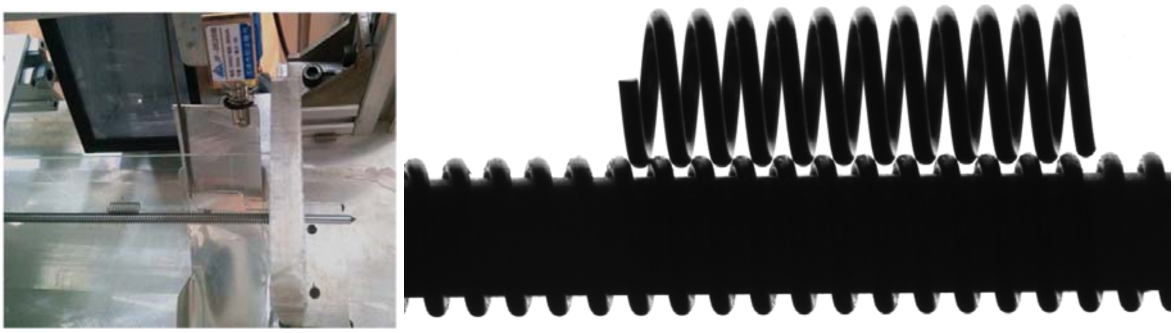
Conventionally, cathode filaments are manually and visually inspected using their amplified images under an optical microscope. There are three surface quality related defects include cracks, deformation, and scratches. Further, there are another five surface shape related defects include deviation of the cutting cross-section, burrs, inner diameter, outer diameters, and lengths of the spiral filaments. Though intelligent and with excellent motor-visual coordination for the detection of scratches, cracks and burrs, it would be difficult, if not impossible for a human operator to quantitatively and objectively meet the technical standard for coil length and pitch accuracy. Typically, the requirement for the process capability index (CPK) for length and pitch accuracy is CPK > 1.33. Failing to meet this standard would result in customer complaints. Further, it is tedious and tiresome to visually inspect the magnified images of the cathode filaments in a dark laboratory room, causing discomfort and stress to both eyes.

With the advancement of computer vision or intelligent inspection, many surface defect detection methods are reported in the literature[5-8]. Particularly, in literature [5], weak scratches and cracks in high-curvature optical lenses were automatically detected using a coarse-to-fine detection strategy applied to complicated dark-field images. However, these methods were not readily applicable to the case of cathode filaments, as the outer diameter of the filament spiral is as small as only 5mm, indicating the high curvature of the circles or spirals contained in a cathode filament. Automatic defect detection of high curvature cathode filaments is a challenging problem. The difficulty comings from its complex surface shape with multiple turns of high curvature spiral circles that occlude each other. Such complex shape prevents capturing of sharp focusing images, which are essential for a computerized automatic detection algorithm. Further, the variable nature of production defects complicated the process of automatic defect detection task.

To ease the problem of defect detection and full surface characterization of high curvature cathode filaments, this paper presents an automatic defect detection method. The rest of the paper is organized as below. A method section first introduces a custom-designed digital scanner that sequentially brings all sections of the filament sides into sharp focusing of the optical imaging system. Then, the method section goes on with a batch of optical imaging systems, which is designed to image multi-sides of the spiral filaments. Following this, the computational algorithm which primarily uses line-detectors to detect and characterized the defect is presented in the section of Method. Following the section of method, the result of a validation experiment is presented. After that a brief summary is given.

Method

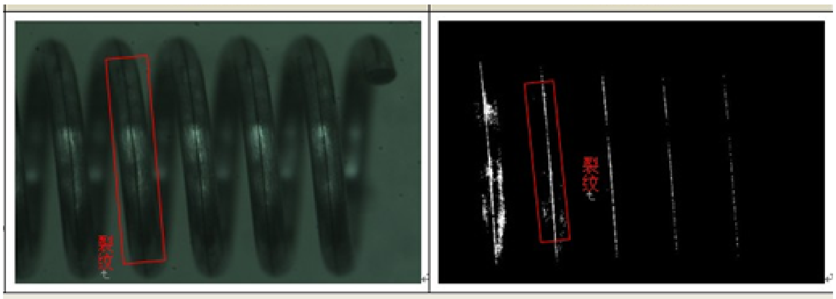
The cathode filament have multiple sides: ten outer left-faces, ten outer right faces, ten out front-faces, ten inner faces. They occlude each other and prevent capturing of sharp focusing images. What is worse, there exist no sorting device which could vibrate cathode filaments to make them proceed in the same gesture through fixed imaging systems in order to capture their images. Without appropriate and clear image, it is impossible to do computerized analysis, let alone automatic defect detection. To overcome the difficult problem of occlusion resulting from multiple turns of high curvature spiral circles contained in a cathode filament, a customized scanning system is designed. The innovative idea of scanning spiral shaped cathode filament is to carry it and rotate it with a spiral tube of same pitch, instead of a conventional translational movement system. Fig. 2 is the picture of the designed scanning system of cathode spirals. The long spiral-tube of scanning system is constantly rotating. The pitch distance of the long transporter spiral matches that of the cathode filament (Fig. 2a). The rotating transporter carries the cathode filament rotate too. In this way, the 360-degree turning of each one of the ten-circles would be carried to sequentially pass through the optical imaging system with a fixed distance. Without it, there would require multiple imaging system to capture the front view, top view, rear view, bottom view of the front faces of the cathode filament. Similarly, all faces of the cathode filament, including its outer left-face, outer right face, inner left face, inner right face, inner front are carried to sequentially pass through the optical imaging systems at fixed relative system. In this way, sharp images of various faces of the spiral cathode are captured. Fig. 2b presents one image of the front view of the cathode filament. By the way, the rotating scanner also serves as the online transportation tool that carries the cathode spirals quickly from the cutting processing stage to the next one, to package the cathode filaments into plastic trays.



(a) (b)

Figure 2. (a) Scanning or transporation system of cathod spirals. (b) The captured digital image of cathode filament

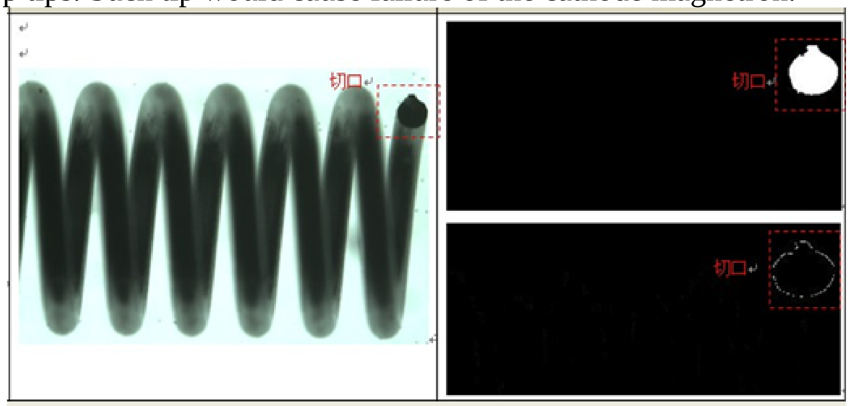
Reflective imaging mode were used to capture images of the various surfaces of cathode filaments. Those images show well crackles, scratches, and burrs. Fig.3a shows the captured image of the front face of the cathode filament. With the rotation of the filament, the bottom view, top view, and rear view were sequentially being captured after the front of view. Line detector was used to detect cracks and scratches. If the length, width, curvature of the line satisfy the predetermined criteria, then the line was classified as a crack. Fig. 3b illustrates the automatically detected cracks on the front face of a cathode filament.



(a) (b)

Figure 3. (a) captured image of the front side of a cathode filament. (b) the automatically detected cracks of the cathode filament

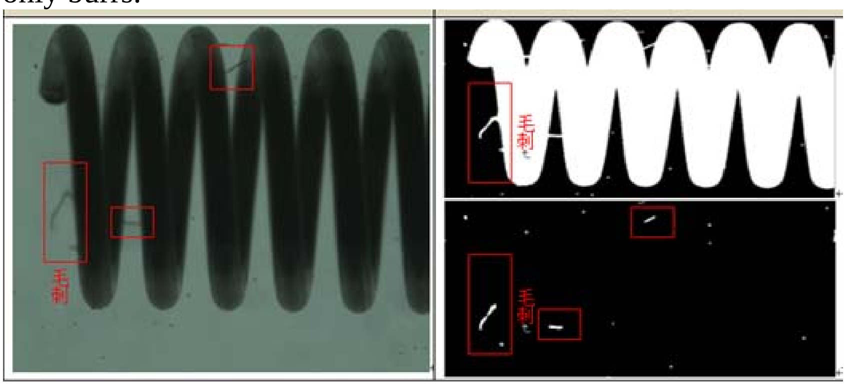
Fig. 4 (a) is a captured image which clearly illustrate the cutting-section of a cathode filament. A threshold operation was conducted to the image to obtain a binary image. In this image, the cathode filament was shown in white while the background shown in black. Further, the end segment of the cathode filament was identifed. This sequence ran contineously until the segmented terminal end clearly showed the cross section of the cathode filament. Fig. 4b shows such a segmented cross-section. With this, it was convenient to automatically detect the shape defect of the cutting section of cathode filament. The normal one would have a nice round shape, while the defected ones may contain sharp tips. Such tip would cause failure of the cathode magnetron.



(a) (b)

Figure 4. (a) captured image of the cutting-section of a cathode filament. (b) the automatically detected defect of shape of the cutting section of cathode filament.

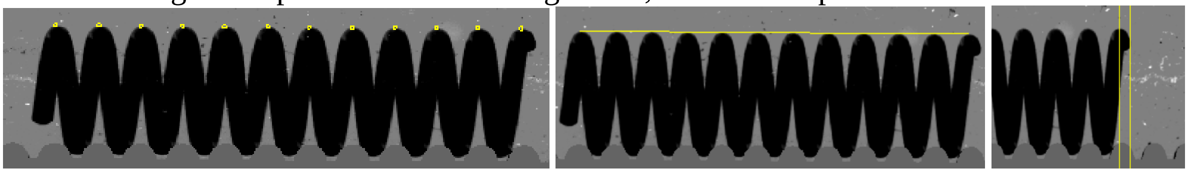
Burrs is detected in a similar was as to the task of detecting shape defect of the the cutting cross-section. Fig. 5 (a) is a captured image which clearly illustrate the burrs of a cathode filament. A threshold operation was conducted to the image to obtain a binary image where the cathode filament was shown in white while the background shown in black. Then the cathode filament was removed,leaving only burrs.



(a) (b)

Figure 5. (a) captured image of the front side of a cathode filament. (b) the automatically detected defect of shape of the cutting section of cathode filament

A dark field optical imaging systems is used to capture images of the cathode filament. Double telecentric optical lenses are employed to reduce optical distortion.The dark field images show excellent contrast between background and the object (Fig. 6a). Edge detection method is used to conturing the cathode, and the cap peak of each contour segment is labeled (Fig. 6a). The distance between two adjacent cap peaks is the pitch of the cathode filament. The mean of the pitches of ten circles, and the deviation of each pitch from the mean could be calculated accordingly. The length of the cathode filament is the length of the straight line that passing through the cap peaks (Fig. 6b). However, this length is further compensated with the length of the partial circles at both ends. Fig. 6c illustrates the length of a partial circle at the right side, the left side partial circle is not shown.



(a) (b) (c)

Figure 6. (a) Identified caps used to measure pitch distance (b) Connecting caps to obtain a straight line, from which the rough length of the cathode filament can be estimated. (c) Refieing the length by compensating the endingsection

Validating Experiment

The proposed method was developed and used to defect the cathode filament product line for a one year period from March 21, 2018 till Feb. 19 of 2019. Table 1 below listed the experimental results. Using the opinions by two skilled human quality inspectors as gold standard. If both of them regard a cathode filament as good one without defect, then it is good or negative without defects. Otherwise, the filament is defected, or positive with defection. Before we further discuss the findings shown in table 1, some definitions are necessary.

False positive: The cathode filament judged by the proposed automatic defect detection method as defected, but the human quality inspector judged as good.

False negative: The cathode filament judged by the proposed automatic defect detection method as good that meet customer requirement, but skilled human quality inspector judged it as defected one.

Table 1. Experiment validation experiment of the proposed automatic defect detection method

Time period	# of samples inspected	Normal	#False negative	False positive
March 21, 2018 ~Feb.16, 2019	14,465,055	13,020,910	939	988583

A total of over 14 million cathode filaments being inspected during the tested time period. With over 13 million evaluated as good products by the proposed automatic methods. Within this good ones according to the proposed automatic method, only 939 cathode filaments were actually defected ones by skilled human quality inspectors. The rate of false negative is defined as:

Rate of false negative = number of false negative/total of samples being inspected = 939/14,465,055=0.0065%.

This false negative rate meets the requirements all customers, which was no bigger than 0.01%, or one out of every 10 thousands. The rate of false positive is defined as:

Rate of false positive = number of false positive/total of samples being inspected = 988583/14,465,055=6.83%.

This means that the percentage of bad ones detected by the proposed automatic method by mistaken is reasonable, not very high.

Summary

This paper proposed a novel method to deal with the problem of automatically detect defects and characterize the cathode filament. To deal with the difficult problem of occlusion exists between the complex surface shape containing of multiple turns of high curvature spiral circles, a custom-designed digital scanner was proposed and developed. This scanner sequentially brings all sections of the filament sides into sharp focusing of the optical imaging system. The proposed auto-detection method also employs multiple optical systems to imaging multi-sides of the spiral filament. The computational algorithm primarily uses line-detectors. Evaluation experimental results indicate that the false negative rate was 0.0065%, and its false positive rate was 6.83%. This indicates that the proposed method could successfully detect all kinds of surface defects at over 99.99% accuracy. It reduces the workload for manual inspection from 100% down to 6.83%, over an order of magnitude reduction.

The false negative rate and false positive rate are competing technical factors for any automatic defect detection methods. One can optimize one of them, or trade low false positive rate for low false positive rate, or vice versa, depending on the optimization goal. Usually it is difficult to lower down both. One advantage of the proposed method is its simultaneous maintenance of rather low false negative rate of only 65 per million as well as a low false positive rate of 6.5%. This good performance is certainly impossible if without high quality images captured by the scanning system.

Acknowledgement

This research was financially supported the National Natural Science Foundation of China (NSFC) (grant no.51775200). Dr. Linghua Kong was also financially supported by the Digital Fujian Industrial Manufacturing IOT Lab.

References

[1] Bourgioti, C., Chatoupis, K. & Moulopoulos, L. A. Current imaging strategies for the evaluation of uterine cervical cancer. World J Radiol **8**, 342-354 (2016).

[2]Avtomonov, N. I. et al. Toward Terahertz Magnetrons: 210-GHz Spatial-Harmonic Magnetron With Cold Cathode. Ieee Transactions on Electron Devices **59**, 3608-3611, doi:10.1109/ted.2012.2217974 (2012).

[3] Mitani, T. et al. Noise-reduction effects of oven magnetron with cathode shield on high-voltage input side. Ieee Transactions on Electron Devices **53**, 1929-1936, doi:10.1109/ted.2006.878238 (2006).

[4] Li, S., Yan, T., Li, F., Yang, J. & Shi, W. Experimental Study of Millimeter Magnetrons With Cold Cathodes. Ieee Transactions on Plasma Science **44**, 1386-1390, doi:10.1109/tps.2016.2585644 (2016).

[5] Tao, Xian, Xu, De, Zhang, Zheng-Tao, Zhang, Feng, Liu, Xi-Long & Zhang, Da-Peng. Weak scratch detection and defect classification methods for a large-aperture optical element. Optics Communications **387**, 390-400, doi:10.1016/j.optcom.2016.10.062 (2017).

[6] Alem, Behrouz & Abedian, Ali. A semi-baseline damage identification approach for complex structures using energy ratio correction technique. Structural Control & Health Monitoring **25**, doi:10.1002/stc.2103 (2018).

[7] Chetverikov, B. S., Chepchurov, M. S. & Teterina, I. A. Automation of component selection of ball-bearing support of drilling bit. International Journal of Advanced Manufacturing Technology **90**, 1059-1065, doi: 10. 1007/s00170-016-9432-4 (2017).

[8] Liu, Yan & Yu, Feihong. Automatic inspection system of surface defects on optical IR-CUT filter based on machine vision. Optics and Lasers in Engineering **55**, 243-257, doi:10.1016/j.optlaseng.2013.11.013 (2014).