Mechanical Analysis of TRB Transition Region

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Abstract. In this paper, the mechanical properties of Tailor Rolled Blank (TRB) transition region were investigated by establishing a true stress-strain constitutive model of the TRB transition region. Firstly, the stress-strain curve obtained by uniaxial tensile test of 1mm, 2mm thick plates is subjected to regression analysis. Based on Ludwig equation, the true stress-strain constitutive equations of 1mm and 2mm thick plates were obtained. Then, the true stress-strain constitutive equation of TRB transition region was established by interpolation method combined with 1mm, 2mm thick plate constitutive equation, volume invariance theory and Von-Mises equivalent strain. Finally, the accuracy of the model is verified by simulation and experimental comparison. The results show: A new constitutive model of TRB was established, which is well responded to the mechanical properties of the transition region.

1. Introduction
Tailor Rolled Blank (TRB) is a plate whose section thickness varies with load carrying capacity [1, 2]. The formed parts are matched to the corresponding thickness according to different bearing capacities, and the safety of the parts is reduced while reducing the weight of the parts. TRB is one of the most promising lightweight profiles [3, 4]. However, the cross-sectional thickness and material properties of TRB are pretty different from equal thickness blank. The non-uniformity of thickness and material properties make it susceptible to cracks, wrinkles, rebounds, etc. during the forming process. The processing and forming of differential thickness plate are greatly restricted [5-7]. Therefore, it is necessary to study the plastic deformation behavior and mechanical properties of TRB thickness variation region.

Due to the particularity of the geometry of the TRB transition region, the traditional uniaxial tensile test cannot directly derive the mechanical properties of the variable thickness region. Therefore, it is necessary to establish a new mathematical model for obtaining the mechanical properties of TRB materials under variable thickness regions.

2. Experimental Part

2.1. Establishment of the Constitutive Equation under Variable Thickness Region
This paper uses the idea of discretization and uses interpolation to establish the constitutive equation of the transition region. Through the uniaxial tensile test of standard tensile specimens of 1mm and 2mm thick plates, the true stress-strain relationship of the equal thickness plates is established. Tensile specimens dimensions and tensile results shown below:
Regressive analyses were conducted on the true stress-strain curves of specimens taken from the 1 mm and 2 mm equal thick blank in fig 3. Based on the Ludwig equation in Eqs. 1. The constitutive equations of the 1 mm and 2 mm equal thick blank are listed in Eqs. 2 and 3.

\[ \sigma = \sigma_0 + k \times \varepsilon^n \]  
(1)

\[ \sigma = -386 + 1221 \times \varepsilon^{0.208} \]  
(2)

\[ \sigma = -683 + 1516 \times \varepsilon^{0.252} \]  
(3)

By setting \( \varepsilon_L \) as the true strain in the length direction, \( \varepsilon_B \) as the true strain in the width direction, and \( \varepsilon_T \) as the true strain in the thickness direction, according to the volume conservation assumption of metal plastic deformation, there is:

\[ \varepsilon_L + \varepsilon_B + \varepsilon_T = 0 \]  
(4)

Since movements in the width direction are constrained during sheet metal forming, the strain in the width direction can be ignored, i.e. \( \varepsilon_B = 0 \), by substituting this assumption into Eq. 4, the following equation can be obtained: \( \varepsilon_L = -\varepsilon_T \).

According to the true strain definition and the above equations, there is:

\[ \varepsilon_T = -\varepsilon_L = \ln(1 + \Delta t / t_0) = \ln(t_0 / t_0 + \Delta t) = \ln(t / t_0) \]  
(5)

where \( t_0 \) is the initial thickness and \( t \) is the actual thickness of TRB after deformation. The Von-Mises equivalent strain \( \varepsilon \) of the blank is adopted to represent the total strain as Eq. 6.

\[ \varepsilon = \sqrt{\frac{2}{3}(\varepsilon_1^2 + \varepsilon_2^2 + \varepsilon_3^2)} \]  
(6)
where, $\varepsilon_1$, $\varepsilon_2$, and $\varepsilon_3$ are three principle stresses. Hence, by combining $\varepsilon_B = \varepsilon_2 = 0$, $\varepsilon_L = -\varepsilon_T$ and the Von-Mises equivalent strain, there is:

$$\varepsilon = 1.15\varepsilon_T = 1.15\ln\frac{t}{t_0} \quad t = t_0 e^{1.15}$$

(7)

The actual cross-section area $A$ of the transition region with a width of $B$ and thickness of $t$ is:

$$A = B \times t$$

The actual cross-sectional area corresponding to the thickness of $t$ can be obtained:

$$A = Bt_0 e^{1.15}$$

(8)

Under the action of the tensile force $F$, the stress of the section is:

$$\sigma = \frac{F}{A} = \frac{F}{Bt_0 e^{1.15}}$$

(9)

According to the transmissibility of force, the force $F$ acting on each discretized equal thick blank in the transition region is equal. Thus, the direct relation between $F$ and $\sigma$ can be established. The piecewise function model of the TRB true stress-strain curve can be constructed as follows.

$$\begin{cases} 
\sigma_1 = -386 + 1221 \times e^{0.208} & t = t_1 \\
\sigma = \frac{F}{Bt_0 e^{1.15}}; \sigma = \sigma_0 + k \times \varepsilon^n & t_1 < t < t_2 \\
\sigma_2 = -683 + 1516 \times e^{0.252} & t = t_2 
\end{cases}$$

(10)

where, $k$, $n$, and $\sigma_0$ are all material parameters defined as:

$$k = \frac{k_1 + k_2}{2}, \quad n = \frac{n_1 + n_2}{2}, \quad \sigma_0 = \frac{\sigma_{01} + \sigma_{02}}{2}$$

$k_1$ and $k_2$ are strength coefficients in the fitted true stress-strain equations of the equal thickness regions with 1 mm and 2 mm in thickness. $n_1$ and $n_2$ are power exponents in these two equations; and $\sigma_{01}$ and $\sigma_{02}$ are the initial stresses of these two specimens. Since the external force applying on each discretized equal thick blank in the transition region is the same, there is:

$$F = \sigma \times S = \left(\sigma_0 + k \times \varepsilon^n\right) \times S$$

(11)

$S_1$ and $S_2$ denote the cross-section areas of the equal thickness regions of 1 mm and 2 mm respectively. Since the thickness of the transition region changes linearly, there is:

$$S = \frac{S_1 + S_2}{2}$$

(12)

By substituting Eqs. 12 and 11 into Eq. 10, the true stress-true strain relation considering blank thickness can be written as:
The relation among stress, strain, and thickness of TRB is graphically presented in Fig. 4.

\[
\begin{align*}
\sigma_1 &= -386 + 1221 \times \varepsilon^{0.208} \quad t = t_1 \\
\sigma &= \frac{-10182.225 + 26069.925 \times \varepsilon^{0.23}}{12.7t_0\varepsilon^{0.15}} \quad t_1 < t < t_2 \\
\sigma_2 &= -683 + 1516 \times \varepsilon^{0.252} \quad t = t_2
\end{align*}
\]

The relation among stress, strain, and thickness of TRB is graphically presented in Fig. 4.

**Figure 4.** TRB stress-strain-thickness relationship

2.2. Verification of Constitutive Model

In order to verify the accuracy of the stress-strain constitutive model in transition region established by interpolation method, the true stress and strain obtained under the algorithm need to be verified. In this experiment, the ABAQUS finite element simulation is used to substitute the real stress and strain obtained from the constitutive model of the transition region into the material properties of the transition region. Under this condition, the uniaxial tensile test of the TRB transition region is simulated and the results are compared with the experiment. Compare and find the error to test the accuracy of the constitutive model. The dispersion of TRB transition region is shown in Figure 5 below.

**Figure 5.** The dispersion of TRB transition region

3. Results and Discussion

Based on the Abaqus finite element software, the tensile test of TRB was simulated. After the different properties assigned to the transition region material by the above method, the simulation results of the tensile test are shown in Fig. 6.
According to the analysis, at the beginning of the experiment, the material first enters the elastic deformation stage, in which the simulated force-stroke curve can be well matched with the test. As the experiment progresses, it gradually enters the stage of plastic deformation. By analyzing the above figure, it can be confirmed that during the plastic deformation stage, the simulation and experimental results are basically consistent. The highest point of force is around 6KN. However, the simulated force and the stroke curve are necked much later than the experiment. This is because the material will break quickly at the location where the neck is produced, and the stress-strain curve obtained by the simulation is a theoretical curve model.

By comparing the results of simulation and experiment, it is shown that the force-stroke curve obtained by the simulation is basically consistent with the conclusions obtained by the experiment. Therefore, The newly established transition region real stress-strain constitutive model can better reflect the change of mechanical properties of the transition region of TRB material.

4. Conclusions
(1) According to the discretization idea, based on the Ludwig equation, the real stress-strain constitutive model of the TRB transition region is established by interpolation.

(2) According to the results of Abaqus finite element simulation, it is found in comparison with the experiment that the true stress-strain constitutive model of the newly established TRB transition region can better reflect the change of mechanical properties of TRB transition region.

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6. References
[1] R.Krux, W.homberg, M. Kleiner. Properties of Large-Scale Structure Workpieces in High-Pressure Sheet Metal Forming of Tailor Rolled Blanks [J]. steel research international, 2005, 76 (12): 890-896.
[2] Huawei Zhang, Lizhong Liu. Study on Unidirectional Drawing Performance of TRB [J]. Journal of Dalian University of Technology, 2012 (5): 648-651.
[3] Lijuan Chen, Bin Han. TRB rolling technology and its application [J]. Rolling steel, 2013 (5): 39-43.
[4] Zhi Fang. Research on Rolling Speed and Rolling Micro Tracking Model of TRB [D]. Northeastern University, 2010.
[5] Yinfang Jiang, Lei Fang. Continuous variable section plate and its key problems in application [J]. Manufacturing technology and machine tools, 2011 (1): 144-148.

[6] Huawei Zhang, Jialu Wu, Xianghua Liu. Study on Wrinkle Defects of Tailor Rolled Blanks [J]. Journal of Northeastern University: Natural Science Edition, 2016, 37 (11): 1554-1558.

[7] N. Ryabkov. Production of blanks with thickness transitions in longitudinal and lateral direction through 3D. Strip Profile Rolling [J]. International Journal of Material Forming. 2008.