Biaxial Tensile Behaviour of PVC Sheets*

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This paper reports on an analysis of tensile behaviour of PVC(plasticized PVC sheet) under biaxial finite deformation. In general, since such sheet of hi-molecular materials are mainly used under biaxial deformation, they should be analyzed by biaxial tensile tests. The specimen used here was made by calendaring, so it shows the dynamic orthotropy. This study is an analysis on the assumption that the material is incompressible. Its deformation history mainly depends on strain rate and temperature.

In this paper, the problem of isochronous plots has been analyzed by F.E.M. considering nonlinearity of the material characteristics and geometrical behaviour.

As the result, numerical data on uniaxial and strip biaxial deformation were in good agreement in quality and quantity. But a disagreement, which resulted from analysis of strip biaxial with a circular hole in its center, was found around the circular hole where stress concentration occurred.

Key Words: Strain Energy, Finite Element Method,
Tensile Testing, Plasticizer, Strain Rate

1. Introduction

The plasticized (PVC) sheet accounts for the majority of PVC plastics produced and it is used not only for industrial proposes but also for various other proposes.

It has many complicated dynamic characteristics, such as visco-elasticity, large deformation and dynamic orthotropy due to calendaring. In general, sheets of PVC materials are mainly used under biaxial deformation and it is necessary to make its analysis by biaxial tests.

Up to this time, the analysis of polymers under large deformation, such as rubber vulcanizates, has been made to determine the formulation of the strain energy function by Mooney⁽¹⁾, Rivlin⁽²⁾ and several others. And recently several rubber vulcanizates, which are designated Mooney's material, were analyzed by F.E.M. applying this strain energy function by Oden⁽³⁾ and several others.

Above investigations described a formulation of the strain energy function on the assumption that these materials were isotropic and incompressible ones, but this is generally difficult in case of orthotropic materials. In this paper, we analyzed it as an ideal nonlinear elasticity by F.E.M. considering the compounded nonlinearity of the material characteristics and geometrical behaviour, and investigated the availability of former analysis comparing the results of analysis and experiments.

2. Experiment

2.1 Materials and specimens

Plasticized PVC sheets, which contained 33.0% plasticizer DOP in weight and whose degree of polymerization was 1050, were prepared for this experiment.

The specimens for uniaxial tension test were cut out in the lateral direction and transverse direction to dimensions 142 x 50 mm overall, the effective length being 50 mm. The specimens for strip biaxial tension test were square sheets of 142 x 142 mm the effective area being a central area of 75 x 75 mm. The specimens which were cut at 45° angle to lateral direction were prepared for calculation of the longitudinal-transverse shear modulus. And the specimens for strip biaxial tension test with a circular hole were square sheets of 142 x 142 mm with a circular hole of 8 mm in diameter. The thickness of every specimen was 0.15 mm. We designate the lateral direction as L-direction and transvers direction as T-direction.

2.2 Apparatus.

A tensile tester of the Instron type was used for uniaxial tension test and a biaxial tensile tester(BISTRON)⁽⁴⁾ for biaxial tension test.

2.3 Experimental method

The uniaxial tension tests was performed under seven strain rates, 0.167, 0.333, 0.500, 0.833, 1.677, 3.333 and 5.000 %-sec, and the range of extension ratios in deformation ranged from $\lambda = 1$ ($=1 + \varepsilon$) to $\lambda = 2.1$. The strip biaxial tension tests was performed in each direction under five strain rates, 0.208, 0.281, 0.388, 0.487 and 0.688 %/sec. The uniaxial tension tests were carried out at 293 + 0.5, 303 + 0.5 and

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313 + 0.5 K temperatures. The deformation of the specimen and around the circular hole were measured by photographing every several seconds. After the specimen was set up in the apparatus, it was left alone for ten minutes to stabilize the temperature of apparatus and the specimen.

3. Results and Discussion

3.1 Stress vs. extension ratio

Figures 1 and 2 show the relations between stress and extension ratio in strip biaxial tension tests. Figure 1, which plots stress ratio at each temperature in L-direction tensile strip biaxial deformation, shows that the temperature rises as Young's modulus decreases and that the PVC is a thermoplastic polymer. Figure 2 shows the results at each strain rate in the same deformation as mentioned above. In general, it is known that the extension rate increases as the elastic modulus and the yielding strength increase in polymers, as recognized with PVC from Fig. 2.

Fig. 1 Plots of stress vs. extension ratio at each temperature in L-direction tensile strip biaxial deformation.

Fig. 2 Plots of stress vs. extension ratio at each strain rate in L-direction tensile strip biaxial deformation.

3.2 Time dependence⁽⁵⁾

As mentioned above the relation between stress and extension ratio in PVC depends on strain rate and temperature greatly. Then in this work the effect of temperature in deformation history could be neglected as a thermostatic oven was used and so it depended on only extension rate. In order to investigate the effect of time the typical data for the strip biaxial tension tests at some constant extension rates are displayed as plots of log f_L and log f_T vs. log t in Figs. 3(a) and (b). Time t can be calculated by

$$t = \frac{\lambda_1 - 1}{\dot{\lambda}_1} \quad (1)$$

where $\dot{\lambda}_1$ is extension rate and λ_1 is extension ratio of tensile side. The lines in Fig. 3 express the relation between stress and time at constant extension ratio, which can be given in all data of extension tests by

$$\ln f = a + b \ln t \quad (2)$$

(a) tensile side

(b) restraint side

Fig. 3 Data from T-direction tensile strip biaxial tests at constant extension ratios at 303 K.

Next, the relation between slope b and extension ratio as shown in Figs. 4 and 5, can be given in a certain range of extension ratios by

$$b = A + B \cdot \lambda \quad (3)$$

Fig. 4(a) Relation between $|b|$ and λ at each side in L-direction tensile strip biaxial deformation. Temperature is 303 K.

Fig. 4(b) Relation between $|b|$ and λ at each side in T-direction tensile strip biaxial deformation. Temperature is 303 K.

Substitution of eqs. (1) and (3) into eq. (2) gives :

$$f = K \cdot t \cdot (B \cdot \dot{\lambda} \cdot t + A + B) \quad (4)$$

This equation means that the term of time can be separated from the relation between stress and strain. Elimination of K from eq. (4) gives eq. (5), i.e.

$$f_j = f_i \cdot \left(\frac{t_j}{t_i} \right)^{(B \cdot \dot{\lambda} \cdot t_i + A + B)} \quad (5)$$

where t_i and f_i are known experimental data, and t_j and f_j are unknown values of extension rate. Constants A and B , which depend on the direction of tension and temperature, are shown in Table 1. In this paper, 60-sec isochronal data were calculated by eq. (5), and the isochronous plots of uniaxial tension test are shown in Fig. 6. It can be supposed that the isochronous plots are free from effect of time and are corrected for the divergence energy. That is to say, it is relation between stress and extension ratio when the constitutive relation of visco-elasticity is replaced with the elasticity term alone excluding the time term. The relation between slope b , from eq. (3), and extension ratio at each side in each direction of tensile strip biaxial deformation is shown in Figs. 4(a) and (b). According to these figures, the value of b at T-direction tension is a little higher than the one at L-direction tension and it is recognized that its dependence on extension ratio is higher. Relation between b and extension ratio of tensile side at each temperature in L-direction tensile strip biaxial deformation is shown in Fig. 5. From this figure, it is recognized that the dependence on temperature increases as the temperature increases. These characters are confirmed in all other experimental data. Therefore in this paper, values of these analysis by experimental data are isochronal values free from the effect of time.

Fig. 5 Relation between $|b|$ and λ_L of tensile side at each temperature in L-direction tensile strip biaxial deformation.

4. Analysis by F.E.M.

4.1 Formulation of incremental method

As described in the preceding chapter, the tensile behaviour of PVC sheet has visco-elastic characteristic and it must be analyzed as a problem of nonlinearity of the material

Table 1 Values of A and B in strip biaxial deformation.

a) for L-direction			
Temperature	side	A	B
293 K	tensile	-0.198	0.084
	restraint	-0.213	0.108
303 K	tensile	-0.295	0.126
	restraint	-0.265	0.121

b) for T-direction			
Temperature	side	A	B
293 K	tensile	-0.180	0.079
	restraint	-0.240	0.117
303 K	tensile	-0.325	0.142
	restraint	-0.305	0.140

Fig. 6 Isochronal plots of stress vs. extension ratio at each direction in uniaxial deformation. Temperature is 303 K.

characteristics and geometrical behaviour. In this paper, the problem of isochronous plots, in which the term of time was separated from the relation between stress and strain, was analyzed as the ideal elasticity by F.E.M. based on incremental method. Now, N means the first situation at one incremental step and $N + 1$ means the last situation at the same step. The principle of virtual stress in the incremental step can be expressed by

$$\int_V (\sigma_{ij}^{(N)} + \Delta \sigma_{ij}) \delta (\Delta \epsilon_{ij}) dV = \int_S (T_i^{(N)} + \Delta T_i) \delta (\Delta u_i) dS \quad (6)$$

where body forces are ignored, and $\Delta \sigma_{ij}$, Δu_i and ΔT_i are increments of stress, displacement and traction, and $\Delta \epsilon_{ij}$ is minute strain. But $\sigma_{ij}^{(N)}$ and $T_i^{(N)}$ are the stress and traction at the situation N . $\Delta \epsilon_{ij}$ is Green's strain increment which is expressed in eq. (7), by

$$\Delta \epsilon_{ij} = \Delta \epsilon_{ij} + \Delta \eta_{ij} = \frac{1}{2} (\Delta u_{i,j} + \Delta u_{j,i}) + \frac{1}{2} (\Delta u_{k,i} \cdot \Delta u_{k,j}) \quad (7)$$

where $\Delta \epsilon_{ij}$ is linear strain increment and $\Delta \eta_{ij}$ is quadratic strain increment. Assuming that Hook's law holds between stress and strain increment, we have

$$\Delta \sigma_{ij} = C_{ijkl} \cdot \Delta \epsilon_{kl} \quad (8)$$

From eqs. (7) and (8), eq. (6) is rewritten as

$$\int_V (\sigma_{ij}^{(N)} \delta (\Delta \eta_{ij}) + \Delta \epsilon_{kl} \cdot C_{ijkl} \cdot \delta (\Delta \epsilon_{ij})) dV = \int_S \Delta T_i \delta (\Delta u_i) dS + \left(\int_S T_i^{(N)} \cdot \delta (\Delta u_i) dS - \int_V \sigma_{ij}^{(N)} \cdot \delta (\Delta \epsilon_{ij}) dV \right) \quad (9)$$

where the term of a high order of strain is ignored. Next, the displacement increment in an element can be expressed by using the shape function ϕ_{ki} and the displacement increment at nodal points as follows :

$$\Delta u_k = \phi_{ki} \cdot \Delta r_i^{(e)} \quad \dots\dots\dots (10)$$

Substituting the the relation between strain and nodal displacement, which is derived from eq. (10), into eq. (9) and differentiating by displacement, we have an element equilibrium equation, i.e.

$$(K_{\sigma ij}^{(e)} + K_{\epsilon ij}^{(e)}) \cdot \Delta r_j = \Delta f_i^{(e)} + R_i^{(e)} \quad \dots\dots\dots (11)$$

where $K_{\sigma ij}^{(e)}$, $K_{\epsilon ij}^{(e)}$, $f_i^{(e)}$ and $R_i^{(e)}$ are expressed by

$$\begin{aligned} K_{\sigma ij}^{(e)} &= \int_V \phi_{mi,k} \cdot \sigma_{kl}^{(N)} \cdot \phi_{mj,l} dV \\ K_{\epsilon ij}^{(e)} &= \frac{1}{4} \int_V (\phi_{ki,l} + \phi_{li,k}) C_{klmn} (\phi_{mi,n} + \phi_{nj,m}) dV \\ \Delta f_i^{(e)} &= \int_S \Delta T_i \cdot \phi_{mi} dS \\ R_i^{(e)} &= \int_S T_i^{(N)} \cdot \phi_{mi} dS - \frac{1}{2} \int_V \sigma_{mn}^{(N)} (\phi_{mi,n} + \phi_{nj,m}) dV \end{aligned} \quad \dots\dots\dots (12)$$

where the subscript (e) identifies each element, and $K_{\sigma ij}$ is geometric matrix or initial stress matrix and $K_{\epsilon ij}$ is minute displacement stiffness matrix. And R_i is an unbalanced nodal force which is induced by ignoring the high order of strain during the incremental step and using the linear constitutive relation. Thereby the assemblage equilibrium equation can be introduced by summing up eq. (12) for every element.

4.2 Calculation of material constants

Material nonlinearity means that the relation of function between stress and strain is nonlinear. Therefore it is necessary to calculate the material modulus at any strain condition. Such orthotropic material as we use in this paper has four independent material moduli in a plane stress problem. In this paper, we calculated them on the next two assumptions by incremental method.

(i) The relation between stress and strain is linear at each incremental step.

(ii) The problem is a plane stress one, and the thickness is restrained by incompressibility. Assuming that the strain increment is minute, from assumption (i), Hooke's law is written as

$$\begin{Bmatrix} \Delta \sigma_L \\ \Delta \sigma_T \\ \Delta \tau_{LT} \end{Bmatrix} = \frac{1}{\nu} \begin{bmatrix} E_L & \nu_{TL} E_L & 0 \\ \nu_{LT} E_T & E_T & 0 \\ 0 & 0 & \nu_{GLT} \end{bmatrix} \begin{Bmatrix} \Delta \epsilon_L \\ \Delta \epsilon_T \\ \Delta \gamma_{LT} \end{Bmatrix} \quad \dots\dots\dots (13)$$

where $\nu = 1 - \nu_{LT} \nu_{TL}$ is used. And Maxwell theorem gives the following relation :

$$\frac{\nu_{LT}}{E_L} = \frac{\nu_{TL}}{E_T} \quad \dots\dots\dots (14)$$

In order to calculate these four, independent material moduli in eq. (13), it is necessary to perform the strip biaxial tensile tests in three directions. When strip biaxial tension tests in two directions are performed as shown in Fig.

7, the relation between stress and strain in T-direction tensile strip biaxial tests are shown by the following equation using the relations of $\epsilon_r = 0$ and $\Delta \gamma_{LT} = 0$:

$$\Delta \sigma_x = \frac{\nu_{LT}}{\nu} \cdot E_T \cdot \Delta \epsilon_y, \Delta \sigma_y = \frac{1}{\nu} \cdot E_L \cdot \Delta \epsilon_y, \dots\dots\dots (15)$$

Fig. 7 State of deformation in each direction and relation between each stress and extension ratio.

And in L-direction tensile strip biaxial tests these are shown by

$$\Delta \sigma_x = \frac{\nu_{TL}}{\nu} \cdot E_L \cdot \Delta \epsilon'_y, \Delta \sigma'_y = \frac{1}{\nu} \cdot E_T \cdot \Delta \epsilon'_y, \dots\dots\dots (16)$$

When strain increment is denoted by $\Delta \epsilon_y$, and extension rate at i times incremental step is by $\lambda_y^{(i)}$, $\lambda_y^{(i)}$ is expressed as

$$\lambda_y^{(i)} = i \cdot \Delta \epsilon_y + 1 \quad \dots\dots\dots (17)$$

From assumption (ii), the thickness $t^{(i)}$ of the sheet at any extension ratio is given by

$$t^{(i)} = \frac{1}{\lambda_y^{(i)}} \cdot t_i \quad \dots\dots\dots (18)$$

where t_i is initial thickness. Figure 7 shows a three-nomial expansion curve of f_L, f_T in strip biaxial tension. From it, the true stress increments $\Delta \sigma_x^{(i)}, \Delta \sigma_y^{(i)}, \Delta \sigma_x^{(i)'} \Delta \sigma_y^{(i)'}$

$$\begin{aligned} \Delta \sigma_x^{(i)} &= f_T^{(i)} - f_T^{(i-1)}, \Delta \sigma_y^{(i)} = f_L^{(i)} \cdot \lambda_y^{(i)} - f_L^{(i-1)} \cdot \lambda_y^{(i-1)} \\ \Delta \sigma_x^{(i)'} &= f_L^{(i)} - f_L^{(i-1)}, \Delta \sigma_y^{(i)'} = f_T^{(i)} \cdot \lambda_y^{(i)} - f_T^{(i-1)} \cdot \lambda_y^{(i-1)} \end{aligned} \quad \dots\dots\dots (19)$$

Therefore, using eqs. (15), (16), (19) and (13), these material moduli can be calculated by

$$\begin{aligned} \nu_{LT}^{(i)} &= \frac{E_L^{(i)}}{E_T^{(i)}} \cdot \frac{\Delta \sigma_x^{(i)}}{\Delta \sigma_y^{(i)}}, \nu_{TL}^{(i)} = \frac{E_T^{(i)}}{E_L^{(i)}} \cdot \frac{\Delta \sigma_x^{(i)'}}{\Delta \sigma_y^{(i)'}} \\ E_L^{(i)} &= \frac{1}{\Delta \epsilon_y} \left(\Delta \sigma_y^{(i)} - \Delta \sigma_x^{(i)} \cdot \frac{\Delta \sigma_x^{(i)'}}{\Delta \sigma_y^{(i)'}} \right) \\ E_T^{(i)} &= \frac{1}{\Delta \epsilon_y} \left(\Delta \sigma_y^{(i)'} - \Delta \sigma_x^{(i)'} \cdot \frac{\Delta \sigma_x^{(i)}}{\Delta \sigma_y^{(i)}} \right) \end{aligned} \quad \dots\dots\dots (20)$$

The longitudinal-transverse shear modulus was calculated by an experimental eq. (21) from minute deformation of strip biaxial tension test at 45° angle to L-direction :

$$G_{LT}^{(i)} = \frac{1}{1.61} \cdot \frac{E_L^{(i)} \cdot E_T^{(i)}}{E_T^{(i)} \cdot (1 + 2\nu_{LT}^{(i)}) + E_L^{(i)}} \quad \dots\dots\dots (21)$$

where G is shear modulus whose torque axis is at 45° angle to width orientation. Such material modulus calculated by eqs. (20) and (21) are for structural principal axis. It is necessary to transform them from structural principal axis (L, T) into generalized co-ordinates (x, y) for analysis by F.E.M. When co-ordinates (L, T) agree with co-ordinates (x, y) in Fig. 8(a), the constitutive relation is expressed by

(a) structural principle axis and generalized coordinate agree. (b) structural principle axis and generalized coordinate disagree.

Fig. 8 Relation between structural principle axis and generalized coordinate.

$$\begin{Bmatrix} \sigma_L \\ \sigma_T \\ \tau_{LT} \end{Bmatrix} = \begin{bmatrix} 1/\nu \cdot E_L & \nu_{TL}/\nu \cdot E_L & 0 \\ \nu_{LT}/\nu \cdot E_T & 1/\nu \cdot E_T & 0 \\ 0 & 0 & G_{LT} \end{bmatrix} \begin{Bmatrix} \varepsilon_L \\ \varepsilon_T \\ \gamma_{LT} \end{Bmatrix} \quad \dots\dots\dots (22)$$

Now when co-ordinates(L, T) are at θ angle with co-ordinates(x, y), eq. (22) is transformed into eq. (23) by using the transformation of co-ordinates of stress and strain tensor and $\gamma_{xy} = 2\varepsilon_{xy}$

$$\begin{Bmatrix} \sigma_x \\ \sigma_y \\ \tau_{xy} \end{Bmatrix} = \begin{bmatrix} l^2 & m^2 & -2lm \\ m^2 & l^2 & 2lm \\ lm & -lm & l^2 - m^2 \end{bmatrix} \begin{Bmatrix} \varepsilon_x \\ \varepsilon_y \\ \gamma_{xy} \end{Bmatrix} \quad \dots\dots\dots (23)$$

where $l = \cos \theta$ and $m = \sin \theta$. These material moduli calculated by eq. (23) are given as ones at any incremental step of F.E.M., in which the equivalent stress is used as a parameter, by :

$$C_{ij} = C_{ij}(\bar{\sigma}) \quad \dots\dots\dots (24)$$

where $\bar{\sigma}$ is equivalent stress.

4.3 Numerical calculating method

As described in paragraphs 4.1 and 4.2, the problem has been analyzed by F.E.M. considering nonlinearity of the material characteristics and geometrical behaviour, and these data as input for boundary condition of F.E.M. are compulsory displacements at boundary nodal points. The series unit method was used for solving simultaneous linear equations, and finite elements were linear strain elements, which were triangular elements having six nodal points. A mesh with 10 units, 200 elements and 441 nodal points was devised for uniaxial and strip biaxial tension. And a mesh with 14 units, 308 elements and 678 nodal points was devised in strip biaxial tension with a circular hole, as shown in Fig. 9(a), and Fig. 9(b) show the division around the circular hole which was cut into small pieces considering the stress concentration. The number of incremental steps was given by a quotient obtained when is the last extension ratio divided by compulsory displacement increment $\varepsilon = 0.01$. And Hammer's method was used for numerical integration.

Fig. 9(a) Finite element division for F.E.M. in strip biaxial tension with a circular hole.

Fig. 9(b) Magnifying diagram of A section in Fig. 9(a).

5. Analyzed Results

5.1 Uniaxial tension

Figure 10 shows the comparison of experimental values of uniaxial deformation at 293 K in L-direction tension with those analyzed by F.E.M. From it, numerical data are found to be in good agreement in quality and quantity as a whole, though they exceed a little experimental values at $\varepsilon = 1.6$. Figure 11 shows analyzed results of the tensile uniaxial deformation in L-direction at 303 K and it shows good agreement in quality and quantity to the extent of large deformation.

5.2 Strip biaxial tension

Figures 12 and 13 show the analyzed results at 293 K and 303 K respectively in L-direction tensile strip biaxial deformation. In the results at 293 K, numerical data exceed experimental data widely in the region from middle to large deformation. And in the results at 303 K, numerical data are in good agreement in quality and quantity at both sides. The

Fig. 10 Comparison of determined values of f_L in L-direction tensile uniaxial deformation at 293 K with analyzed ones by F.E.M..

Fig. 11 Comparison of determined values of f_L in L-direction tensile uniaxial deformation at 303 K with analyzed ones by F.E.M..

Fig. 12 Comparison of determined values of f_L, f_T in L-direction tensile strip biaxial deformation at 293 K with analyzed ones by F.E.M..

Fig. 13 Comparison of determined values of f_L, f_T in L-direction tensile strip biaxial deformation at 303 K with analyzed ones by F.E.M..

Fig. 14 Comparison with analyzed values of F.E.M. on each incremental step number.

reason for the disagreement at 293 K is that the cumulative error caused by tangential stiffness matrix increased because the slope of constitutive relation on tensile side at 293 K is steep. Figure 14 shows the comparison with analyzed values for each incremental step number, the incremental step number increases from 20 to 80 as analyzed values converge monotonously.

5.3 Strip biaxial tension with a circular hole

The analysis of a finite width flat board containing a central circular hole can yield an exact solution about elastic body, but it is impossible to get a solution about high polymer large deformation materials. Then in this paper, as an application of paragraphs 5.1 and 5.2, we analyzed the strip biaxial deformation with a circular hole. Figure 15 shows the analyzed result in L-direction tensile deformation at 303 K. In it, numerical values of boundary nodal force are nearly in good agreement. Next, looking at the state around the hole, where stress concentration occurred, we see from Fig. 16 the strain distribution around the hole, where a is a radius of the hole and the axis of

Fig. 15 Comparison of determined values of f_L, f_T in L-direction tensile strip biaxial deformation with a circular hole at 303 K with analyzed ones by F.E.M..

Fig. 16 Comparison between the experimental result and the result by F.E.M. with respect to the strain distribution around a hole in L-direction tensile strip biaxial tension at 303 K, where a is a radius of a hole before deformation, and X_1 and X_2 are lengths of a hole after deformation.

abscissa indicates extension ratio at tensile side and the axis of ordinate does that at restrained side. From it, the numerical result by F.E.M. is found in a very good agreement to the extent of $\varepsilon = 1.2$, but as the extension ratio increases beyond $\varepsilon = 1.2$, the error, in particular one at the state where maximum stress concentration occurs becomes large. the reason can be supposed to be such isochronous plots as given in this experimental extent can not follow them, because in such a state, the specimen assumes a milk white color and the plastic effect appears by re-configuration of molecules, though in this paper the tensile behaviour of PVC sheet is exchanged for ideal linear elastic one by using the isochronal values.

6. Conclusion

From the results about the tensile behaviour of plasticized PVC sheet under biaxial finite deformation and the analyzed value by F.E.M. considering complex nonlinearity, the following are concluded.

(1) From the determined values of each tension test, the engineering stress f can be expressed by

$$f = f(\lambda) \cdot t^0$$

in this experimental scope.

Analyzed results by F.E.M.

(2) The numerical data in uniaxial deformation at 293 K and 303 K are in good agreement in quality and quantity. Then this analysis method is found effective.

(3) In strip biaxial tensile deformation, though the numerical values on tensile side at 293 K exceed the extent of middle deformation, they are in good agreement in quality, while numerical values at 303 K are in good agreement in quality and quantity. Then this analysis method is found effective.

(4) In strip biaxial tensile deformation with a circular hole, this analysis method gives effective values to an extent of $\lambda = 1.2$.

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