

Non-linear, Strain Rate-dependent Behavior of Polymer at Room Temperature: Experimental Findings

Hiroyuki MAE*

Kenji TAKADA*

Junichi TAKAHASHI**

Toshiharu YAMAMOTO**

ABSTRACT

Due to the strong non-linearity and the difficulty of obtaining data on the behavior of polymers at high strain rates, most crash simulations use material data based on quasi-static testing.

This study therefore attempted to obtain material data for polymers used in the interior and exterior of automobiles at high strain rates. The material data obtained differs from data obtained through the linear interpolation of stress to model the behavior of polymers at high strain rates. The results of the tests conducted in this project have been compared with results obtained using commercial finite element models.

1. Introduction

Recently, crash simulations have been introduced to vehicle body design in automotive development. Crash simulations for steel materials, which are the main materials used in automobiles, currently exhibit high calculation accuracy in axial buckling calculations for structural components, and have reached a level that is sufficient for practical application⁽¹⁾. One factor for this is that the stress-strain behavior of steel materials at high strain rates is accurately obtained⁽²⁾. On the other hand, in simulations using polymers, the materials exhibit more complex stress-strain behavior, so there have been few research cases⁽³⁾. In addition, there was also the issue that when attempting to obtain material data at high strain rates, the measurement value fluctuation due to vibration is larger than the stress-strain behavior of the test specimen⁽⁴⁾.

Therefore, this study constructed a method allowing measurement of stress-strain behavior at high strain rates, which had been difficult for polymers. In addition, findings are also reported regarding the stress-strain behavior of

polymers at high strain rates, which is difficult to estimate using conventional extrapolation. Finally, the simulation results of applying the obtained stress-strain behavior to finite element models are presented.

2. Mechanical Properties of Polymers

This section describes an overview of the mechanical properties of polymers.

The mechanical properties of polymers include the five items of viscoelasticity, strain rate dependence, hydrostatic pressure dependence, extrusion molding flow direction dependence, and humidity dependence. These properties are known to differ greatly for each polymer type. The main goal of crash calculations is to calculate the high-speed deformation of materials, so the stress-strain behavior of materials during high-speed deformation is an important factor. Therefore, this study focused on the viscoelasticity and strain rate-dependence that are highly dependent on the material deformation rate. Figure 1 shows a typical example of these characteristics.

* Tochigi R&D Center

** Asahi Kasei Corporation

This paper reports on tests conducted to measure the viscoelasticity and strain rate-dependence of polymers in consideration of applying polymers to crash simulations, and presents findings regarding the high-speed deformation of polymers. In addition, a comparison with calculation results using the finite element method is also shown.

3. Tensile and Bending Tests

This section describes an overview of the tensile and bending tests performed in this study.

Currently various test apparatuses exist for measuring material properties at high strain rates, and test methods suited to each strain rate range were proposed⁽⁵⁾. According to these methods, the Split-Hopkinson bar method⁽⁶⁾ and one bar method⁽⁷⁾ are suitable for strain rates from 10^3 sec^{-1} to 10^5 sec^{-1} , and methods such as the servo-hydraulic systems are suitable for strain rates from 10^0 sec^{-1} to 10^3 sec^{-1} . In consideration of the effects of different test specimen shapes, this study used a servo-hydraulic system in order to conduct tests using identically shaped test specimens over the widest range possible from the high-speed to low-speed tensile range. These high strain rate test methods consist of accelerating a large mass and impacting it into the piston to start movement of the clamping device before the load is applied to the test specimen. Therefore, the load measurement time becomes shorter at higher strain rates, and the time needed for elastic deformation within the load cell to become uniform is roughly equal. This causes the phenomenon where the elastic wave that reflects multiple times within the load cell becomes noise and has a great effect on the measurement value, and resolving this was an issue for measurement.

Therefore, the high-speed tensile test in this study used a compact and lightweight clamping device and load cell. This increased the natural frequency of the measurement portion to 3.4 times that of the conventional method, and reduced vibration caused by the impact input, making it possible to obtain the measurement value of high-speed tensile test.

3.1. Tensile Test Apparatus and Test Method

This study used a Type AG screw-driven system (AGS-1000G: maximum tensile speed $1.7 \times 10^{-2} \text{ m/s}$) to obtain mechanical characteristics in the static to quasi-static range (strain rate 10^{-4} sec^{-1} to 10^{-1} sec^{-1}), and Type A

(EHF-U2H-20L: maximum tensile speed $1.5 \times 10^1 \text{ m/s}$) and Type B (HITS-T10: maximum tensile speed $2.0 \times 10^1 \text{ m/s}$) servo-hydraulic high-speed impact test apparatuses to obtain mechanical characteristics during medium- to high-speed deformation. The Type A and Type B test apparatuses both operate on the same principle. However, the natural frequency of the Type A test apparatus including the load cell is not sufficiently high, so the impact-induced noise was pronounced at a strain rate of 10^2 sec^{-1} , which made it difficult to obtain accurate data. In contrast, the Type B test apparatus differed from the Type A test apparatus in that it used a lightweight and high rigidity load cell. Figure 2 shows the principle of operation for these high-speed impact test apparatus.

These test apparatuses perform the tensile test after accelerating a hydraulic cylinder to the prescribed speed over the approach (80 mm) of the piston installed on top of the test specimen. This test was used to measure the stress-strain behavior of polymers over the strain rate range from 10^0 sec^{-1} to 10^2 sec^{-1} . Figure 3 shows a photograph of the high-speed tensile test apparatus.

Note that changes in the cross-section shape of the test specimens were recorded at all times during the tensile test in order to measure changes. This was done using a home video camera (SONY) in the low-speed tensile range, and a high-speed video camera (NAC) capable of recording 20 000 frames/s in the medium to high-speed tensile range.

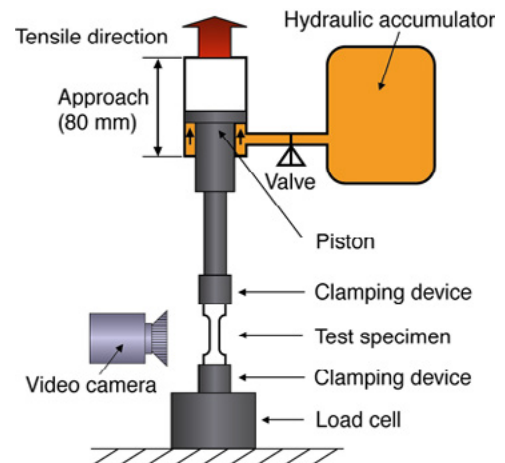


Fig. 2 Schematic illustration of tensile testing apparatus

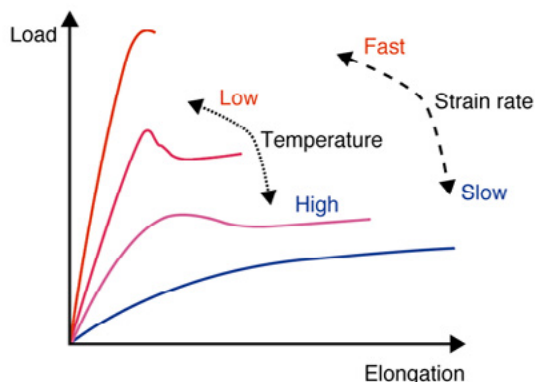


Fig. 1 Dependence of strain rate and temperature in material data

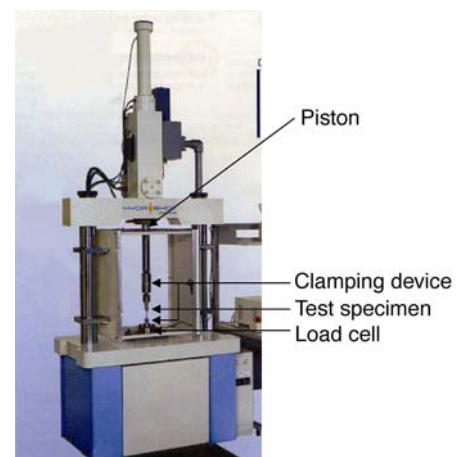


Fig. 3 High-speed tensile testing apparatus

3.2. Tensile Test Specimen Materials and Shapes

Three types of test specimen materials were selected for this study from among polymers widely used in the interior and exterior of automobiles. These three types were polypropylene, which is a thermoplastic crystalline material, polycarbonate, which is a thermoplastic amorphous material, and epoxy, which is a thermosetting polymer. These three materials were selected in order to compare and investigate each polymer type.

JISK7113 No. 2 dumbbell shape (parallel portion width 6 mm) test specimens were used from the static tensile to the medium-speed tensile (up to a strain rate of 10^1 sec^{-1}) range, and compact test specimens designed exclusively for the test apparatus were used only in the high-speed tensile (strain rate 10^2 sec^{-1}) range. Figures 4 and 5 show the respective test specimen shapes.

This test used two types of test specimens with different shapes, so two types of clamping devices were also used. Figure 6 shows a photograph of clamping device A, and Fig. 7 shows a photograph of clamping device B. Clamping device A and B are both made of titanium. Clamping device B has a more compact and lightweight design compared to clamping device A, and while clamping device A has a natural frequency of 5.0 kHz, the natural frequency of clamping device B has been raised to 17 kHz.



Fig. 6 Clamping device A



Fig. 7 Clamping device B

3.3. Bending Test Apparatus and Test Method

The bending test was performed using the same type of test apparatus as the low-speed tensile test. Figure 8 shows a schematic drawing of the bending test, and Fig. 9 shows a photograph of the bending test apparatus. The distance between the fulcrums is 40 mm, and the test was performed by moving the compression rod at a strain rate from 10^{-4} sec^{-1} to 10^{-2} sec^{-1} . A strain gauge was attached to the reverse side of the contact surface of the compression rod and the test specimen, and a measurement was performed up to the maximum measurable strain of 2.0×10^{-2} .

3.4. Bending Test Specimen Material and Shape

The bending test used only the thermoplastic crystalline material polypropylene, and the test specimen was shaped as a rectangular slab of dimensions 100 x 10 x 3 mm.

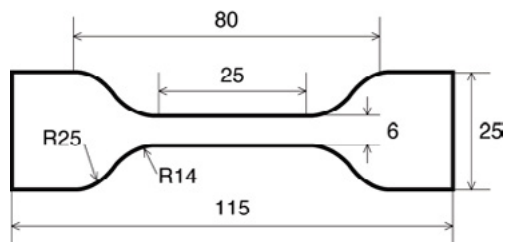


Fig. 4 Schematic illustration of tensile test specimen

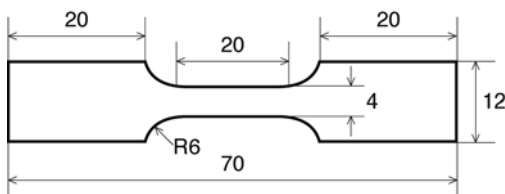


Fig. 5 Schematic illustration of high-speed tensile test specimen

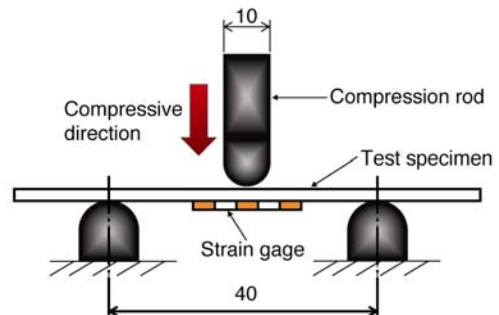


Fig. 8 Schematic illustration of bending test



Fig. 9 Bending test apparatus

Table 1 Tensile test conditions

Crosshead velocity	Strain rate	Testing apparatus
8×10^{-6} m/s	10^{-4}	Type AG: AGS-1000G JIS2 test specimen
8×10^{-5} m/s	10^{-3}	
8×10^{-4} m/s	10^{-2}	
8×10^{-3} m/s	10^{-1}	
8×10^{-2} m/s	10^0	Type A: EHF-U2H-20L JIS2 test specimen
8×10^{-1} m/s	10^1	
4×10^0 m/s	10^2	Type B: HITS-T10 Special test specimen

4. Test Results and Findings

Different tensile test apparatus were used for quasi-static, medium and high strain rates, so this section first compares the measurement values for each test apparatus at the same strain rate. Next, the true-stress true-strain curves for each strain rate are shown as the results of the tensile tests using three types of polymers and the bending test using one type of polymer. Finally, calculations using a general finite element method solver are performed for the tensile tests and compared with the tensile test measurement values.

4.1. Results due to Differences in Test Apparatuses

These tests used different tensile test apparatuses according to the strain rate as shown in Table 1 for the performance of test apparatus and the elimination of the

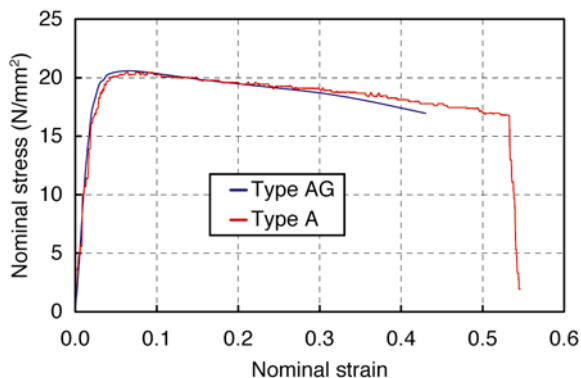


Fig. 10 Stress-strain curves of type AG and A

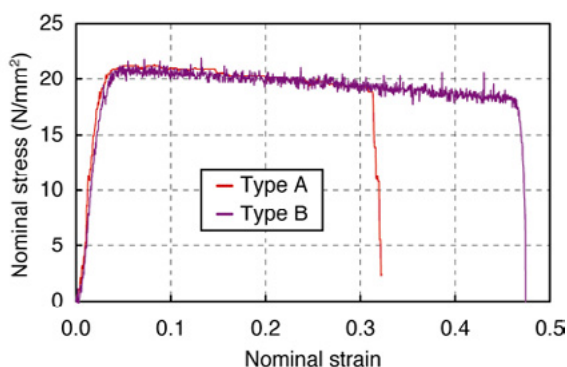


Fig. 11 Stress-strain curves of type A and B

above-mentioned vibration of the high-speed tensile test.

First, the tensile test was performed at a strain rate of 10^{-1} sec^{-1} for polypropylene to verify the difference between the screw-driven system (Type AG) and the high-speed impact test apparatus (Type A). Figure 10 shows the stress-strain curves for these test apparatuses, and the elastic modulus and the stress values were confirmed to match.

Next, the tensile test results for polypropylene at a strain rate of 10^0 sec^{-1} are compared to verify the difference between the two types of high-speed impact test apparatuses (Type A, Type B). These results are shown in Fig. 11, and likewise Fig. 10 the elastic modulus and the stress values were confirmed to match.

4.2. Tensile Test Results

This study obtained tensile test data from the quasi-static to the high-speed ranges using the test apparatuses shown in Table 1 for the three material types of the thermoplastic crystalline polymer polypropylene, the thermoplastic amorphous polymer polycarbonate, and the thermosetting polymer epoxy.

Figure 12 shows the true stress-true strain curves of polypropylene.

As shown in this figure, viscoelastic effects are seen where the elastic modulus increases according to the tensile speed, and the rupture strain also tended to become smaller as the strain rate rose.

Figure 13 shows the difference in the acquired data when using different high-speed test apparatuses for the strain rate 10^2 sec^{-1} data.

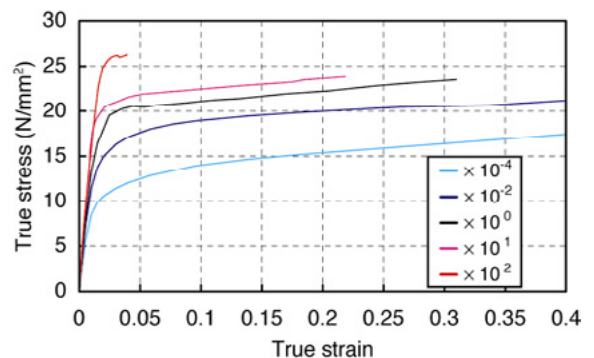
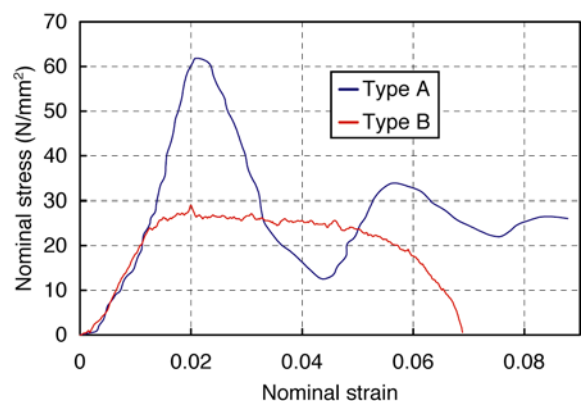


Fig. 12 Stress-strain curves of polypropylene at various strain rates

Fig. 13 Stress-strain curves of polypropylene at strain rate 100 sec^{-1}

In the data acquired using the high-speed impact test apparatus (Type A), the impact input-induced noise is transmitted through the test specimen as mentioned previously, making it difficult to obtain accurate elastic modulus and stress values. On the other hand, stress-strain curves without impact input-induced noise could be obtained from the data acquired using the high-speed impact test apparatus (Type B).

Next are some observations on the stress values obtained at a strain rate of 10^2 sec^{-1} . Generally there are two methods for handling high-speed deformation such as in crash simulations. The first method interpolates the material properties during high-speed deformation by extrapolation based on the stress-strain curve of the component material obtained in the low-speed to medium speed ranges. The second method uses a strain rate-dependent yielding stress only in the low-speed range, and maintains a constant yielding stress in the medium-speed and high-speed ranges. Comparing the extrapolated values for the high-speed range with the stress increase values obtained in this study show that the stress increase values at strain rates from 10^1 sec^{-1} to 10^2 sec^{-1} obtained in this study are much larger than the values calculated based on the stress increase values at strain rates from 10^0 sec^{-1} to 10^1 sec^{-1} .

The stress values at a strain rate of 10^2 sec^{-1} is considered based on the relationship between the impact energy absorption of polypropylene and temperature. In terms of the mechanical properties of polymers, the tensile stress-strain curve at high strain rates and the tensile stress-strain curve at low temperatures are known to show the same stress increase tendencies⁽⁸⁾. Figure 14 shows the relationship between the impact energy absorbed by polypropylene and temperature. Here, the impact energy absorption is seen to drop sharply as

the temperature decreases⁽⁹⁾. When this impact energy absorption is substituted for the absorbed energy in the tensile stress-strain curve, the sudden decrease in the absorbed energy at a strain rate of 10^2 sec^{-1} can be assumed to resemble the decrease in energy absorption as the temperature drops. Based on this observation, this study assumed that the above-mentioned rapid change in the absorbed energy exists for polypropylene between the strain rates of 10^1 sec^{-1} to 10^2 sec^{-1} . However, further investigations are necessary. In addition, tensile tests must be conducted at even more strain rate levels to understand the strain rate boundary values.

Next, Fig. 15 shows the true stress-true strain curves for the thermoplastic amorphous polymer polycarbonate. Likewise for polypropylene, this test data also shows pronounced viscoelasticity and strain rate-dependence. However, polycarbonate differs from polypropylene in that variance was seen in the rupture strain. Figure 16 shows photographs of the entire test specimens following this test, and Figs. 17 and 18 show photographs of craze deformation that occurred on the test specimen surface.

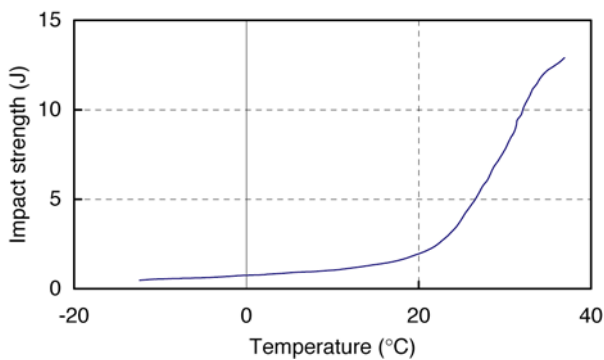


Fig. 14 Temperature dependence at absorption of impact energy in polypropylene

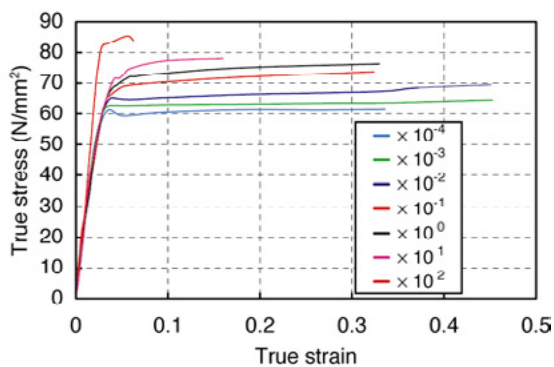


Fig. 15 Stress-strain curves of polycarbonate at various strain rates

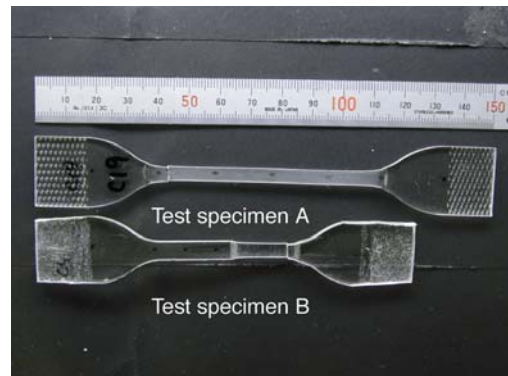


Fig. 16 Photograph of test specimens

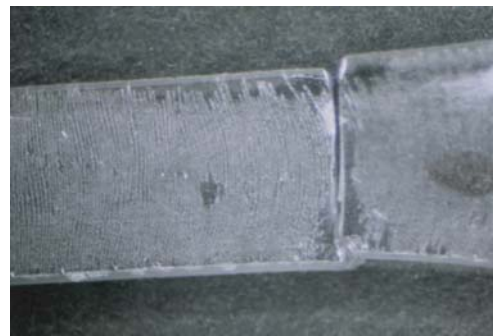


Fig. 17 Magnified photograph of test specimen A



Fig. 18 Magnified photograph of test specimen B

Test specimen A in Fig. 16 is the test piece for a strain rate of 10^{-3} sec^{-1} , and test specimen B is the test piece for a strain rate of 10^1 sec^{-1} . This photograph clearly shows that necking occurred along the entire length of the parallel portion of test specimen A. On the other hand, necking appeared only locally in test specimen B. The necking formation similar to test specimen A was observed at strain rates of 10^{-2} sec^{-1} or less, and the necking formation similar to test specimen B was observed at strain rates of 10^{-1} sec^{-1} or more.

In addition, craze deformation was observed at a high density on the surface of test specimen A as shown in Fig. 17, but craze deformation occurred only locally on the surface of test specimen B as shown in Fig. 18. Local rupture strain in the necking portions was measured in reference to marks made at 1.0 cm intervals on the surface of each test specimen. The results confirmed that at strain rates of 10^{-1} sec^{-1} or more, the rupture strain tended to decrease as the strain rate increased. However, a clear correlation between the local rupture strain and the strain rate was not observed at strain rates of 10^{-2} sec^{-1} or less. Based on these observation results, a critical strain rate at which craze occurs at high density is assumed to exist, and it is difficult for a correlation between the strain rate and the rupture strain to appear at strain rates below that level. However, further verification is necessary. In addition, polycarbonate differed from polypropylene in that the rupture strain was smaller in the low strain rate range. This difference in the rupture strain is known to depend largely on whether the material is crystalline or amorphous. For crystalline polymers, the orientation of the polymer chain within the substance faces the loading direction, the rupture strain increases. However, amorphous polymers have a structure with randomly positioned amorphous molecules and do not have a crystal structure, so they are thought to rupture at a smaller strain than for crystalline polymers.

Lastly, Fig. 19 shows the true stress-true strain curves for the thermosetting polymer epoxy. These results show that a strain rate-dependent change in the elastic modulus was observed like for polypropylene and polycarbonate. On the other hand, most rupture occurred within the elastic region.

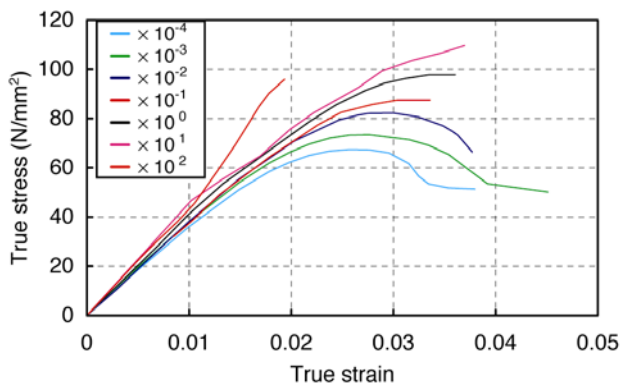


Fig. 19 Stress-strain curves of epoxy at various strain rates

4.3. Bending Test Results

In addition to tensile tests, this study also performed bending tests for the thermoplastic polymer polypropylene. The bending test was performed using strain gauges at the strain rates of 10^{-4} sec^{-1} , 10^{-3} sec^{-1} and 10^{-2} sec^{-1} , and Fig. 20 shows the corresponding bending stress-strain curves. Viscoelastic effects were also observed in the bending test, with the bending elastic modulus increasing together with the strain rate.

4.4. Application to Finite Element Models

Verification of the tensile test at a strain rate of 10^2 sec^{-1} for polypropylene was performed by simulation using a general finite element method solver. Calculations were performed for the two conditions of case A, which was based on the stress-strain behavior including the strain rate of 10^2 sec^{-1} , and case B, which obtained the stress-strain behavior in the strain rate range in excess of 10^1 sec^{-1} by extrapolation, and these were compared with the maximum load during the tensile test. The maximum load value was 460 (N) for case A and 347 (N) for case B, and the measured value was 445 (N). Figures 21 and 22 show the deformation diagrams of the test specimens for the Von Mises stress distribution at a tensile displacement of 2 mm. Areas with high stress values are indicated by red, and areas with low stress values are indicated by blue.

Figures 21 and 22 clearly show that the case A calculation results have higher stress values than the case B results. This is because in case B, the stress values obtained by linear interpolation from the experimental data at strain rates of 10^0 sec^{-1} and 10^1 sec^{-1} are smaller than the experimental values. These results confirmed that using high strain rate test data enhances simulation reproducibility at high strain rates compared to the extrapolation-based calculation results.

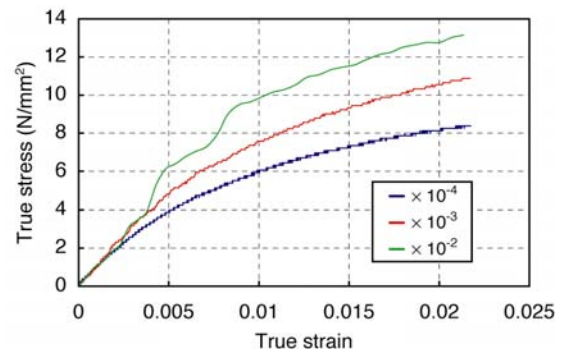


Fig. 20 Stress-strain curves of polypropylene at various strain rates



Fig. 21 Deformation of tensile test piece (Case A)



Fig. 22 Deformation of tensile test piece (Case B)

5. Conclusion

Tensile tests and bending tests were performed for polymers used in the interior and exterior of automobiles, and observations were made regarding the non-linear behavior, strain rate-dependence, and rupture behavior of these polymers. In addition, tensile test simulations were performed using a general finite element method solver. In the future, the authors intend to analyze the rupture surface in these polymer tests, and to formulate a new modeling of polymers.

The following conclusions were obtained through this study.

- (1) A method was constructed for measuring the high-speed deformation of polymers, which had thus far been difficult to measure.
- (2) The stress-strain behavior of polymers at high strain rates, which is difficult to estimate using conventional extrapolation, was understood.
- (3) Applying the stress-strain behavior obtained from experiments to finite element models confirmed that simulation reproducibility is enhanced at high strain rates.

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■ Authors ■



Hiroyuki MAE



Kenji TAKADA



Junichi TAKAHASHI



Toshiharu YAMAMOTO