Detection of Micro-scratch Found on Surface of Steel Filament Using Eddy Current Sensor

Kim Sang Tran
Vice President
Bilal Global Management Consulting
10 Bandy Fields Place Salford UK
kimsang91@gmail.com, kimsang@bilalconsultancy.uk

Abstract

This paper presents an approach for the detection and analysis of micro-scratch detected on the surface of steel cord (steel filament) using eddy current sensor (ECS). This work aims to point out and eliminate the defective products and containing surface defect in wet drawing process. In other words, a quality gate was established to prevent sending defective goods to customer. During wet drawing process, steel filaments were manufactured by drawing process through multi-dies system ranging from bigger diameter called brassed wire to smaller diameter called filament. An eddy current sensor was used to generate a high-frequency magnetic field around the sensor coil where the filament went through at the output end. The test coil was centered inline of wire path and connected to pre-amplifier then send the signal to instrument which was used to set working conditions for the experiment. If a defect appears when filament passes through the test coil, the eddy current will appear and sensor will send the signal to stop the wet drawing process. The artificial defect was created on a sample and the amplitude of those defects were measured to set the threshold. The amplitude signal of artificial defect was about 10% corresponding to specification of crack's depth of 20 micrometers. The production was carried out with applied setting condition under inspection of eddy current sensor. we produced 182 products x 38,000m, the defective ratio was 26.37%. There were two typical types of defect: the longitudinal scratches and the hole defect which containing an additional particle. In future works, the surface scratches will be collected, and then analyzed two positions including inside and outside of defect area in order to identify the atomic ingredients to identify the origin of the defects.

Keywords

Micro-scratch, Surface defect, Steel filament, Eddy current sensor (ECS), Brassed wire.

1. Introduction

In the manufacturing industry, the application of state-of-the-art technology is by far the most important in quality field. Among key performance indicators such as safety, cost, delivery and quality, continuous improvement in product's quality is the trend of most of suppliers. Nowadays, it is necessary to reduce the risk of failure goods at the end users, it is the responsibility of steel cord manufacturers. There were many inspection approaches using the cutting-edge technologies to innovate the products in terms of quality, overall equipment efficient, cycle time, etc. In the current steel cord manufacturing site, the filament or steel wire is produced from many steps ranging from dry drawing, brassed plating, wet drawing and stranding. Among inspection technologies, a new defect inspection method called vision-based was developed to enable defective defection for steel wire rod so as to innovate the accuracy of inspection (Yun et al., 2013), or as (Wu et al., 2015) mentioned about a novel sensor system using the orthogonal test method to inspect the defect of wire rope. (Zhou et al., 2022) provided a visual sensing inspection to figure out the defect of wire rope with a better speed. However, the image technology is unable to investigate or prevent the defective goods to customer owing to a high volume in production and the shapes of surface defect are unlimited while the shapes of reference samples are limited. As mentioned before, the steel wire making process is conducted with a very high speed (input 400 meters/minute) and temperature (over 300^{0}C) and the researchers only considered the wire rope with big diameters. Therefore, we present a new approach to inspect the filament with very small diameter in the production lines using eddy current sensor as a quality gate to prevent sending failure goods to customer by early detection and eliminate the defective products at manufacturer side.

The rest of this paper is organized as follows: the literature review is introduced in section 2. In section 3, an inspection method is established to detect and eliminate the defective products. Furthermore, it is about data collection and analysis where the surface defect will be separated from products and detail analysis will be performed. Results and discussion are mentioned in section 4. Finally, conclusions are provided in section 5.

1.1 Objectives

This paper aims to propose a novel methodology to early detect the surface micro-defects on steel wire in order to prevent sending failure goods to customers and reduce the risk of accidents at the end user. It has been intended to give a hand to manufacturer to inspect the quality of filament so that the steel maker can optimize the resource for their budget as well as reduce the manual steps. The proposed methodology utilized eddy current sensor to solve the technical issue in terms of quality and improvement and responds the critical question that is optimized according to customer requirement and steel cord manufacturing industry.

2. Literature Review

There is a wide range of approaches for surface defect inspection in steel cord manufacturing industry. Eddy current sensor is widely used in variety of application such as aircraft, automotive, pipe and tube inspection as well, in other words it can be called non-destroy testing (NDT) inspection. In terms of surface defect detection, traditional inspection method provides the disadvantages of low response, poor real-time defect detection, low efficiency, and high labor intensity (Zhang et al., 2021). Beside the detection function, surface defect classification should be taken in to account to this phenomenon. Various methodologies are based on signal processing according to an inspected classifier, it means that all potential defect types would be covered by the created defects (Saludes-Rodil et al., 2015). Wire break issue was also a big trouble in steelmaking industry, and many solutions were given to reduce the risk of wire break during production. However, at the production workshops, various technical or quality issues remain to be resolved (Yoshida et al., 2003). In another view, finite element analysis and experimental set up were also established to investigate the growth and disappearance of artificial cracks/scratches on the wire surface. The relationship between the properties and the characteristics was also investigate in (Shinohara and Yoshida 2004). Furthermore, another author focused on the survey on the available techniques for inspection of fabric defects, it was really hard to investigate due to scale of stochastic variation, stretch and skew of fabric defect owing to the environment (Jasper and Potlapalli 1995). Another textile inspection method called computer vision, it presented a simple system designed for fabric inspection and illustrated its efficiency in visualizing 12 kinds of typical defects (Conci and Proenca 2000) and (Lane 1998). Or in (Daugman 1985), (Sari-Sarraf and Goddard 1998), (Brzakovic and Sari-Sarraf 1994), spectral methodologies were also applied in the past, its problem was the accurate localization, according to (Zhang and Won 2010), an image processing algorithm was proposed to detect scratch defect in wire rod surfaces, this approach detected the scratch defect of wire rod images and locate the accurate position. (Filipovic et al., 2006) proposed a method to eliminate the defects or minimize their impact on bar and steel wire by improving the quality of steel wire surface before rolling, the root cause was also investigated and as a result, surface defects caused by low ductility during rolling. (Filipovic 2007) mentioned about the frequency of defect's appearance in roll products, especially in wire rod, the role of defect inspection is really important because of the application of wire rod. In order to reach the needs of market, defect-free wire rod is indeed necessary to be a criteria condition. Of course, the defective goods should be rejected as scrap which is very costly for production budget. Hence, reducing the cost of failure rate and improving the quality of product are always the trend of steel wire makers.

3. Methods

This research focuses on developing a novel approach to identify the defective steel cord to satisfy customer specifications and enable the function of eddy current sensor to answer the critical questions regarding solutions to be taken. In order to carry out the experiment, a set of eddy current sensor was installed including the coil where the filament passed through, EDS analysis was ordered.

Figure 1 indicates the wet drawing procedure, the input of wet drawing process is brassed wire (steel wire was plated by brass (coper and zinc)), this brassed wire passes through wet drawing machine to get the smaller diameter via multi dies system. The output of wet drawing process is filament where the eddy current sensor was placed to inspect the quality of the product. The entire procedure can be divided into 4 steps.

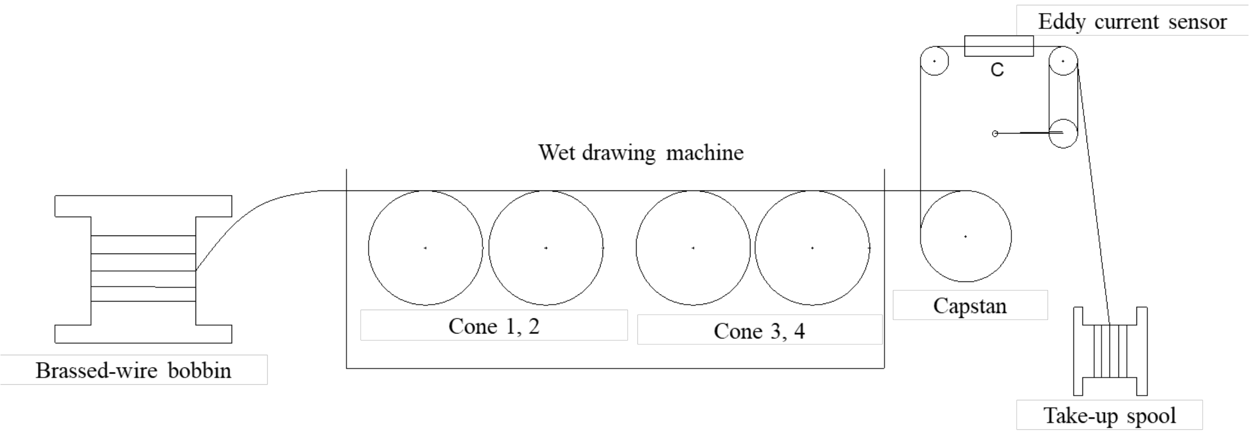


Figure 1. Wet drawing procedure

Step 1: Experimental setup:
The eddy current sensor was placed between two top rollers of wet drawing machine and the test coil was centered inline of wire path. The test coil was connected to pre-amplifier then send the signal to instrument as shown in the Figure 2, which was used to set the working conditions for the system.

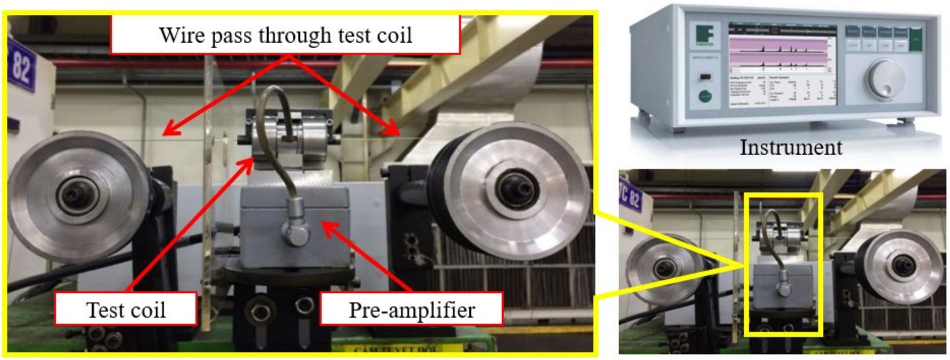


Figure 2. Eddy current sensor system

Step 2: Testing sample and setting for working condition:
Artificial cracks with depth of 20 and 80 micrometers were created on the surface of a 0.38mm filament sample, as shown in Table 1 and Figure 3.

Table 1. Artificial crack dimensions

Crack	**No. 1**	**No. 2**
Dimension (depth x width)	20 x 73	80 x 73

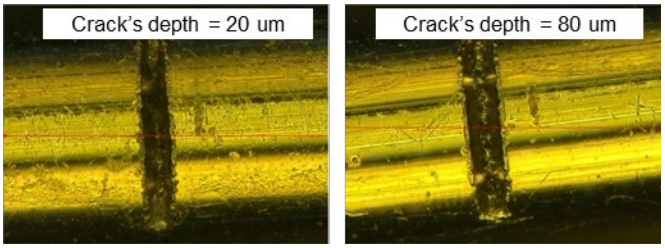


Figure 3. Artificial crack

At the beginning, the setting parameters were adjusted as eddy current sensor supplier, as illustrated in Table 2. F1 threshold was a referent value and F2 threshold value was used to enable the system to stop the process and record any relevant information about the defects. Frequency and sensitivity were controlled at 1000 Hz and 43 dB, respectively. In the next step, the sample was tensed and manually pulled through the test coil to measure the amplitude signal corresponding to the created depths and finally, the recoding results were analyzed to obtain the setting condition for mass production.

Table 2. Setting condition of Eddy current sensor for testing sample

Frequency	**Gain dB**	**F1 Threshold**	**F2 Threshold**
1000 Hz	43 dB	40%	60%

Step 3: Apply into production lines and collect surface defects
With the setting condition defined from step 2, install Eddy current sensor into the wet drawing at the output stage of this process to make sure it is a quality gate to eliminate the defective goods and prevent sending failure products to customer.

Figure 6 shows the recorded information of a completed product. It should reach 38,000 m of length without defect or with insignificant defects containing its amplitude signal under 10%. When a peak of defect appears in the monitor of eddy current sensor with the amplitude signal over the threshold value, the manufacturing process will be stopped immediately. Furthermore, the defect products will be separated and detail analysis will be performed.

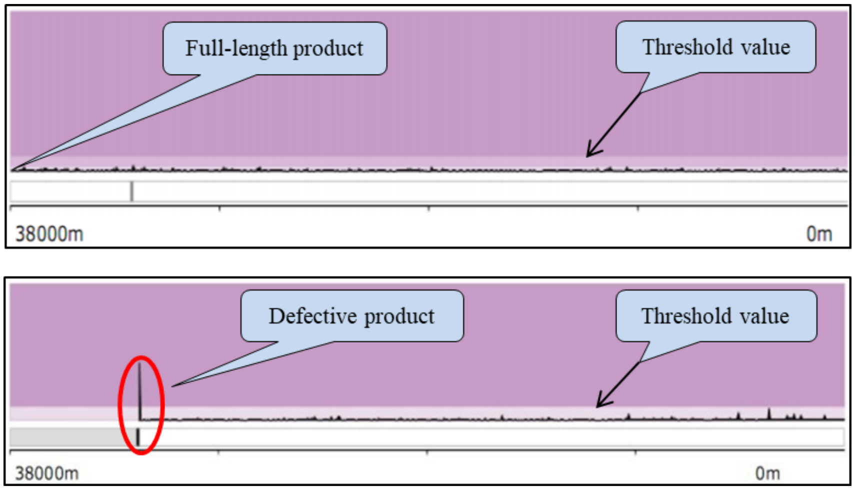


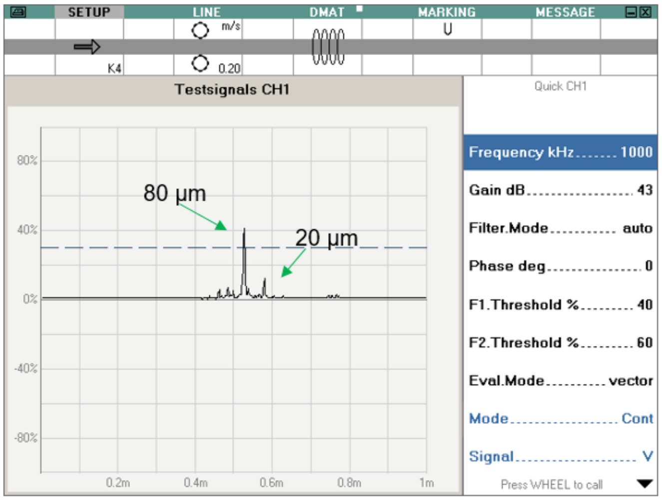
Figure 6. Production monitoring interface

Step 4: Defect analysis
In order to verify the detected defects on filaments, we selected 13 short-length products to pull pack through eddy current sensor in order to measure the amplitude signal of the surface defect and compare to those obtained during

production when eddy current sensor stopped the machine. Furthermore, the typical surface defects were identified using microscope.

4. Results and Discussion

As a result, the amplitude signals of created defects were about 10% and 41% corresponding to 20 µm and 80 µm of depth, respectively. The noise was also found after the created defects, it stood at 3% due to the rusting of the wire after removing brassed layer, as shown in Figure 4.



Frequency kHz....... 1000
Gain dB.................. 43
Filter.Mode........... auto
Phase deg................ 0
F1.Threshold %......... 40
F2.Threshold %......... 60
Eval.Mode.......... vector
Mode.................. Cont
Signal...................... V

Figure 4. Amplitude signal of artificial cracks

Figure 5 shows a linear relationship between amplitude signal and the depth of artificial cracks created on steel wire with diameter of 0.38 mm. It is obviously that if we set the threshold value of 10% in order to detect the surface defect with the depth of 20 µm, then the eddy current sensor will detect all the surface defects containing the crack's depth over 20 µm during production.

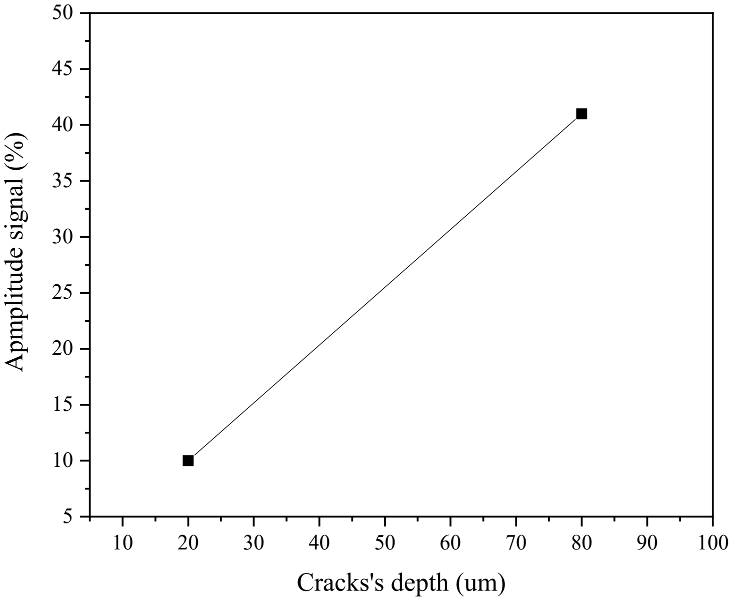


Figure 5. Amplitude signal and crack's depth relationship of sample

Based on the experimental results, the setting conditions for eddy current sensor were established and roll-out into production to satisfy the requirement of customer. Those parameters were illustrated in the Table 3.

Table 3. Setting condition of Eddy current sensor for production

Frequency	**Gain dB**	**F1 Threshold**	**F2 Threshold**
1000 Hz	43 dB	0%	10%

For this project, 182 products were produced at wet drawing machine and 48 defective products were detected by eddy current sensor as summarized in Table 4. The defective ratio accounted for 26.37% corresponding to the percentage of products containing the surface scratch with the depth larger than 20 micrometers.

Table 4. Defective ratio of production using eddy current sensor

Categories		**No. of spool**	**Remark**
Full length	Without defect	134	Passed
Short length	Detected defect	48	Failed
	Wire break	0	
	Other reason	0	
	Total	48	
Total produced products		182	
Defective ratio		**26.37%**	

Figure 7 demonstrates that the identified defects on short-length products were picked up correctly. The difference was insignificant and it is because of sample tension by hands and the speed of testing. It is obvious that the amplitude signal of most of defects ranges from 10% to 35%, except 1 defect where the amplitude signal was significantly higher than others, standing at about 70%.

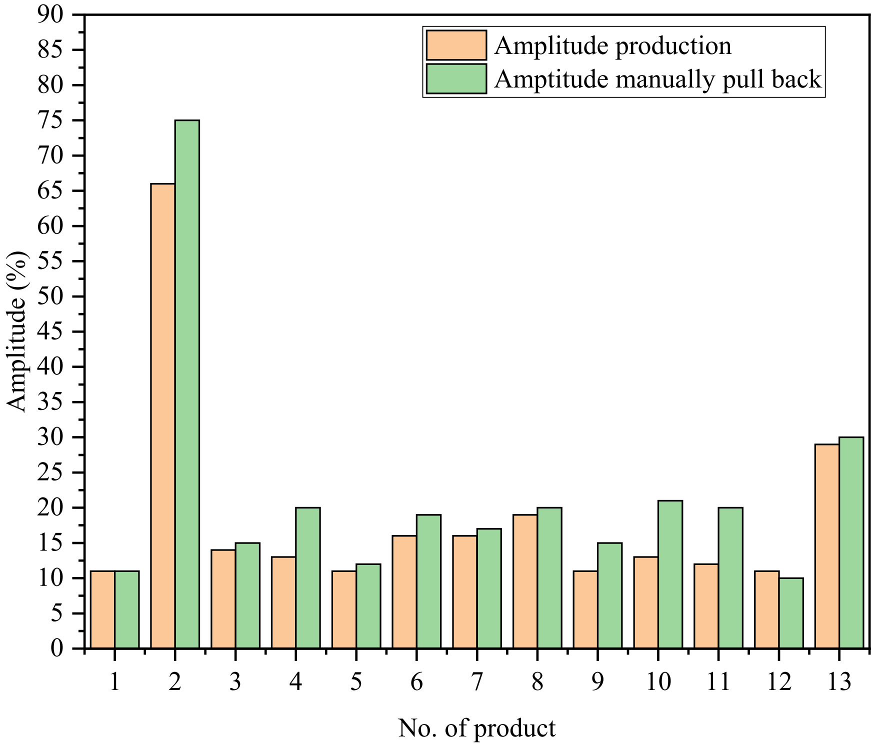


Figure 7. Amplitude signal of defective products comparison

Figure 8 illustrated the position of microcrack where the eddy current sensor stopped the machine after detecting the defect with the depth larger than 20 µm. It is obvious that the surface defects appeared randomly according to the length of each products.

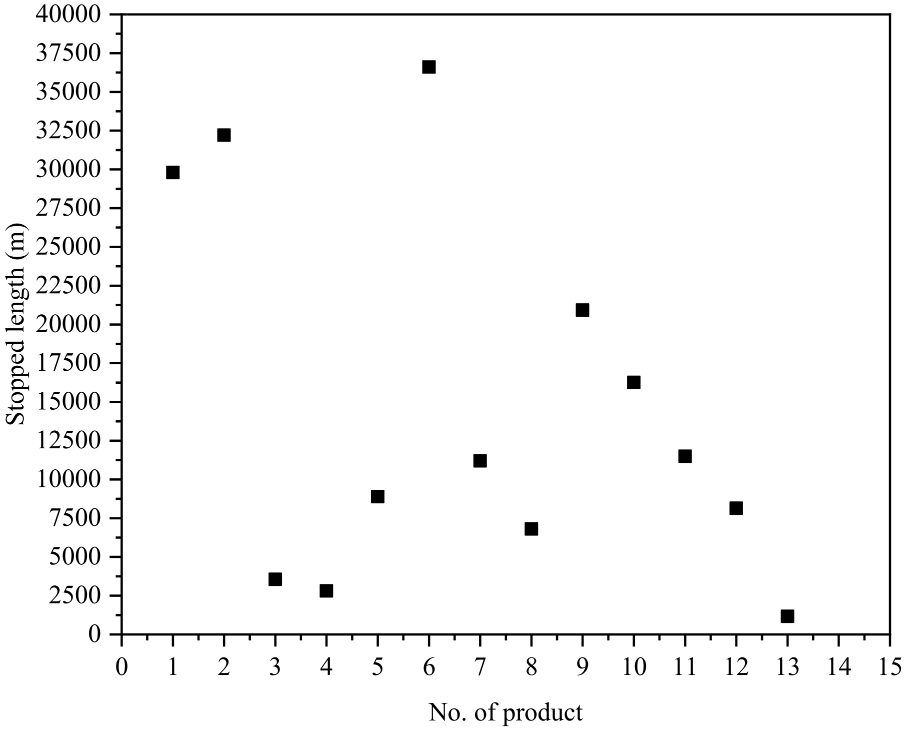


Figure 8. Stopped length of defective products

After detecting the surface micro scratch, wet drawing machine ran more 26 meters before absolutely stopping. By removing the additional length and rewinding backward through the sensor, the eddy current instrument detected the same signal with the previous product recorded in the system. Finally, the surface defects were identified. The defects were clarified under microscopy so as to mark the position as shown in Figure 9.

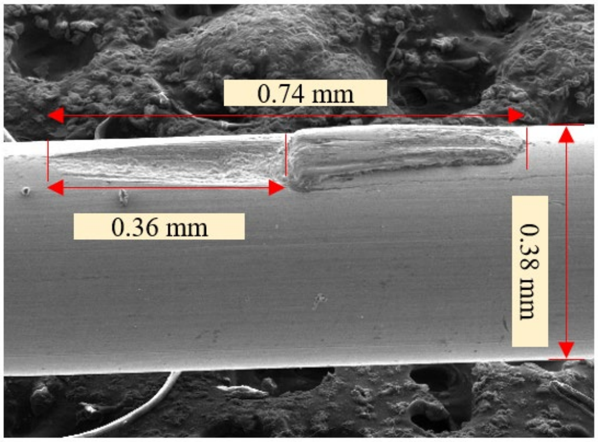


Figure 9. Surface defects on filament visualized by microscopy

Under microscopy, the elements containing the defect were cut into small pieces and fixed in parallel by tapes before putting into a mold, illustrated in Figure 10.

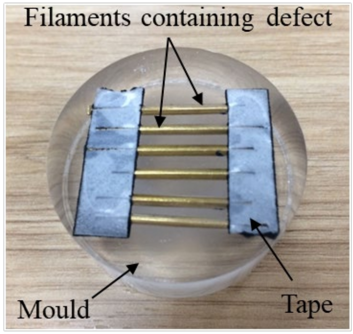
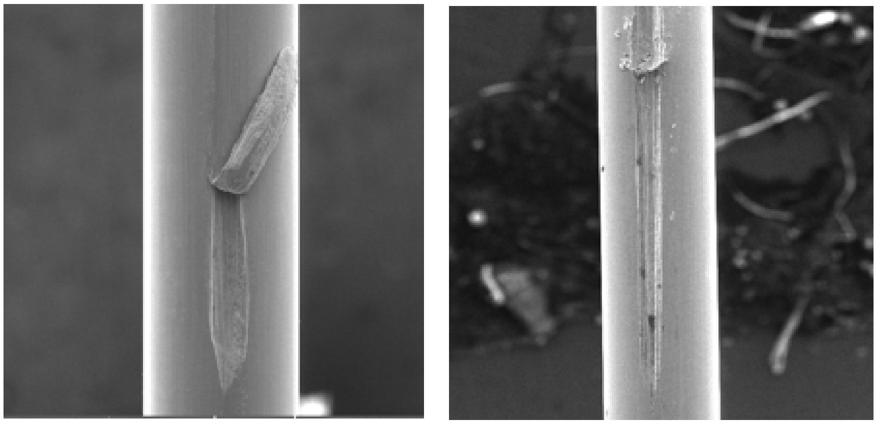
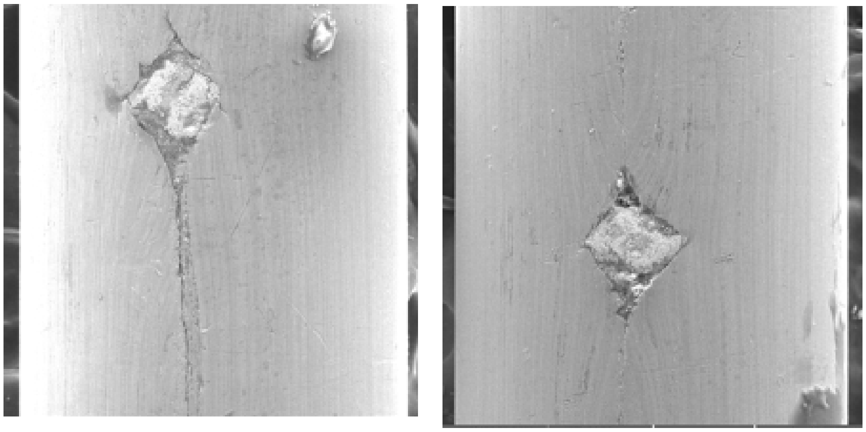


Figure 10. Created mold with defective filament

There are two typical types of defect, as shown in Figure 11 (a) is a result of scratch and it is possible to predict the initial and ending points of these scratches, almost defects found were similar to Figure 11 (a). However, Figure 11 (b) shows a special defect which containing a special material in side of the defects.



a. Type 1



b. Type 2

Figure 11. Typical types of surface defect

5. Conclusion and Future Research

In this research, we have proposed a comprehensive methodology for detecting micro surface defect on steel wire, using eddy current sensor technique. Eddy current sensor was tested with an artificial surface defects in order to set the working condition to apply for mass production and separated defective products which found with surface defects. This method can be applied in many various applications including manufacturing field as steel wire production, it can be set as a quality gate where the out-of-specification goods will be eliminated and improve the customer satisfaction. With this method, the failure rate occupied at 26.37% with 182 manufactured products, this defective rate will be calculated as a standard for the output yield. The detected surface defects were also verified by manually pulling back and compared the manual results to those obtained from eddy current sensor during production. There are two kinds of surface scratch, the first one is longitudinal defect with initial point and ending point and the second defect is diamond shape containing an external material. The novelty of this work is providing a state-of-the-art approach to defect the micro defect during a very high speed of machines, it helps to reduce the man power and replace human in terms of quality standard and reduce the failure risk at end user such as flat tire on the road, broken hose wires, etc. In the future works, surface scratches will be analyzed more detail such as cross-sectional, energy dispersive spectroscopy (EDS) analysis, dimensions in vertical and longitudinal direction as well, root cause/origin analysis and perform quality improvement.

References

Yun, J. P., Choi, D. C., Jeon, Y. J., Park, C., & Kim, S. W., Defect inspection system for steel wire rods produced by hot rolling process, *The International Journal of Advanced Manufacturing Technology*, 70(9), 1625-1634, 2014.

Wu, B., Wang, Y. J., Liu, X. C., & He, C. F., A novel TMR-based MFL sensor for steel wire rope inspection using the orthogonal test method, *Smart Materials and Structures*, 24(7), 075007, 2015.

Zhou, P., Zhou, G., Wang, S., Wang, H., He, Z., and Yan, X., Visual Sensing Inspection for the Surface Damage of Steel Wire Ropes with Object Detection Method, *IEEE Sensors Journal*, 2022.

Zhang, G., Tang, Z., Fan, Y., Liu, J., Jahanshahi, H. and Aly, A.A., Steel Wire Rope Surface Defect Detection Based on Segmentation Template and Spatiotemporal, Gray Sample Set, *Sensors*, 21(16), p.5401, 2021.

Saludes-Rodil, S., Baeyens, E. and Rodríguez-Juan, C.P., Unsupervised classification of surface defects in wire rod production obtained by eddy current sensors, *Sensors,* 15(5), pp.10100-10117, 2015.

Yoshida, K., Norasethasopon, S., Shinohara, T. and Ido, R., Influence of flaws of wire rod surface, inclusions and voids on wire breaks in superfine wire drawing, *JSME International Journal Series A Solid Mechanics and Material Engineering*, 46(3), pp.365-370, 2003.

Shinohara, T. and Yoshida, K., Deformation analysis of surface defects in wire drawing, *In AIP Conference Proceedings* (Vol. 712, No. 1, pp. 594-599), *American Institute of Physics*, 2004.

Jasper, W.J. and Potlapalli, H., Image analysis of mispicks in woven fabric, *Textile Research Journal*, 65(11), pp.683-692, 1995.

Conci, A. and Proença, C.B, A computer vision approach for textile inspection, *Textile Research Journal,* 70(4), pp.347-350, 2000.

Lane, J.S., Milliken Research Corp, *Textile fabric inspection system, U.S. Patent* 5,774,177, 1998.

Daugman, J.G., Uncertainty relation for resolution in space, spatial frequency, and orientation optimized by two-dimensional visual cortical filters, *JOSA A*, 2(7), pp.1160-1169, 1985.

Sari-Sarraf, H. and Goddard, J.S., Vision system for on-loom fabric inspection, *In 1998 IEEE Annual Textile, Fiber and Film Industry Technical Conference* (Cat. No. 98CH36246) (pp. 8-1). IEEE, 1998.

Brzakovic, D.P. and Sari-Sarraf, H., Automated inspection of nonwoven web materials: A case study, *In Machine Vision Applications in Industrial Inspection II* (Vol. 2183, pp. 214-223), SPIE, 1994.

Zhang, J., Kang, D. and Won, S., Detection of scratch defects for wire rod in steelmaking process, *In ICCAS 2010 (pp. 319-323)*, *IEEE*, 2010.

Filipović, M., Eriksson, C. and Överstam, H., Behaviour of surface defects in wire rod rolling, *Steel research international,* 77(6), pp.439-444, 2006.

Filipovic, M., Evolution of artificial defects during shape rolling (Doctoral dissertation, KTH), 2007.

Biography

Kim Sang Tran is a PhD candidate at Monash university, Vice President at Bilal Global Management Consulting (BGMC). He holds a B.S in Mechanical Engineering (Honours) from Vietnam National University – HCM and a Msc in Intelligent Micro/Nano in Konkuk university, South Korea. Mr. Kim Sang was an Engineering Assistant Manager at R&D Center, Hyosung Vietnam company. He also worked as Senior Manufacturing Engineer at Robert Bosch Vietnam before working for Stada Group as Senior Deputy Head of Operational Excellence where he received a best employee award from Stada company, he has hands-on experience in Lead Auditor, Quality management, Global integrity strategy. He is also a Global senior consultant for BGMC and joins many consultant projects for companies in various nations. Mr. Kim Sang has certified Lean Six Sigma Black Belt from Six Sigma Management Institute. He has carried out the training course for professional problem solving (8D), Quality management systems, and Continuous improvement. He is working as a PhD candidate at Monash University in Australia and he has published 2 journal and 4 conference papers. His research interests include manufacturing optimization, lean manufacturing, continuous improvement, micro/nano positioning manipulation and control system.