Research on Repeated Loading and Unloading Deformation Behavior of High-strength Steel

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Abstract. 3D variable cross-section roll forming is a forming method that adopts multi stands gradually roll forming. In the process of plate material forming, deformed region goes through once stand, one phenomenon of elastic-plastic deformation occurs. Through multiple stands, the phenomenon of repeated loading and unloading occurs on plate material. In this paper, the elastic deformation behavior of TRIP590 (transformation induced plasticity steel) after multi elastic-plastic deformation was obtained, and the elastic strain and elasticity modulus of TRIP590 was also obtained by taking one directional tensile test. The above results provide experimental data for the calculation of bending rebound of 3D variable cross-section roll forming.

Introduction

In general, researching elastic deformation of the material and determining the elastic modulus of the material is determined by the amount of deformation before yield which is described in Hooke’s law. The elastic deformation behavior of 3D variable cross-section roll forming is to study the plasticity deformation stage of the plate which goes through the stretching deformation before yield, and the deformation of the plate after unloading, that is the elastic deformation of the material. 3D variable cross-section roll forming is a method of adopting multi stands progressive forming\(^{[1-4]}\).

Such as the process of six stands, in the forming process of metal sheet, the variable cross-section zone passes through a single stand and the elastic-plastic deformation occurs. After six passes, the plate occurs six times the elastic-plastic deformation, namely the plate is repeatedly loaded six times. Focus on the problem, in this paper, TRIP590 high strength steel was selected for repeated loading and unloading experiments to explore the deformation behavior of the plate after muti loading and unloading\(^{[5]}\).

Introduction of Experimental Equipment

The control system has been developed based on the hardware platform of the variable-proportional load/strain rate bidirectional tensile testing machine developed by the lab of Roll Forming of North China University of Technology then one-way tensile repetitive loading control was realized\(^{[6,7]}\). The deformation of the length direction was collected by a extensometer with a distance of 50mm, and the deformation of the width was collected by a extensometer with a distance of 12.5mm, the tensile speed was set to 1.5mm/min. Before the experiment, force sensor and extensometer were calibrated, the error of the calibration is less than 1%. The experimental equipment is shown in figure 1.

Repeat Loading –unloading Experiments and Results

The static tensile test-piece is prepared according to the national standard, for TRIP590 plate along the rolling direction 0°, 45°, 90° are taken one test-piece separately. According to figure. 2, the TRIP590 adopts laser cutting machining, the thickness of the TRIP590 is 1.5mm\(^{[8,9]}\).
The load \( F/N \) and the deformation \( \Delta l/mm \) datum were obtained by one directional tensile test, and the datum were processing by the stress strain calculation. The nominal stress \( \sigma' / MPa \) and the nominal strain \( \varepsilon' \) are calculated by Eq. 1 and Eq. 2. The real stress \( \sigma / MPa \) and the real strain \( \varepsilon \) are calculated by Eq. 3 and Eq. 4.

\[
\sigma' = \frac{F}{A} \quad (1)
\]

\[
\varepsilon' = \frac{\Delta l}{l} \quad (2)
\]

\[
\sigma = \sigma'(1 + \varepsilon') \quad (3)
\]

\[
\varepsilon = \ln(1 + \varepsilon') \quad (4)
\]

The real stress-real strain curve of one directional tensile test of TRIP590 high strength steel is shown in figure 3.

In order to more visually reflect the deformation history of the repetitive loading process, the curve of the deformation amount with the time of stretching is plotted, as shown in figure 4.
From figure. 3, it can be seen that the strain of the material reduces after unloading, repeated loading, then again unloading after the material entering the plastic deformation, the strain reduces again. The amount of the reduction is the inherent elastic deformation of the material. Each loading-unloading curve tends to approximate straight line, which conforms to the elastic deformation relation described by Hook’s law. The elastic modulus is determined by curve fitting according to the data of repeated loading curve, which is more consistent with the elasticity deformation behavior of the material in the 3D variable section roll forming process.

From the figure. 4, the maximum and the minimum points of the repeated loading curves are extracted, and the difference value between each pair of maximum and minimum points is calculated, and the elastic deformation of each load and unload is obtained. The measuring distance of the extension meter is 50mm, then the elastic strain is calculated.

The elasticity data of six times repeated load of TRIP590 is shown in figure. 5. It can be seen from the figure. 5 that the elastic strain increases with each loading, and the $0^\circ, 90^\circ$ direction of plate rolling is the same, and the sixth time the elastic strain ratio is reduced by the fifth time. It can be seen from the figure. 4, the stress-strain curve under repeated loading, that the reason is that the sixth time loading is near the fracture, while the elastic strain of the $45^\circ$ direction has been increasing, and the sixth load distance is relatively far. The elastic strain of three directions of the plate is compared with the average value, the values are relatively close, while the $45^\circ$ direction is slightly larger.
Figure 5. The repeated loading elastic strain of TRIP590.

The elastic deformation results of TRIP590 obtained by repeated loading experiments are shown in table 1.

| Num . | Load Times | Maximum point [mm] | Minimum point [mm] | Elastic deformation [mm] | Elastic strain \( ε \) | Elasticity modulus [GPa] |
|-------|------------|--------------------|--------------------|--------------------------|-----------------|-------------------------|
| 0º    | 1          | 2.2927             | 2.1136             | 0.1834                   | 0.003668        | 213.05                  |
|       | 2          | 3.9272             | 3.7190             | 0.2082                   | 0.004164        | 208.92                  |
|       | 3          | 5.9378             | 5.6983             | 0.2395                   | 0.004790        | 206.71                  |
|       | 4          | 7.9462             | 7.6887             | 0.2575                   | 0.00515         | 205.18                  |
|       | 5          | 9.9568             | 9.6926             | 0.2642                   | 0.005284        | 205.02                  |
|       | 6          | 11.9719            | 11.7167            | 0.2552                   | 0.005104        | 202.66                  |
| Average | -          | -                  | -                  | 0.2347                   | 0.004693        | 206.92                  |
| 45º   | 1          | 1.9457             | 1.7755             | 0.1702                   | 0.003404        | 213.57                  |
|       | 2          | 3.9451             | 3.7279             | 0.2172                   | 0.004344        | 211.16                  |
|       | 3          | 5.9535             | 5.7094             | 0.2441                   | 0.004882        | 207.39                  |
|       | 4          | 7.9596             | 7.6977             | 0.2619                   | 0.005238        | 206.90                  |
|       | 5          | 9.9568             | 9.6814             | 0.2754                   | 0.005508        | 203.80                  |
|       | 6          | 11.963             | 11.6809            | 0.2821                   | 0.005642        | 203.06                  |
| Average | -          | -                  | -                  | 0.2418                   | 0.004836        | 207.65                  |
| 90º   | 1          | 1.9502             | 1.7666             | 0.1836                   | 0.003672        | 214.62                  |
|       | 2          | 3.9496             | 3.7414             | 0.2082                   | 0.004164        | 210.36                  |
|       | 3          | 5.9513             | 5.7139             | 0.2374                   | 0.004748        | 208.39                  |
|       | 4          | 7.9574             | 7.7022             | 0.2552                   | 0.005014        | 206.37                  |
|       | 5          | 9.9703             | 9.6949             | 0.2754                   | 0.005508        | 204.02                  |
|       | 6          | 11.9719            | 11.7010            | 0.2709                   | 0.005418        | 202.98                  |
| Average | -          | -                  | -                  | 0.2385                   | 0.004769        | 207.79                  |
| Total average | - | - | - | 0.2383 | 0.004766 | 207.45 |

Summary

The process of elastic deformation of material, the elastic deformation and elastic modulus of the material were obtained by the one directional tensile loading-unloading experiment of TRIP590 high strength steel sheet.

The experimental data shows that the experimental method is feasible and reliable, which provides experimental data for the calculation of the bending springback of 3D variable section roll forming, furthermore which is applied to roll bending design.
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