THE IMPROVEMENT OF RESIDUAL STRESS FOR LASER CUTTING COIL

BY

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SYNOPSIS:

Pickled and oiled (PO) steel coils need to be cut by laser to meet the customer's requirement. The laser head of the automatic laser cutting system will be damaged while the steel sheets warp after cutting. The damaged laser head not only costs repairing time but also affects the production schedule. In order to solve this problem, residual stress analysis was performed in this study. However, the residual stress analysis by using both the destructive slitting method and non-destructive magnetic sensor demonstrated that the deflected steel sheets and flat steel sheets had different residual stresses profiles (magnitude and direction along the depth and width). Mechanical bending in the process of hot rolled strip coiling might be the key factor. In such process, residual stress is induced when bending force exceeds the yield strength. On the premise of not significantly affecting the mechanical properties, we tried to reduce the CT (coiling temperature) so as to raise the yield strength and reduce the plastic ratio.

As a result, the values of the residual stress profiles on both surfaces of the newly fabricated coils are getting closer, demonstrating a satisfying cutting quality by 60% in warpage reduction. More than 90% of the steel coils have great improvement from the feedback of the customers.

KEYWORDS: laser cutting、residual stress、mechanical bending、yield strength

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1. INTRODUCTION

The laser cutting steel coils usually undergoes manufacturing processes such as hot rolling, water cooling, tempering, and pickling. Each process of the production line induces different profiles of residual stresses. Residual stresses bring harmful effect to flat products in two aspects [1]. The **first one is** distortion and dimensional instability. The situation can be better explained by the FEM simulation as shown in Fig. 1. A plate having a T-C-T residual stresses 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 by any means because of the lacking of reliable measurement technology. **Second,** flatness issues such as C-bow and L-bow deflection [2] 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 sheet. 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. Different profiles of residual stresses are induced in different manufacturing processes of the production line. The steel coil after cutting causes deformation due to the release of residual stress, and this deformation can be of two types as follows: (1) up and down warping or (2) left and right bending.

In order to solve the problems of warping and bending, the causes of residual stress can be roughly divided into three types: **1. Mechanical bending 2. Uneven cooling 3. Microstructure changing.** Mechanical bending is mainly due to the opposite force on the upper and lower surfaces during the rolling, leveling or coiling process. This kind of residual stress has an N-shaped feature profile in the thickness direction.[3]

Uneven cooling is usually caused by poor temperature control. Generally, overheating generates tensile stress and undercooling generates compressive stress. The profile of residual stress is uneven in tension and compression. During the hot rolling process, water is sprayed to precisely control the temperature. If the temperature of the steel plate is unevenly distributed along its width direction, it leads to left and right bending after slitting. If the temperature of the steel plate is non-uniform on the upper and lower surfaces, it easily causes warping such as L-bow and C-bow, featured by vertical deformation along its rolling and cross directions.

Microstructure changing is the residual stress induced by phase transformation due to cooling rate and temperature changing in the quenching process [4]. In the process of quenching, the transformation of austenite to martensite makes ferrite generate hydrostatic tensile stress. Meanwhile, martensite generates compressive stress due to volume expansion. The profile of residual stress induced by the phase transformation is opposite to the ones induced by temperature.

This study used the measured residual stress to track back the cause of the phenomenon in the process, and then changed the process parameters to verify the inferred results. On the premise of not affecting the product's mechanical properties, the key process conditions were changed, and the residual stresses on the surface and thickness direction were re-measured. The results showed that this research and judgment were positively helpful to improve the pickled and oiled steel coils after laser cutting, and also prevent the orders from encroaching by imported materials.

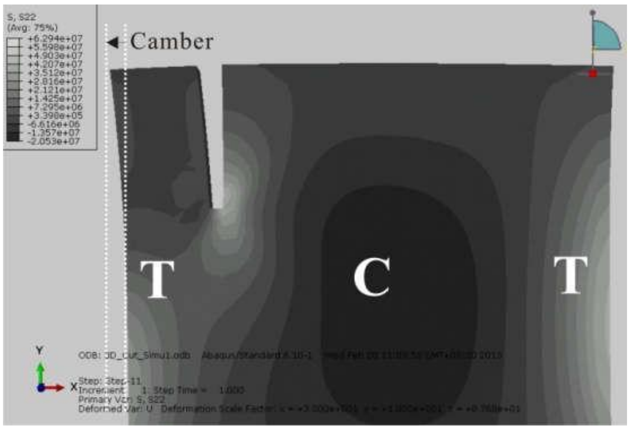

Fig.1. Deformation caused by residual stress during cutting process
(T: Tension; C: Compression)

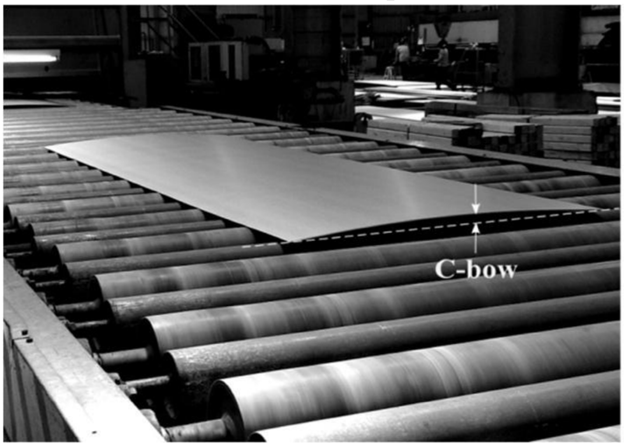

Fig.2. C-bow deflection on the production line

2. MEASUREMENT TOOLS AND APPROACHES

2.1 Portable magnetostrictive device

Residual stress is an invisible force locked inside the material which often brings harmful effect to 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 devoted to develop a portable magnetostrictive sensor which is aimed for on-site residual stress measurement [5]. 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 Bluetooth connectivity for data transfer [6-7]. Personnel can collect the data with a mobile phone through a user friendly App. With assistance of the portable device, flatness improvements were carried out throughout years. Fig. 3 demonstrates compact size portable sensor delivering real-time stress data through its wireless function.

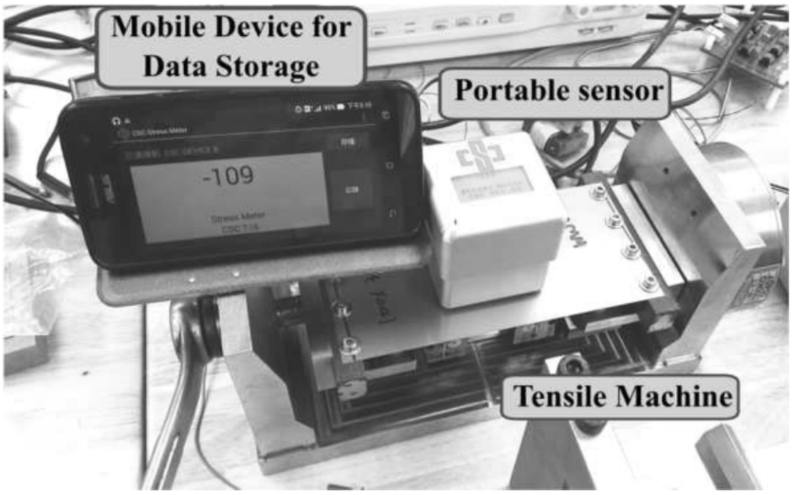

Fig. 3. The developed portable device exhibits its wireless connectivity

2.2 Slitting method

The residual stress distribution in the thickness direction of the material implies a lot of quality and process information, which can be measured by the slitting method. The slitting method is a destructive residual stress measurement method. First, a strain gauge is attached to the back of the sample, and cutting the front side of the sample. During the cutting process, the residual stress is released while deformation occurs. The strain gauge is used to obtain the information of the cutting depth and strain. According to the strain curve, the residual stress can be calculated.

In the experiment, a four-point bending mechanism was used to manufacture the standard test sample and the residual stress can be estimated by the sample. Fig. 4 shows the measurement results of the slitting method, FEM simulation result and theoretical calculation values, which the three curves are quite close.

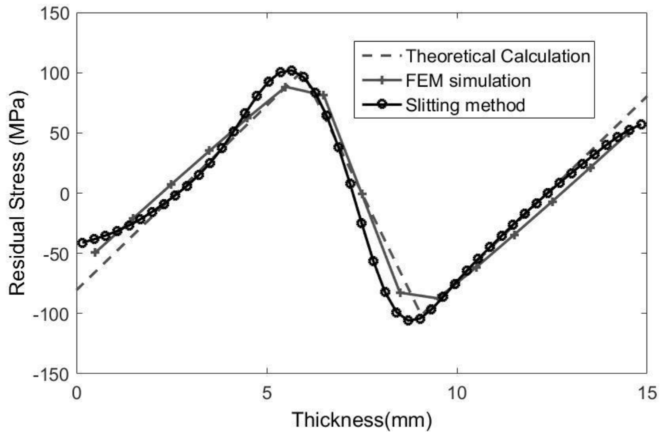

Fig.4 Four-point bending test results measured by slitting method, FEM simulation and theory.

It can be seen from the above results that the residual stress of four-point bending in the thickness direction has the characteristics of N shape, and the residual stresses of compression and tension are on the upper and lower surfaces.

3. MEASUREMENT AND APPLICATION RESULTS

3.1 Residual Stress measurement

The PO (Pickled and oiled) steel coil manufactured by CSC was once rejected by the customer because of large out-of-plane deflection after the laser cutting process. The portable device was used to obtain residual stress data of samples cut down from different positions of the coil and were scanned by the probe across the width on both surfaces. As shown in Fig. 5, the separated residual stress profiles on front and back surfaces indicate a sign of excessive bending deformation during the coiling process.

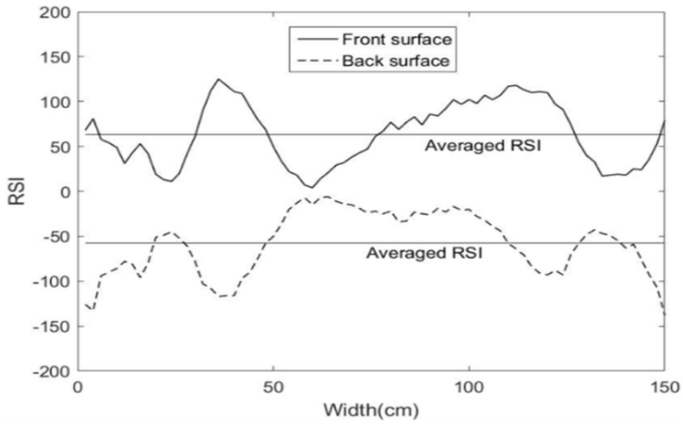

Fig.5 Residual stress measurement results: A large gap between two profiles

3.2 Identify the source of residual stress

To identify the key parameters leading to such problem, the slitting method was used to obtain residual stress data of samples cut down from the coil. It was found there is obvious the compressive stress on the upper and lower surfaces, but the black dotted line in the center has a feature of N-type distribution as shown in Fig. 6. The compressive stresses on the upper and lower surfaces were caused by the cooling of water spray in the hot rolling process. The cooling process is inevitable and almost no parameter can be changed to improve the large discrepancies of upper-lower surfaces. However, the N-type distribution feature implies very large bending has been imposed on the material, which might be the reason of the ill-flatness, we decide to investigate how the plastic deformation was induced by the coiling process.

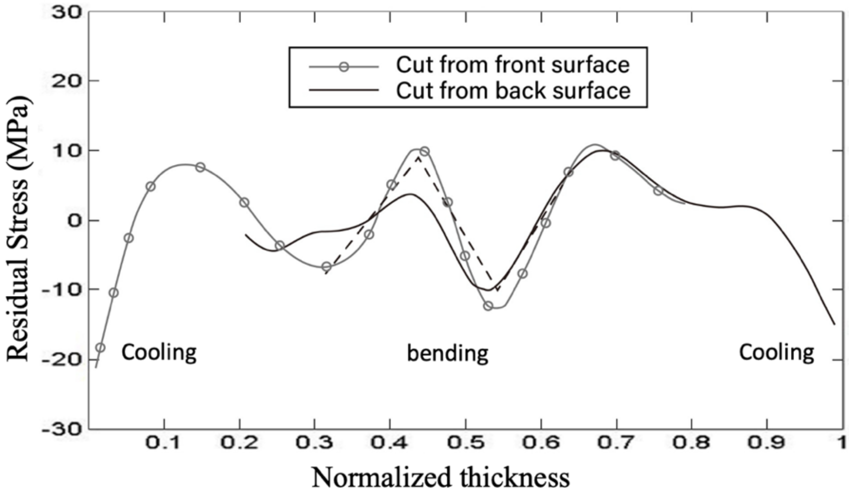

Fig.6 The residual stress distribution measured on the thickness direction of steel coil using slitting method.

3.3 Change coiling process parameters

Because the coiling causes mechanical bending and leads to the undesired-residual stress, we try to reduce the CT (coiling temperature) about 30 degrees. In this way, the yield strength of the steel coil is increased, and the steel coil is more resistant to permanent deformation during the coiling process. Therefore, the amplitude and depth range of the plastic deformation extends from the coil surface can be reduced.

4. ANALYSIS AND IMPROVEMENT

In order to verify the effect of reducing CT, three test pieces were taken for a Fig. 7 shows the stress-strain curves of the test pieces at 610 °C, 580 °C and 550 °C.

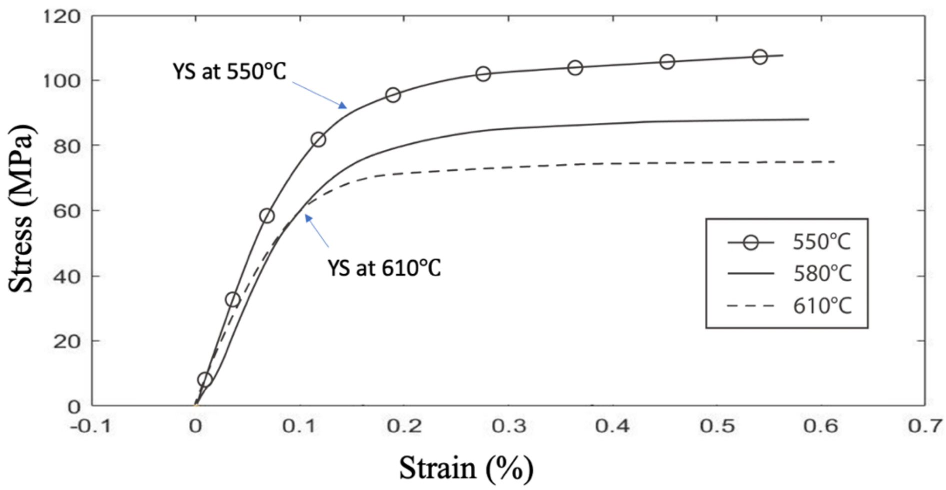

Fig.7 The stress-strain curves of test specimens at 610, 580 and 550 degrees

Observe the curve characteristics after the coil temperature decreases by 60 degrees (dashed curve to circle curve), the figure shows that YS (Yield Strength) increases, indicating that the amount of plastic deformation decreases. According to the stress-strain curve, the elastic strain ε_y of the steel coil at different temperatures are about 610°C: 0.1%, 580°C: 0.14%, and 550°C: 0.17%.

Fig. 8 shows the relationship between thickness and strain. The middle part belongs to the Ze elastic zone. When the deformation is too large, the upper and lower surfaces will enter the Zp plastic zone. The larger Zp region indicates the greater chance of laser cutting warping.

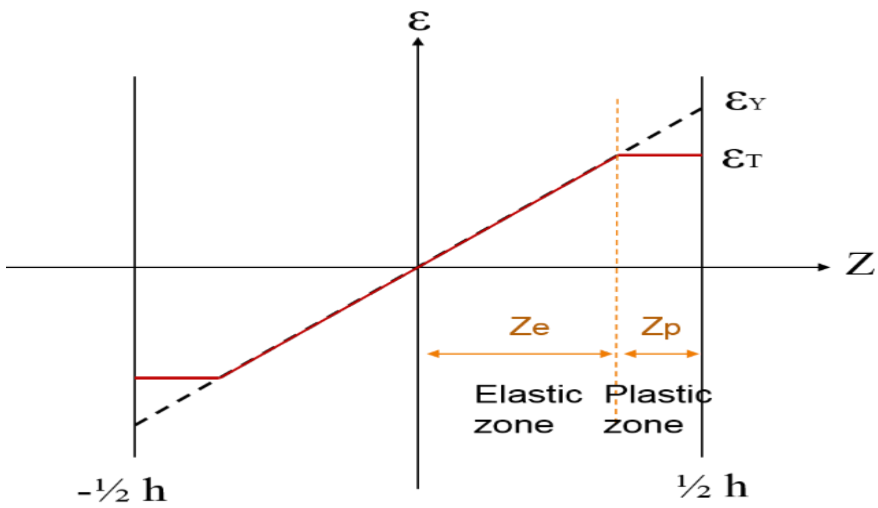

Fig.8 The strain diagram along the thickness direction

The proportion of the plastic zone can be calculated by $Z_P = \frac{\frac{h}{2} - Z_e}{\frac{h}{2}} = \frac{\varepsilon_T - \varepsilon_Y}{\varepsilon_T}$. The results showed that ZP is 74% at 610°C, 64% at 580°C, and 56% at 550°C, which means that the lower the temperature, the less the proportion of plastification. On the premise of not significantly affecting the mechanical properties, the CT is regulated at 580 °C. It is not easy to produce plastic deformation and therefore induces less residual stress. By doing so, the diminished gap between the front and back surfaces averaged data represents a smaller deformation (Fig.9). The improvement is impressively shown in Fig.10. The original deflection of 5mm (Fig. 10a) was reduced to less than 2mm after the cutting process (Fig. 10b).

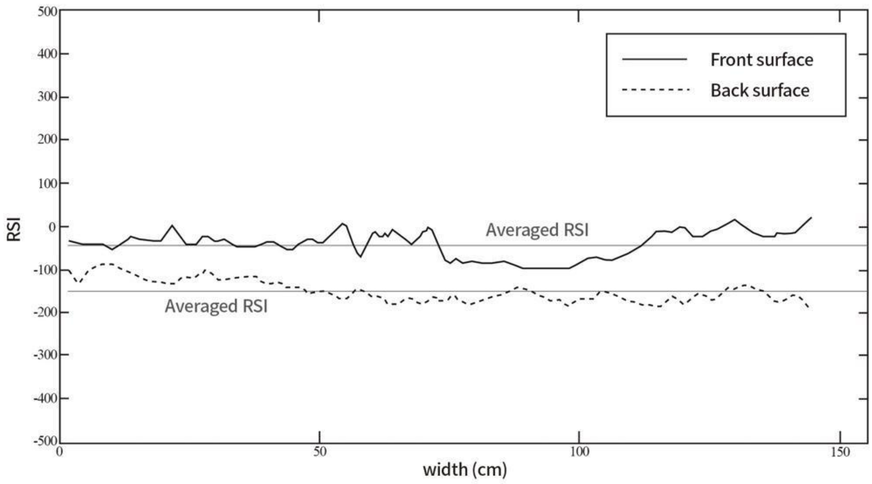

Fig.9 The gap becomes smaller after improvement

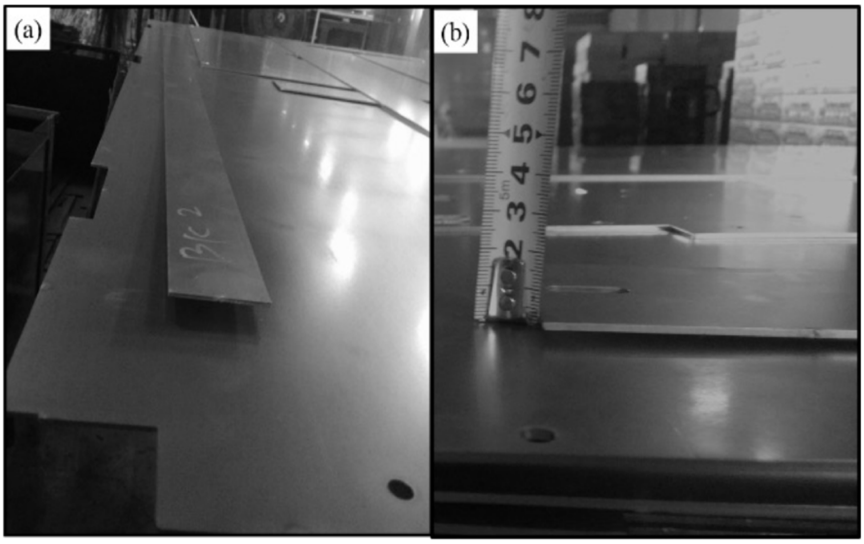

Fig. 10. The deflection of the laser cutting pieces (a) Original 5mm deflection(b) Less than 2mm after improvements

5. CONCLUSIONS

Residual stress is difficult to detect not only due to its invisible nature, but also to the commercial unavailability of the technology. In order to solve the warping problem, residual stress analysis were performed in this study. It was found that the residual stress caused by the coiling effect is relatively obvious, so adjusting the CT (coiling temperature) was adopted to improve quality and have great feedback from customers.

6. REFERENCES

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