Development of a Residual Stress Sensor and its Applications for Flatness Improvements of Steel Coils and Plates

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Residual stress is an invisible force locked inside the material which often brings unfavorable effects to the flatness and dimensional accuracy when it is released by material removal process. Efforts have been attempted to control the residual stress on the production lines of coils and plates, but little can be achieved due to insufficient information. To overcome the problem, China Steel Corporation (CSC) has been devoted to developing a portable magnetostrictive sensor which is aimed at archiving on-site residual stress measurement. The sensor has attractive features such as a compact size of 63×63×66mm^3, high data throughput at 10 measurements per second, as well as wireless connectivity for data transfer. With assistance of the portable device, flatness improvements were carried out throughout years. In this paper, three typical cases are reported, namely flatness improvement of POL coil sheet, reduction of sheet deflection after laser cutting process, and minimizing camber deflection of TMCP plate.

Keywords: residual stress, magnetostrictive, measurement, flatness

1. INTRODUCTION

Quality defects due to poor residual stress management is always a challenging problem in the steel industry. There are two aspects in which residual stresses bring harmful effect to flat products. First, distortion and dimensional instability caused by the release of residual stress during material removal process such as cutting, milling or drilling which often leads to excessive profit losses and increased remanufacturing cost. The situation can be better explained by the FEM simulation as shown in Fig.1. A plate having T-C-T residual stress distribution experiences significant camber-style deformation when cutting along its length direction. For most steel providers, it is very difficult to detect such defects before product shipment because of the lack of reliable measurement technology. Second, flatness issues such as C-bow and L-bow deflection are related to the irregular plastic deformations induced by the manufacturing process. Fig.2 shows a typical C-bow deflection on the production line of hot roll coil. Such deformation is always accompanied by residual stresses with certain features or patterns. Therefore, the cause of the poor flatness issues could be identified by acquiring useful residual stress information.

Various methods have been proposed for measuring residual stress over the decades, including both destructive and non-destructive techniques. Destructive

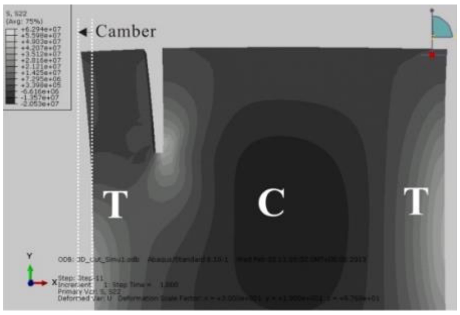


Fig.1. Deformation caused by residual stress during cutting process (T: Tension; C: Compression)

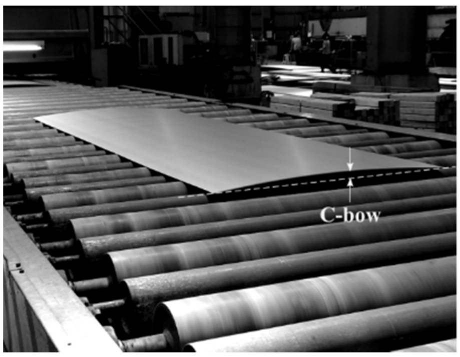


Fig.2. C-bow deflection on the production line

methods such as hole-drilling, contouring and slitting methods(1-4) are well-known for quantitative accurate measurements. CSC has developed a lab-based slitting method, mostly applied to aluminum plates, for measuring quenching stress distribution in thickness direction (5,6). Even though the informative measurement data serves as an important basis for analysis, such technique is time consuming and relies heavily on years of operating experience. On the contrary, non-destructive methods offers convenient ways to obtain surface stresses with acceptable accuracy(7-9). Among them, the magnetic method which originates from the ferromagnetic nature of steels offers high resolution stress data near the surface. This paper presents the development of a portable residual stress sensor suitable for on-site measurements based on the magnetic method. Section 2 explains the underlying magnetostrictive principle as well as design philosophy of the probe. System integration and lab-testing results are outlined in section 3. As accumulative results have been obtained by applying the sensor for solving flatness problems of plates and coils, three cases with remarkable results are reported in section 4. Finally, conclusions are drawn in section 5.

2. RESIDUAL STRESS MEASUREMENT

In this section, we introduce a probe design for measuring residual stress of steel by taking advantages of its ferromagnetic properties. The idea is to amplify the magnetostrictive phenomena by geometrically designing the probe based on the differential measurement principle so as to generate very sensitive magnetic flux due to elastic deformations.

2.1 Magnetostrictive principle

Since the probe is a technological application of magnetostrictive principle, a brief explain of such phenomena is illustrated as follows. Magnetostriction characterizes the strong relation between the magnetic property and physical deformation of ferromagnetic material, through a well-known effect termed spin-orbit coupling (10). Fig.3 shows how the deformation, i.e. size variation of an atom, changes the magnetization state, i.e. the magnetic dipole of outer shell electrons, through this quantum interaction. As a result, a tensile strain will slightly increase the magnetic permeability of steel, while a compressive strain with the same magnitude results in a much more significant degradation of magnetic permeability(11).

2.2 Sensor design based on differential magnetic flux

The objective of the probe design is to quantitatively measure magnetostrictive effect using electromagnetic principles. To this end, a structure with eight iron cores as shown in Fig.4. is proposed. Magnetic fluxes are generated and sensed by the coils on the iron cores, which can be divided into two groups, namely excitation coils and receiving coils. During the measurement, the probe is placed onto the material under investigation with its pole faces attached to the surface, while the excitation coils are powered by amplifiers at 100Hz so that sinusoidal time-varying closed magnetic loops are formed in both directions. Because of such design, coils at the corners pick up the flux difference φ_x-φ_y and is amplified in a physical way by 1200 turns of the wiring loop. The output voltage signal is then quadrupled by connecting the four coils in series, which can be expressed as follows,

$$V = K(\varphi_x-\varphi_y) \qquad (1)$$

When the area under the probe has tensile stress in x-axis, the net fluxes pick up by the receiving coils is in phase with the x-axis excitation coils, and vice versa. By placing the probe along the rolling or transverse directions of the sheet/plate sample, residual stress distribution can be obtained.

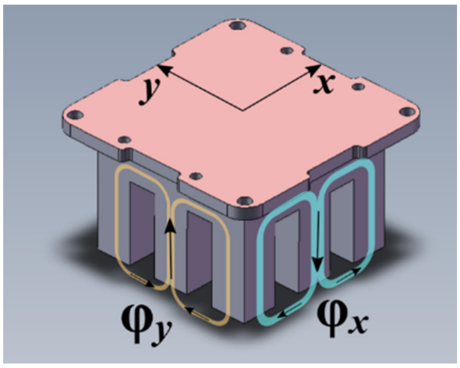


Fig.4. High sensitivity probe design

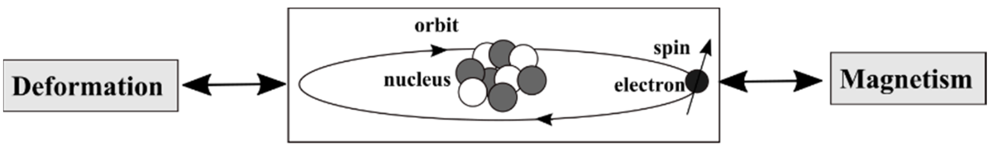


Fig.3. Magnetostriction is a physical phenomena driven by spin–orbit coupling

3. SYSTEM INTEGRATION AND LAB TESTING

The probe can be easily turned into a laboratory device with adequate peripheral devices including a sine-wave driven power amplifier to deliver driving currents to the coils, as well as an oscilloscope for signal digitization and observation. However, the application of such a bulky system is limited, especially when on-site measurement is demanded. To this end, it is highly desired to transform the measurement system into a portable device.

3.1 Signal processing method

In order to observe how the coil signal responses to different deformation states, the probe was placed on a steel sheet sample which was stretched by a tensile machine. Fig.5. shows the signals of different stress states generated at various levels of tension and compression forces. It is seen the amplitude of the pick-up coil voltage is proportional to the strain, and is in (out-of) phase with the excitation voltage when tensile (compressive) deformation is applied. It was observed that the two signal levels are orthogonal in time space, by having a comparably small pick-up voltage and the phase difference by 90° when no deformation is applied. A Residual Stress Index (RSI) is proposed for calculation stress state through coil voltages,

$$RSI = \int_0^T E(t)R(t)dt \quad (2)$$

where E(t) and R(t) represents excitation and pick-up voltages, respectively. By integrating over a certain time period of 0.1 second (T), the amplitude and phase relations between voltage waveforms can be converted into a single value RSI. Since (2) is a neat and simple equation which can be easily realized by a micro-processor, developing a portable measuring device becomes a practical task.

3.2 Portable device development

Efforts have been dedicated to the development of the portable device. First, a printed circuit board (PCB) was designed by integrating current driving and signal acquisition functions. After which, RSI is calculated by a micro-processor and transmitted wirelessly at 10Hz. Second, the probe, the aforementioned PCB and a battery were incorporated into an aluminum case having an easy handheld size of 63×63×66mm^3. The battery powered device could sustain over 6 hours of continuous measurement in the lab test. Finally, the portable device was equipped with Bluetooth connectivity such that personnel can collect the data with a mobile phone through a user friendly App. Fig.6 demonstrates compact size portable sensor delivering real-time stress data through its wireless function.

3.3 Repeatability test

Before sending the portable device into real world applications, laboratory tests were performed in advance so as to evaluate the repeatability. In order to further increase sensitivity, probes manufactured by steel of different grades were tested, and the material with the largest coil signal was chosen for mass production. Eventually, four probes manufactured with exactly the same

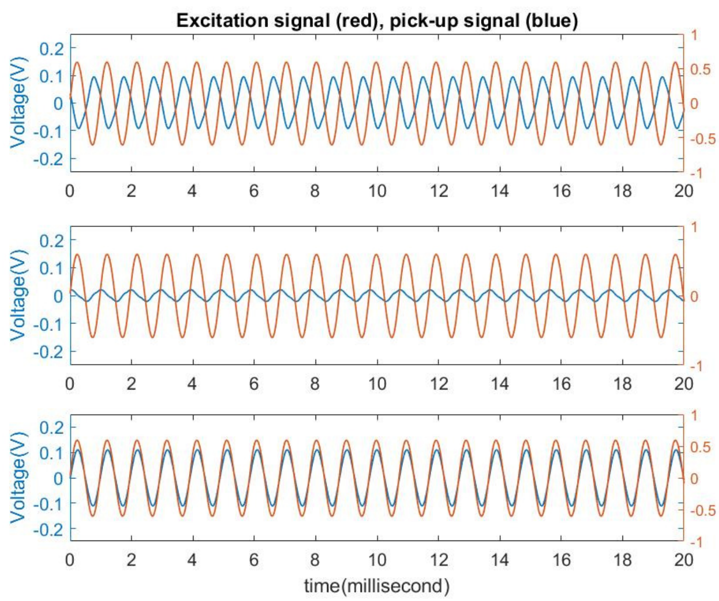


Fig.5. Voltage signal at different stresses, compression (top), no stress (middle), tension (bottom)

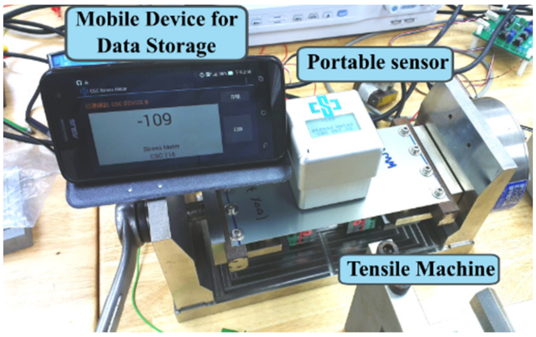


Fig.6. The developed portable sensor exhibits its wireless connectivity

material were put to test. The repeatability test was performed in two ways. First, the force-RSI relation was calibrated by four probes on the tensile machine. The curves in Fig.7 shows satisfactory repeatability, along with a logarithm relation with the increasing forces. Second, a 2mm steel sheet sample with known manufacturing process was sampled for lab test. As depicted in Fig.8, measurement results obtained by scanning different probes along the width of the sample showed highly agreeable data.

4. MEASUREMENT AND APPLICATION RESULTS

Since the portable device was customized for on-site measurement, it has been served as a basic tool for analyzing the manufacturing process by providing valuable residual stress data. In this section, three cases with impressive results are presented to explain how the residual stress measurements can improve the manufacturing process.

4.1 Flatness improvement of POL coil sheet

The POL (pickled and oiled line) coil was sent to the customer's site for subsequent process. However, the flatness remained unsatisfactory even after several runs of the roller leveling process. Since it was difficult to identify the key parameters leading to such a problem, the portable device was used to obtain residual stress data of samples cut down from different positions of the coil. It was found all the measurement data has the periodic feature of 25cm in its stress profile as shown in Fig. 9, which was coinciding with the arrangement of the back-up roll interval in the tension leveller. The stress concentration resulted by the discontinuities of the roll profile was then removed by grinding the roll surface. The reproduction shows a much smoother stress profile (Fig.10), which agrees with the customer's experience.

4.2 Improvement of laser cutting deflection of steel coil

For steel plants, there is an increasing demand in offering steel coils with minimum residual stresses due to the requirements of strict manufacturing standards for the purpose of precision assembly. A SPHC coil manufactured by CSC was once rejected by the customer because of large out-of-plane deflection after the laser cutting process. Again, steel sheets were sampled from coils and were scanned by the probe across the width on both surfaces. As shown in Fig.11a, the separated residual stress profiles on front and back surfaces indicate a sign of excessive bending deformation during the coiling process. The deflection of the steel sheet was not obvious because of counterbalancing effect imposed by its own weight. Large deflection appears only when the sheet was cut into smaller pieces. One way to change the plastification is to elevate material strength by adjusting the coiling temperature. By doing so, the diminished gap between the front and back surfaces averaged data represents a diminshed deformation (Fig.11b). The improvement is impressively shown in Fig.12. The original deflection of 8mm (Fig.12a) was reduced to less than 2mm after the cutting process (Fig.12b).

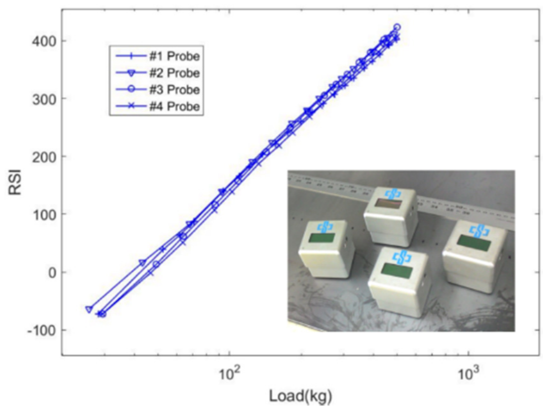


Fig.7. RSI is in linear relation with log(σ)

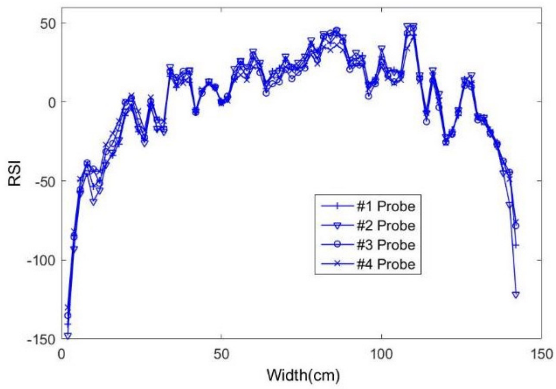


Fig.8. Repeatability test performed on the same steel sheet sample

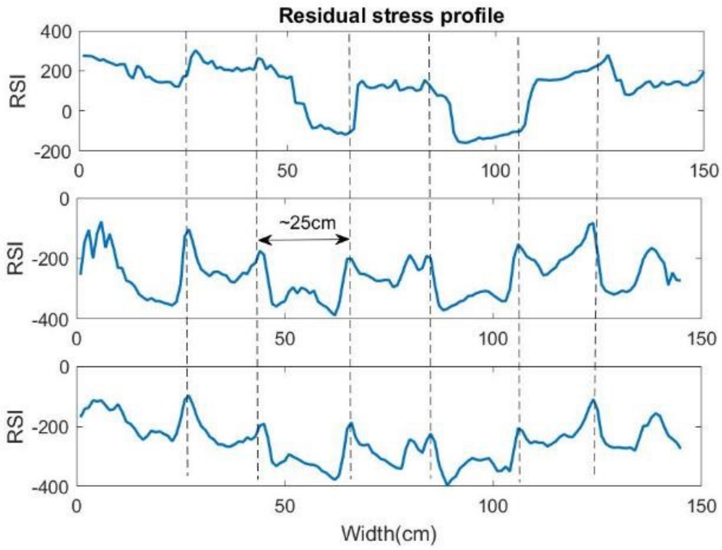


Fig.9. Residual stress profiles having the same periodic feature was identified

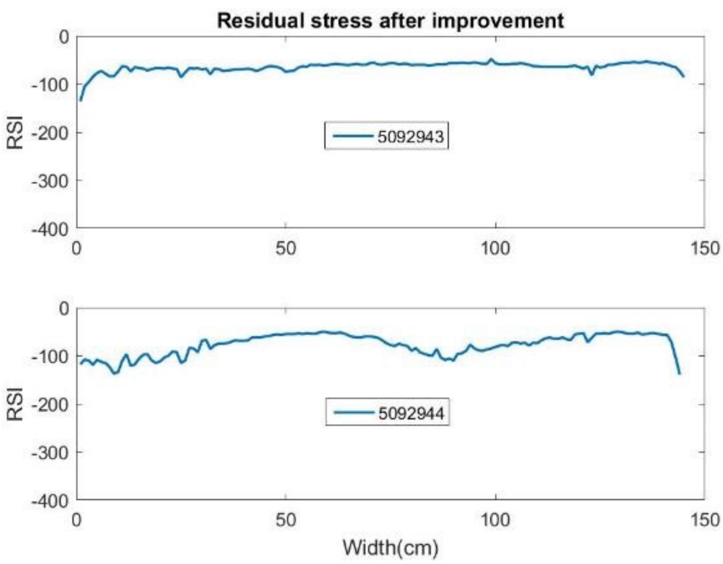


Fig.10. Measurement data shows the localized plastic deformation was removed

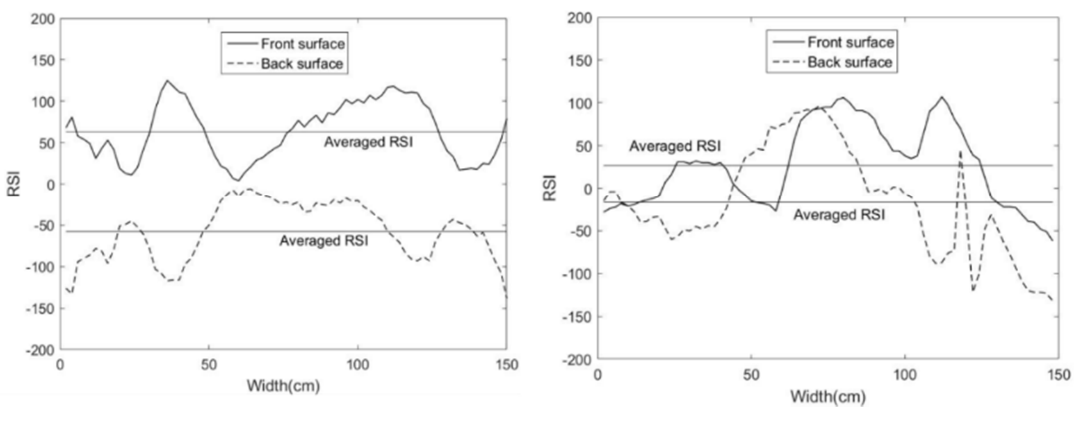
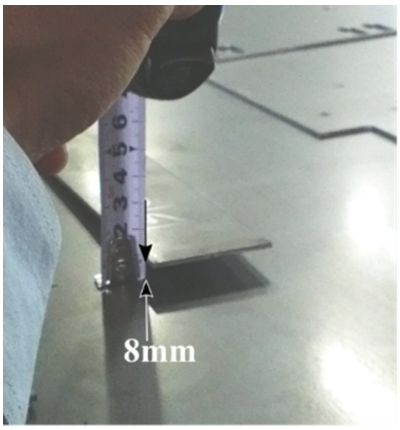
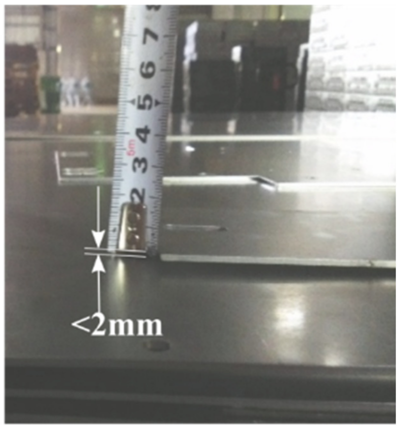


Fig.11. Residual stress measurement results. (a) A large gap between two profiles (b) The gap becomes smaller after improvement



(a)

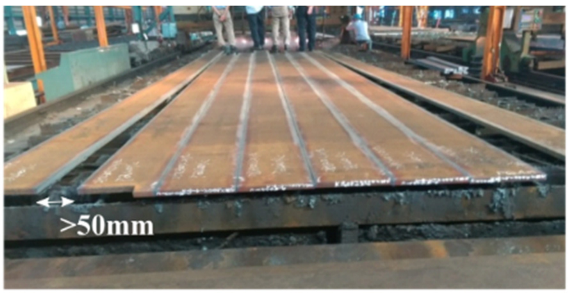


(b)

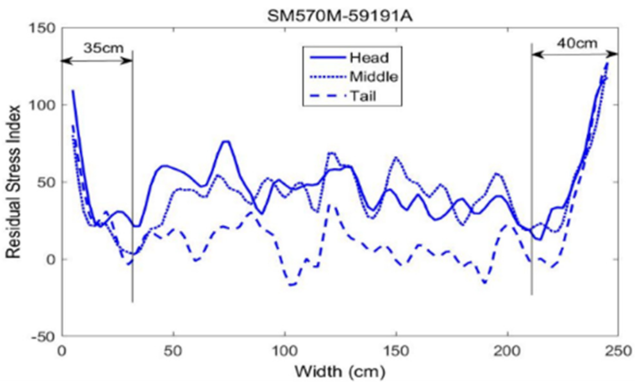
Fig.12. The deflection of the laser cutting pieces (a) Original 8mm deflection (b) Less than 2mm after improvements

4.3 Minimization of camber deflection in TMCP plate

This case demonstrates how the minimization of camber deflection of TMCP (Thermo- Mechanical Controlling Process) plate was assisted by the portable sensor. Due to the uneven water distribution during the quenching process, residual stresses were built such that over 50mm of deformations as shown in Fig.13a were observed when the plate was slitted into several pieces with equal size. The distorted geometry is unacceptable for further assembly process such as fastening and welding. To investigate the problem, the residual stress data is acquired by the portable sensor on the production site before the slitting process. As shown in Fig.13b, the measurement results featuring very large tensile stress on the edges agree with the low cooling rates due to ill-controlled edge-masking during water quenching. A possible remedy to such a problem is to run an additional leveling process. To investigate the effectiveness, a 3D Finite-Element simulation was performed, to show an attenuated stress magnitude can be obtained through multiple reverse bending applications as applied by a roller leveller. This can be illustrated in Fig.14, in which the large stress gradient was significantly reduced after bending multiple times. This stress reduction effect can be proven by the real production process. Fig.15a shows the residual stress of the same plate was greatly reduced after the roller leveling process, as predicted by the simulation. As a result, less than 5mm of deflection was achieved and is depicted in Fig.15b, demonstrating the feasibility of applying the sensor to validate the stress developing process and to improve the quality of the TMCP plate. Traditionally, the roller leveller is known for improving out-of-plane deformations such as L-bow and C-bow by applying opposite bending with decaying magnitudes repeatedly. The value of this study is to demonstrate that roller leveling is also effective for correcting in-plane deflections.



(a)



(b)

Fig.13. Camber deformation of plate (a) Unacceptable deformation (b) measurement data with large tensile stress near edges

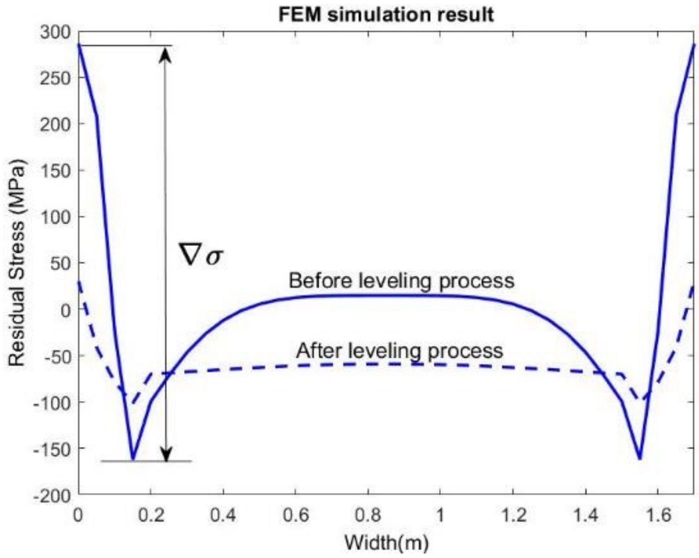


Fig.14. Demonstration of stress attenuation by FEM simulation result

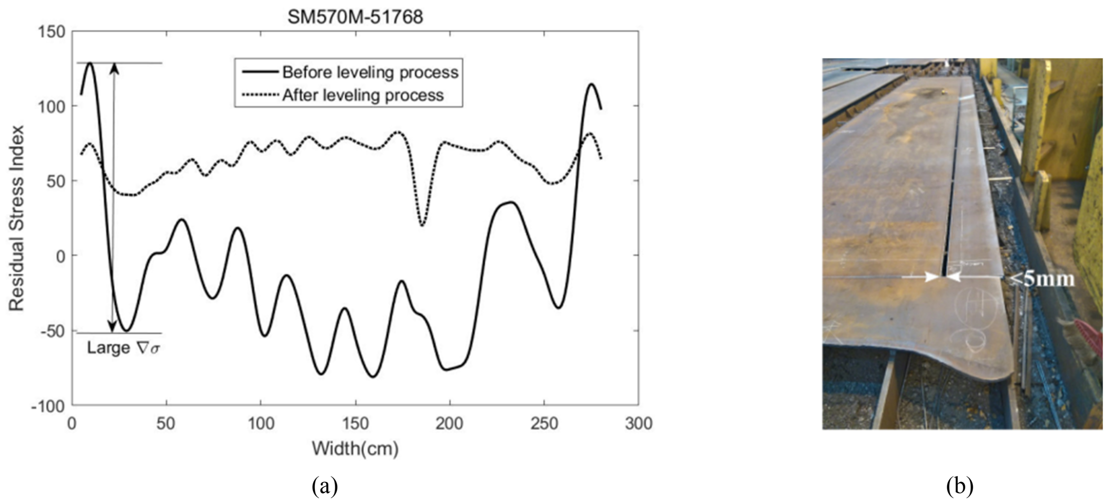


Fig.15. Improvement of camber deformation (a) Large stress gradient is reduced (b) less than 5mm deformation

5. CONCLUSIONS

Residual stress is difficult to detect not only due to its invisible nature, but also to the commercial unavailability of the technology. CSC has developed a residual stress sensor based on the magnetostrictive principle. The sensor is portable, highly sensitive, having fast response, and equipped with wireless connectivity. Because of the user friendly design, the sensor has been applied to measure steel plates and coils with serious flatness problems. Sufficient residual stress data can be obtained in minutes, and was subsequently used for analyzing complicated deformations accompanied by the manufacturing process. With the help of the technology, key factors such as roll profile, coil temperature control, and leveling parameters were found having significant impact on flatness. As a result of the quality improvements, order replacement was prevented and customer satisfaction was restored.

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