

## A precise magnetic flux leakage method for the defects detection within the steel thin sheet

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### Abstract

Defects detection of ferromagnetic steel thin sheet is very important in metallurgical industry. In this article, a new magnetic flux leakage (MFL) technology is used to complete this task. In our work, a tiny permanent magnet is used to replace the conventional coils to magnetize testing specimen and precise Tunnel Magneto-resistive (TMR) sensor is employed because of its superior sensitivity and linear operation range over traditional magneto-resistive sensors. Two kinds of thin sheets were selected: galvanized sheet and cold-rolled sheet. The experimental results indicate that the present method is reliable for detecting defects of steel thin sheet, and defects with diameter of 400 and 20  $\mu\text{m}$  can be detected clearly for galvanized sheet and cold-rolled sheet, respectively. This accuracy fully satisfies the metallurgical production requirement. This method exhibits its potential to realize *in-situ*, online inspection process of thin sheet production.

**Key words:** magnetic flux leakage; permanent magnet; Tunnel Magneto-resistive; steel thin sheet

### 1. Introduction

In metallurgical industry, steel thin sheet is a kind of steel with large aspect ratio, its thickness usually locates at the range of 0.2 ~ 4 mm<sup>1,2)</sup>. Nowadays, steel thin sheet such as galvanized sheet<sup>3,4)</sup>, cold-rolled sheet<sup>5-7)</sup>, stainless steel sheet and silicon steel sheet, accounts for 50% of all rolled products. Despite the use of new construction materials, the steel thin sheet still widely used in the production of tractors and automobiles, in building, in power industry, in railroad, and elsewhere<sup>7)</sup>. Therefore, the defects detection of steel thin sheet is a very important process in metallurgical industry.

Ferromagnetic property is another distinct characteristic of steel thin sheet, hence the magnetic flux leakage (MFL) technology<sup>8-13)</sup> can be employed in its defects detection process. MFL technology is a non-destructive testing and commonly used to detect metal losses caused by corrosion in steel constructions. This technology focus on the detection of defects by detecting magnetic anomalies in magnetic flux lines using magnetic sensors.

In this article, we detect the defects of galvanized sheet and cold-rolled sheet using tunnel magneto-resistive (TMR) sensor MFL technology, and expect this technology can be applied in *in-situ*, online inspection process of steel thin sheet. The measurement principle and process are shown in the next section, and the results and discussions can be found in the section 3 and 4.

### 2. Measurement principle

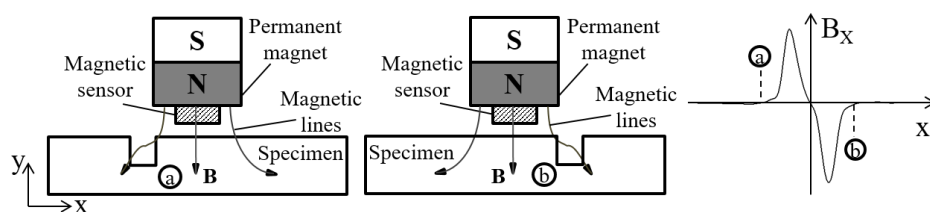


Fig. 1: The basic principle of the new MFL method used in this experiment

The basic idea of MFL technology is that the ferromagnetic material is magnetized under the applied magnetic field<sup>8</sup>. The principles are shown as Figure 1. When there is no defect within the specimen, the magnetic flux lines remain within the ferromagnetic material and undisturbed; when the defects are presented within specimen, the magnetic resistance increase acutely because the magnetic permeability of the defects is much smaller than that of the specimen itself, and consequently the magnetic flux in this area is distorted. The magnetic flux lines leak out of the specimen surface, and the magnetic leakage field obtained by using sensitive magnetic sensors<sup>14, 15</sup>. In recent years, the MFL technology has frequently used Giant Magneto Resistive (GMR)<sup>16</sup>, Giant Magneto Impedance (GMI)<sup>17</sup> and Magneto Optical (MO) sensors<sup>18</sup> as well as Hall sensors and search coils<sup>19</sup>. When the defect passes underneath the magnet as shown in Figure 1, the signal will character the sinusoidal shape.

### 3. Experimental process and results

#### 3.1. Experiment setup

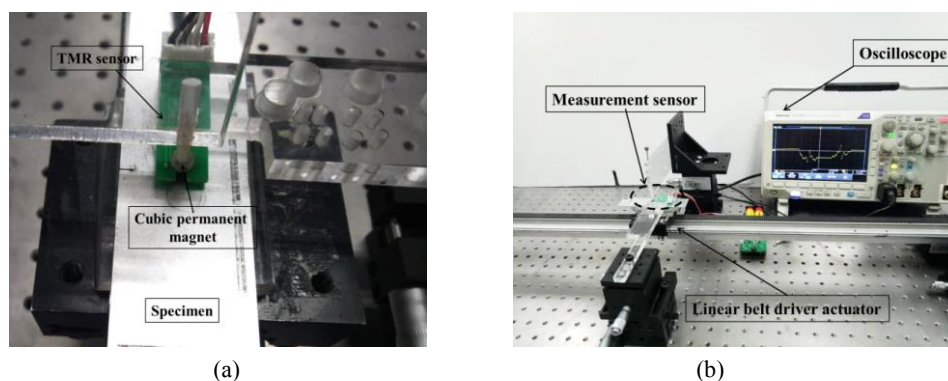


Fig. 2: Experimental setup. (a) Detailed arrangement presentation. (b) General view

In order to complete the detection assignment, an experimental apparatus is built. The detail about the measuring sensor can be found in Figure 2(a). In this experiment, a cubic permanent magnet with width of 2 mm is applied to magnetize the ferromagnetic specimen, and a precise TMR sensor is employed because it has superior performance in sensitivity and linear operation range over conventional magnetic sensor.<sup>20</sup> It is reported that TMR possess an exceptional 70% change in resistance while GMR can only achieve 10-15%<sup>20</sup>. This inherent property grants TMR sensor yields very high sensitivity to the variation of magnetic field. As depicted in Figure 2(b), the steel thin sheet specimen is placed closely on a linear belt driver and move with it in a constant speed. The measuring sensor is fixed above the specimen with the interval of 0.3 mm. A sophisticated oscilloscope (MDO-3022, Tektronix Company) is used to record the signals.

#### 3.2. Experiment results

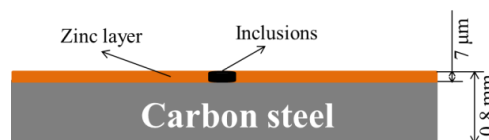


Fig. 3: The sketch of the structure of galvanized sheet

The structure of the galvanized sheet specimen, which comes from a metallurgical plant, is schematically depicted in Figure 3. Zinc layer is coated in hot-dip process in order to obtain a high corrosion resistance of the thin sheet production. During this process, the oxygen inclusions are often introduced and extruded, which will be seriously harmful to the final production quality. The thickness of galvanized sheet and

zinc layer are 800 and 7  $\mu\text{m}$ , respectively. In this specimen, normally, the threshold size of inclusions is controlled under 500  $\mu\text{m}$ .

In Figure 4, two galvanized sheet specimen, marked as No.1 and No.2, are employed in the experiment. For comparison, the electron microscope images of defects are shown in Figure 4(a) and (c) indicating that the defects are irregular and their equivalent diameters are 396 and 405  $\mu\text{m}$ , respectively. The corresponding measurement signals obtained using MFL technology is shown in Figure 4(b) and (d). It is evident that the signals yield a high signal-to-noise ratio (SNR) (exceed 10 db) and character positive-negative peak. Fluctuations at begin and end of the signal are formed because the specimen is uneven. The measurement taken at different direction indicates the MFL technology is reliable.

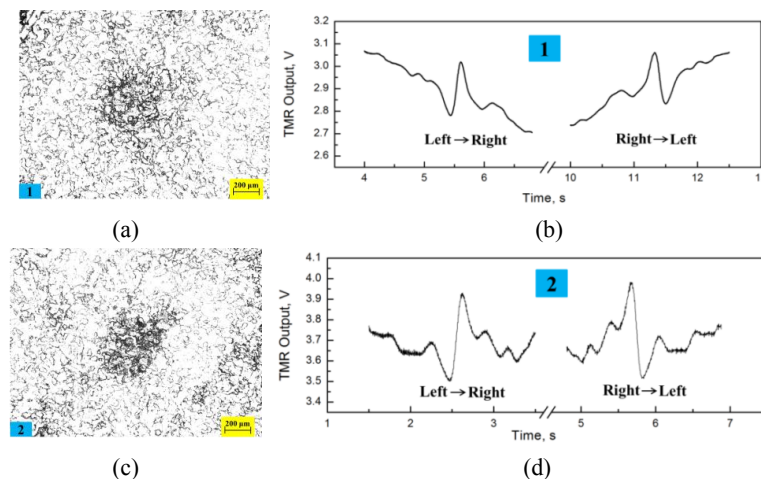


Fig. 4: The images of two galvanized sheet specimen defects (a) and (c) taken by electron microscope and the corresponding measurement signals (b) and (d)

As to cold-rolled sheet, the detection of defects with size exceed 20  $\mu\text{m}$  is of important significance for production process. Similarly, another cold-rolled sheet specimen is detected using MFL technology and the result is presented in Figure 5. Upper electron microscope image show that the diameter of the defect is about 20  $\mu\text{m}$ . The signals are verified via the superposition of perpendicular moving direction and they are also apparent and repeatable. This experimental result suggests that this new MFL method can satisfy the requirement of cold-rolled sheet defects detection.

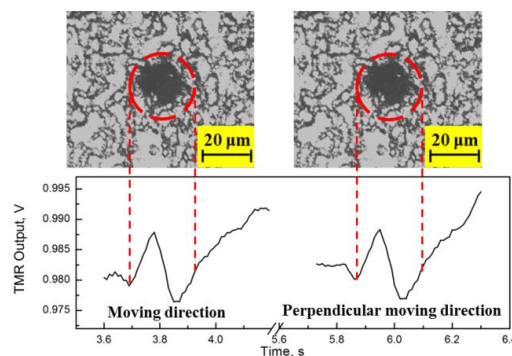


Fig. 5: The electron microscope image and signal of the 20  $\mu\text{m}$  defects in cold-rolled sheet

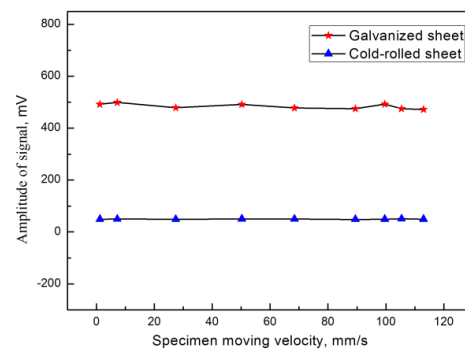


Fig. 6: The relationship between moving velocity and amplitude of signal

In present article, the relationship between amplitude of signal and specimen moving velocity is investigated as seen as Figure 6. The moving velocity is at 0~120 mm/s. For galvanized sheet and cold-rolled sheet, the moving velocity has few impacts on the amplitude of signal. This is because at low

moving velocity, magnetic Reynolds number  $R_m = \mu_0 \sigma v L \ll 1$ , so that the induced magnetic field generated by eddy current can be neglected, and the leakage magnetic field mainly from the applied magnetic field.

#### 4. Conclusions and prospects

In this study, a new MFL technology is applied to detect the defects of steel thin sheet. A tiny permanent magnet is used to substitute the conventional coils and precise TMR sensor is used to acquire the change of magnetic field. Galvanized sheet and cold-rolled sheet are selected as testing specimen, and corresponding defects with diameter of 400 and 20  $\mu\text{m}$ , which can satisfy the metallurgical plant requirement, can be detected clearly. The experimental results in this article indicate that this new method is a reliable and convenient to inspect the defects of steel thin sheet. In the future, *in-situ*, online defects detection technology is an irresistible trend. Therefore, MFL-based sensor array should be applied in steel thin sheet producing process for detecting the defects. Our future research work will focus on this topic.

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#### References

1. M. Takahashi: *ISIJ Int.*, **55** (2015), 79-88.
2. A. B. Maksimov and I. S. Erokhina: *Steel Transl.*, **47** (2017), 752-755.
3. S. Li, Z. Yu, P. Zhang, X. Li, D. Qiu and X. Liu: *ISIJ Int.*, **56** (2016), 637-646.
4. K. Hoshino, M. Nagoshi, W. Tanimoto, Y. Yamasaki, S. Furuya, A. Matsuzaki and N. Yoshimi: *ISIJ Int.*, **57** (2017), 895-904.
5. J. Hu, W. Cao, C. Wang, H. Dong and J. Li: *ISIJ Int.*, **54** (2014), 1952-1957.
6. T. Kizu, K. Okuda, Y. Nagataki, T. Urabe and K. Seto: *ISIJ Int.*, **55** (2015), 1502-1511.
7. I. V. Doshchechkina, S. S. D'Yachenko, I. V. Ponomarenko and I. S. Tatarkina: *Steel Transl.*, **46** (2016), 364-367.
8. Y. Shi, C. Zhang, R. Li, M. Cai and G. Jia: *Sensors*, **15** (2015), 31036-31055.
9. D. A. G. Trevino, S. M. Dutta, F. H. Ghorbel and M. Karkoub: *IEEE Trans. Magn.*, **52** (2016).
10. W. Han, J. Xu, M. Zhou, G. Tian, P. Wang, X. Shen and E. Hou: *IEEE Trans. Magn.*, **52** (2016).
11. Y. Sun and Y. Kang: *Appl. Phys. Lett.*, **103** (2013).
12. Y. Sun, B. Feng, S. Liu, Z. Ye, S. Chen and Y. Kang: *J. Nondestruct. Eval.*, **34** (2015).
13. E. Yavuz and C. Mustafa: *Measurement*, (2018), 163-174.
14. Y. Zhang, Z. Ye and C. Wang: *Ndt & E International*, **42** (2009), 369-375.
15. A. N. Pechenkov, V. E. Shcherbinin and J. G. Smorodinskiy: *NDT&E Int.*, **44** (2011), 718-720.
16. J. W. Wilson and G. Y. Tian: *NDT&E Int.*, **40** (2007), 275-283.
17. M. M. Tehranchi, M. Ranjbaran and H. Eftekhari: *Sensor Actuat A: Phys.*, **170** (2011), 55-61.
18. V. Babbar and L. Clapham: *J. Nondestruct. Eval.*, **22** (2003), 117-125.
19. L. Yang, L. Jie, H. Xuezhi and Z. Duoduo, *Proceedings of the 2009 Asia Communications and Photonics Conference and Exhibition* (2009), 2.
20. B. Wu, Y. J. Wang, X. C. Liu and C. F. He: *Smart Mater Struct.*, **24** (2015).