Evaluation of Young's modulus of thin coated layer on cold-rolled steel sheet

Hideyuki Kuwahara[*1], Tetsuya Yamamoto[2] and Masayoshi Akiyama[3]

[1] MPT, Fukakusa, Fushimi-ku, Kyoto 612-8431, Japan
[2] Canon Machinery Inc., Shiga 525-8511, Japan
[3] Kyoto Institute of Technology, Kyoto 606-8585, Japan
*Corresponding Author: h_kuwahara@ninus.ocn.ne.jp, Tel.: +66-258-0334

Abstract

Tremendous number of research works has been carried out on the strengthening of material surface such as those on the coating of titanium nitride in order to improve the wear resistance. However little has been investigated clearly on the high performance of the modified surface, because elastic moduli of coated surface and substrate are necessary to evaluate the wear response of the coated surface.

Present study is a trial for measuring Young's moduli of cold-rolled steel sheet of 0.8 mm in thickness and of a thin coated layer of titanium nitride of 2 μm in thickness. After predicting the response of cantilevers sectioned from these sheets with and without a coated layer simple bending test was carried out to check the validity. The results are as follows:

(1) The Young's modulus of cold-rolled steel sheet of 0.8 mm in thickness was 192 GPa on the tension side but the estimated Young's modulus on the compression side was 162 GPa.

(2) The Young's modulus of the coated TiN layer was estimated to lie between 1009 and 1063 GPa on the basis such that the Young's modulus of substrates was 201 GPa after a simple tension test.

(3) If the Young's modulus of substrate on the compression side is lower than that on the tension side the Young's modulus of coated layer of TiN is estimated to lie between 400 and 700 GPa.

***Keywords**:* Cantilever, Tension test, Bending test, Coated layer, TiN

1. Introduction

There are many studies for the development of high performance materials used under various conditions such as high temperature, corrosive circumstance, high speed, high torque, and so on. It is difficult for part of single material to maintain operating performance under these plural conditions at the same time. As it is difficult to solve the problems by developing only bulk materials, there is a long history on the development of a thin coated layer on the surface of a bulk material to ensure higher performance of the products. A number of research results have been presented on the methodology for modifying the features of material surface such as those for reducing the friction on the surface by using a coating technology of a thin layer of TiN. However little has been investigated for the clarification of the mechanical properties of a thin coated layer such as the Young's modulus.

Present study is a trial for measuring the Young's modulus of a cold-rolled steel sheet of 0.8 mm in thickness and that of a 2 μm coating thin layer of titanium nitride. Bending test of a cantilever was carried out after simple tension tests of a parent steel sheet and a coated sheet.

2. Experimental Procedures

Cold-rolled steel sheet was prepared to measure its tensile properties such as the Young's modulus, since it was easy to compare them with the data in previous works.

2.1 Tensile test of cold-rolled steel sheet and steel sheet with coated TiN layers on both sides

The geometry of specimen for tension test was 26 mm in length, 9 mm in length of parallel part, 3 mm in width of parallel part, and 0.8 mm in thickness. Specimens were prepared by wire cutting method in order to avoid strain due to machining. Strain gauges were placed on both sides of the specimen. Tension test was carried out under constant cross head speed of 0.5 mm/min.

2.2. Bending test of cold-rolled steel sheet and steel sheet with coated TiN layers on both sides

Bending test specimen taken from a cold-rolled steel sheet of which shape was 150 mm in length, 5 mm in width, and 0.8 mm in thickness was prepared by wire cutting method in order to avoid strain due to machining. And bending test specimen of coated TiN layer on both sides of the cold-rolled steel sheet was also prepared by the same method.

Bending test was carried out on a cantilever: one end of the specimen (20 mm in length) was fixed and the other end of specimen was loaded to the maximum weight of 37.3g in an incremental manner and a unit weight of 3.73 g was added to a light plastic bag piece by piece until the total weight became 37.3 g. The deflection of the loaded point of cantilever was measured by tracing the point using an optical microscope. In order to check the repeatability of bending test was carried out twice; setting one surface of specimen on the upper side and setting the same surface on the lower side.

3. Results and Discussion

Figure 1 shows a typical result of stress-strain curve of a cold-rolled steel sheet on the tension side obtained after tension test. When the stress is under 100 MPa, there is a good proportionality between the nominal stress and nominal strain, and the Young's modulus is 192.1 GPa when the tangent of stress-strain curve is calculated between the stress levels of 20 MPa and 100 MPa. This fact suggests that the Young's modulus can be applied to bending test when the maximum tensile stress in the

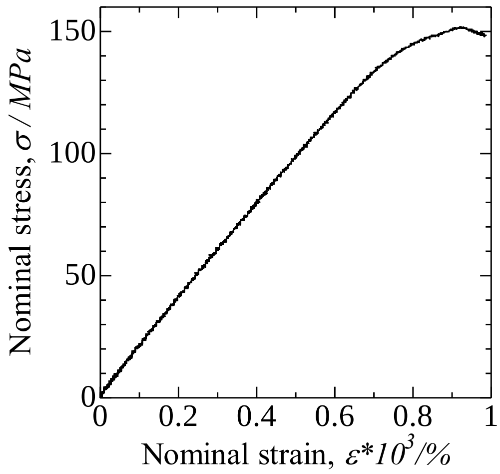

Fig. 1 Stress-strain curve of cold-rolled steel sheet by tension test.

cantilever is under 100 MPa. The Young's modulus of 192.1 GPa is a slightly lower value than that of a heat-treated steel's of 200 GPa. However, it agrees well with that of pure iron's of 190 GPa [1]. This result coincides with the fact that the gradient of stress-strain curve in the elastic region decreases with the increase in plastic strain due to cold rolling.

Fig. 2 shows the results of bending test and both of the suffixes of "Front" and "Back" to R1 and R2 show bending test was carried out twice on the same specimen, i.e. both sides were bent. There is no remarkable discrepancy among the results, and it is deemed that the loading and unloading processes were perfectly elastic, because the unloading curve, or line, exactly returned to the original point as it is clearly indicated in Fig. 2.

Furthermore, Yamamoto [2] carried out a theoretical analysis to calculate the maximum stress at the root of the cantilever. It was 60.6 MPa on the tension side and -60.6 MPa on the compression side. Theoretical results show that

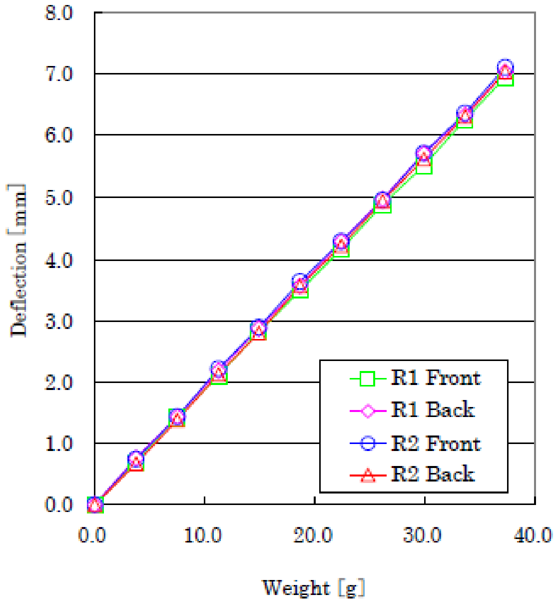

Fig. 2 Comparison of load-deflection curve of cantilever made of cold-rolled steel sheet.

the deflection is limited to the elastic range. Theoretical result on the deflection of cantilever suggests that the Young's modulus of cold-rolled steel sheet should be 177.6 MPa if the same value of Young's modulus is assumed on tension and compression sides. This value is smaller than 192.1 MPa obtained by tension test. The difference can be explained by the side effect of Bauschinger's effect.

If the Young's modulus of 192.1 GPa is adopted on the tension side, the result of theoretical analysis on the deflection of cantilever suggests that the Young's modulus on the compression side should be 162.6 GPa. If the average or the same value is necessary both for tension and compression sides, it is 177.6 GPa that exactly predicts the experimental data of deflection. However, the measured value of the Young's modulus on tension side was 192.1 GPa, which gives a smaller deflection. Therefore, it is necessary for a precise prediction of deflection to assume that the Young's modulus on the compression side be 162.6 GPa which is a lower value that that on the tension side.

Further experiment and analysis were carried out on a steel sheet with thin layers of TiN on both sides. Tension test showed that the Young's modulus on the tension side was 206.5 GPa that was about 10 GPa higher than that of the parent sheet. The Young's modulus of the coated TiN layer was an unknown parameter and its value was estimated in an iterative manner by changing it until the calculated deflection of cantilever met the measured one. The basic assumption on the coated layer of TiN was that the Young's moduli on the tension and compression sides were the same.

Conventional bending theory of a cantilever is based upon a hypothesis that the plane perpendicular to the axis remains perpendicular to the axis after bending. If this theory is adopted and the Young's modulus of coated layer should lie between 1009.4 and 1050.0 GPa because the deflection of top end is smaller than the parent sheet's. In other words smaller deflection means higher rigidity and in order to compensate the decrease in deflection higher Young's modulus on the coated layer must be assumed.

The result is about 2.5 times as large as that of a sintered bulk TiN that lay between 450 and 500 GPa [3]. If a smaller value of Young's modulus of substrate is assumed on the compression side the estimated value of Young's modulus of TiN decreases. Numerical analysis shows that if the Young's modulus of substrate on the compression side lies between 160 and 165 GPa the estimated Young's modulus of TiN lies between 400 and 700 GPa.

In general, there is a tendency that a hard coated film has a large residual elastic strain generated throughout the coating process. Present hard coated TiN layer also has a possibility of having high intensity of larger elastic strain since it was deposited on the cold-rolled steel sheet surface by a PVD (Physical Vapor Deposition) process. It is surely needed to evaluate the result in many aspects.

6. Conclusion

Tension test and bending test were carried out on a cold-rolled steel sheet and on the same sheet coated with a thin layer of TiN in order to estimate the Young's modulus of the coated TiN. The results are as follows:

(1) The Young's modulus of cold-rolled steel sheet was calculated from the stress-strain curve drawn after tension test and it was 192.1 GPa and was lower than the ordinary value of steel due to cold rolling.

(2) The Young's modulus on the compression side of the cold-rolled steel sheet was estimated after bending test to be 162.6 GPa, but there is some uncertainty in determining the value.

(3) The Young's modulus of cold-rolled steel sheet seems to recover about 10 GPa after coating a thin layer of TiN on it.

(4) The Young's modulus of coated TiN layer was estimated after bending test of a coated cold-rolled steel sheet. Under the assumption such that the Young's moduli of substrate are equal to the measured values on both compression and tension sides, the Young's modulus of coated TiN layer lies between

1009.4 – 1050.0 GPa. It may give a better matching to re-estimate these values if the decrease in the Young's modulus due to the Bauschinger's effect is taken into consideration.
(5) If the Young's modulus of substrate decreases the estimated value of Young's modulus of the coated TiN layer decreases and lies between 400 and 700 GPa.

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