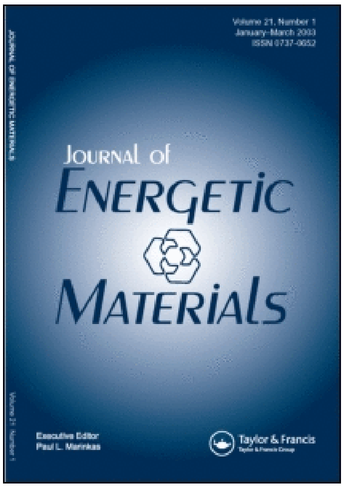

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An experimental study on mechanical properties of energetic materials in triaxial compression due to impact

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An experimental study on mechanical properties of energetic materials in triaxial compression due to impact

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Abstract—An experimental apparatus of triaxial compression, which is available to measure the mechanical response of explosives at different temperatures and strain rates, is developed by authors. Dynamic and static compressive experiments of Comp. B and TNT are performed and the material properties, such as compressive modulus, Poisson's ratio and yield strength etc., are obtained. The results show that there exist clear effects of temperature and strain rate for TNT and Comp. B. It also can be found that compressive modulus and strength of Comp. B are larger than that of TNT. In addition, a new method to determine the yield strength in triaxial loading state is presented.

1. INTRODUCTION

Very little information about the mechanical properties of molecular organic polycrystalline solids is available. In an effort to understand these materials and, in particular, to determine failure conditions, an experimental apparatus is designed and made by authors which can be used to measure the mechanical response of energetic materials under uniaxial and triaxial compression and the properties of trinitrotoluene (TNT) and Composition B (Comp. B) are investigated. Comp. B is made up of 39.5% TNT, 59.5% cyclotrimethylene trinitramine (RDX), and 1% wax. Both TNT and RDX are organic polycrystalline solids. It is shown from the experimental results that these materials fail by brittle fracture in uniaxial loading state but by yielding in triaxial loading state.

TNT and Comp. B are important military explosives. Knowledge of their mechanical properties and, in particular, the conditions for failure are significant before in use. Mechanical failure of explosives is thought to play a critical role in ignition/initiation[1~5]. To model the behaviour of these materials during cast cooling, handling and in use such as projectile launch, measurements are made at two strain rates, a quasi-static rate which is appropriate for cast cooling and some handling conditions, and a dynamic one which is applicable to weapons use such as artillery launch. To consider the temperature effect, measurements are also made at different temperatures.

Yield strength is another important parameter in the ignition/initiation mechanism of energetic materials under impact, but its measurement has not been settled very well up to date. J. Pinto and coworkers[6] proposed a method to evaluate the yield strength in triaxial compression,

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but it is difficult to use. In this paper, a new method is presented.

2. EXPERIMENT

A scheme of experimental set-up for triaxial compression is shown in Fig. 1. It consists of following parts: an axial loading system, an environment room of triaxial compression for energetic materials, heating and maintaining system and data handling system.

The axial loading control is performed on a servo-hydraulic material test machine system. The system can apply a load of up to ± 10000 Kg and achieve the maximum free run velocity of 1m/s. Strain rate of explosive samples can attain about 3 s^{-1}. Failure of a test specimen may take place in approximately 5 to 7 milliseconds.

The environment room of triaxial compression is the key part of the test(see Fig. 2). Thermocouples are attached to various locations on the tube, anvils, and metal parts in contact with the test fixture. The experiment is carried out when all of the thermocouples indicate that thermal equilibrium has been attained.

The measurement, analysis and treatment of data are conducted by means of displacement sensor, load sensor, strain gages, dynamic strain instrument and digital oscilloscope.

The samples are made into the form of cylinders with lengths about 38. 2 mm and diameters close to 19. 1 mm. The average density of the cylinder samples is 1. 686 g/cm^3 for Comp. B and 1. 616 g/cm^3 for TNT respectively. In order to minimize frictional force inside the tube, the whole specimen is coated with a thin film of graphite powder before being placed in the tube. A tight fit must exist between the specimen and the wall of the tube. The thermal coefficients of expansion of Comp. B and TNT are greater than that of steel, which enables the specimen to come into contact with the whole wall of tube.

The steel cylinder and tray are taken off from the triaxial compressive apparatus so as to make up the apparatus of uniaxial compression.

When the desired test temperature is achieved the test fixture is brought into contact with the load cells. A small pre-load of approximate 5 Kg is applied to the specimen.

3. MEASURING THEORY

3. 1. Determination of Young's modulus E and Poisson's ratio v

As shown in Fig. 3, the cylinderically shaped specimen is in three dimensional stress states. The specimen is enclosed in a close fitting thickwalled cylinder made of steel and compressed along x axis. For isotropic materials, the stress-strain relationships can be written as

$$\varepsilon_x = S_{11}\sigma_x + S_{12}\sigma_y + S_{12}\sigma_z \qquad (1a)$$

$$\varepsilon_y = S_{12}\sigma_x + S_{11}\sigma_y + S_{12}\sigma_z \qquad (1b)$$

$$\varepsilon_z = S_{12}\sigma_x + S_{12}\sigma_y + S_{11}\sigma_z \qquad (1c)$$

Where Young's modulus E and Poisson's ratio v are

$$E = \frac{1}{S_{11}} \tag{2a}$$

$$\nu = -\frac{S_{12}}{S_{11}} \tag{2b}$$

Because the cylinder tube is much stiffer than the test specimen, the strains of the specimen in y and z directions are negligible, i. e.

$$\varepsilon_y = \varepsilon_z = 0 \tag{3}$$

From the axial symmetry, i. e.

$$\sigma_y = \sigma_z = \sigma_r \tag{4}$$

the following relation is obtained at once

$$\sigma_r = \frac{\nu}{1-\nu}\sigma_x = m\sigma_x \tag{5}$$

where m is the slope of the curve of radial stress σ_r versus axial stress σ_x in the elastic region. So Poisson's ratio ν can be solved as

$$\nu = \frac{m}{1+m} \tag{6}$$

Furthermore, Young's modulus can be derived from eqns (1a), (4) and (5) in the form

$$E = \frac{\sigma_x}{\varepsilon_x}\left(1 - \frac{2\nu^2}{1-\nu}\right) \tag{7}$$

3. 2. The relationship between σ_r and ε_θ

σ_r is the inner radial stress of steel tube, and ε_θ is the outer hoop strain of the restrained tube. This hoop strain may be measured by the strain gages glued on the outside of the tube. The relationship between σ_r and ε_θ can be written as

$$\sigma_r = \frac{E_s(b^2 - a^2)}{2a^2}\varepsilon_\theta \tag{8}$$

where a and b are, respectively, the inner and outer radii of the test cylinder, E_s is the elastic modulus of the tube.

3. 3. Yield criteria

Various criteria can be used to determine yield strength. The Von Mises criterion is stated

$$Y_{vm} = \sqrt{\frac{1}{2}\left[(\sigma_x - \sigma_y)^2 + (\sigma_y - \sigma_z)^2 + (\sigma_z - \sigma_x)^2\right]} \tag{9}$$

The Tresca criterion is stated

$$Y_t = |\sigma_x - \sigma_y| \tag{10}$$

These two yield criteria, eqns (9) and (10), are not identical in general. However, for the triaxial compressive conditions in this work, i. e. $\sigma_y = \sigma_z = \sigma_r$, we can obtain from both eqns (9) and (10) that

$$Y = |\sigma_x - \sigma_r| \tag{11}$$

4. RESULTS AND DISCUSSION

The material properties of Comp. B and TNT are measured under uniaxial and triaxial compression at strain rates of 3 s^{-1} and 1×10^{-4} s^{-1} and at temperatures of 20, 40, and 60℃.

The results of the uniaxial compression for Comp. B are shown in table 1 and Figs 4 to 8. The effects of temperature are described in Figs 4 and 5. The strain rate dependence is described in Fig. 6. Figs 7 and 8 indicate the tendency of the compressive strength σ_m and the Young's modulus E for Comp. B with temperature changing.

Table 1 Summary of the uniaxial compressive data for Comp. B

Strain rate	3/s			10^{-4}/s		
Temperature (℃)	20	40	60	20	40	60
Young's modulus (GPa)	4.33	3.70	2.21	3.18	1.79	1.15
Compressive strength σ_m(10MPa)	1.86	1.65	1.20	1.51	0.72	0.52
Strain ε_m(10^{-3})	5.03	4.35	4.75	5.12	4.60	4.50

Table 2 Summary of the triaxial compressive data for Comp. B

Strain rate	3/s			10^{-4}/s		
Temperature (℃)	24	42	62	23	40	51
Young's modulus(GPa)	4.10	3.95	2.20	3.63	3.30	2.87
Yield strength (10MPa)	6.00	6.45	3.00	5.07	4.30	3.35
Poisson's ratio	0.38	0.39	0.45	0.34	0.36	0.37

Table 3 Summary of the uniaxial compressive data for TNT

Strain rate	3/s			10^{-4}/s		
Temperature (℃)	22	32	40	22	32	40
Young's modulus (GPa)	3.05	1.92	1.88	2.48	1.58	0.77
Compressive strength (10MPa)	1.96	1.53	1.26	1.37	0.74	0.63

Table 4 Summary of the triaxial compressive data for TNT

Strain rate	3/s			10^{-4}/s		
Temperature (℃)	21	37	49	23	36	51
Young's modulus(GPa)	3.25	3.09	1.79	3.22	2.98	2.53
Yield strength (10MPa)	3.85	4.14	1.97	3.32	2.84	2.96

The results of the triaxial compressive experiment are summarized in table 2 and Figs 9 to

15. The typical curves of σ_z versus t , σ_z versus ε_z and σ_r versus σ_z at strain rate of 3 s^{-1} are given in Figs 9, 10 and 11, respectively. The tendency of the Poisson's ratio ν and the yield strength Y with different temperatures for Comp. B can be found in Figs 12 and 13. The results for TNT are shown in tables 3 and 4.

The comparison between Comp. B and TNT are illustrated in Figs 14 and 15 and their differences can also be found in table 1 to 4. From the data we could conclude that Comp. B is stronger and stiffer than TNT for all conditions. The presence of RDX particles in Comp. B might reasonably be expected to improve the mechanical properties of energetic materials. The effect of the RDX are presented and discussed in considerably detail in reference [5] and [6]. R is the correlation coefficient of least—square fit in figures 7 to 15.

Using the intersection technique, Pinto and Weigand[6] obtained the yield strength Y , i. e. Y was calculated as the difference between σ_z and σ_r at the point of intersection of the straight lines obtained from the elastic (initial) and yield regions. It is found that it is considerably random to determine the yield regions from our experimental curves of σ_r versus σ_z .

A new method to determine yield strength Y under triaxial compression is developed by us. The key points of the method are

(1). The moment $\bar{t}_s$ at which the yield occurs is determined by the turning point on the curve of displacement u versus time t .

(2). $\bar{\varepsilon}_z$ at the moment $\bar{t}_s$ is found on the curve of ε_z versus t .

(3). From $\bar{\varepsilon}_z$, corresponding $\bar{\sigma}_z$ on the curve of σ_z versus ε_z is determined.

(4). Finally from $\bar{\sigma}_z$, corresponding $\bar{\sigma}_r$ on the curve of σ_r versus σ_z is gotten, and in the light of the equation (11), the yield strength Y is obtained.

As mentioned above, the method is simple and feasible, and the value determined is definite but random.

From the data obtained, we find that Comp. B and TNT is sensitive to strain rates. Compressive strength σ_m , yield strength Y , and Young's modulus E increase with strain rate increasing. The properties of Comp. B and TNT are also dependent on temperatures. As temperature increasing, the values of E, Y and σ_m decrease. It is also found that Poisson's ratio ν increases slightly with temperature increasing and the E, Y and σ_m of Comp. B are larger than that of TNT.

The yield strengths reported by wiegand, Pinto and Nicolaides (refs 6) are smaller than the values reported here as is the case for Comp. B and TNT. The moduli reported in refs 5 and 6 are also smaller than the values reported here. This difference suggested a systematic error or other reasons.

5. SUMMARY AND CONCLUSIONS

(1). A test equipment of uniaxial and triaxial compression is presented which is available to determine the mechanical response of explosives at different temperatures and strain rates. Measurements of TNT and Comp. B explosives have been made under uniaxial and triaxial compression. Some parameters, such as compressive strength σ_m, Young's modulus E, Poisson's ratio ν and yield strength Y have been obtained.

(2). The experimental results show that there are clear effects of temperature and strain rate for TNT and Comp. B. The values of E, Y and σ_m decrease with temperature increasing, but increase with strain rate increasing.

(3). A new method to determine the yield strength in triaxial loading state has been proposed.

(4). The results indicate that Comp. B is stronger and stiffer than TNT for all conditions. The presence of RDX particles in Comp. B might reasonably be expected to improve the mechanical properties of energetic materials.

ACKNOWLEDGEMENTS

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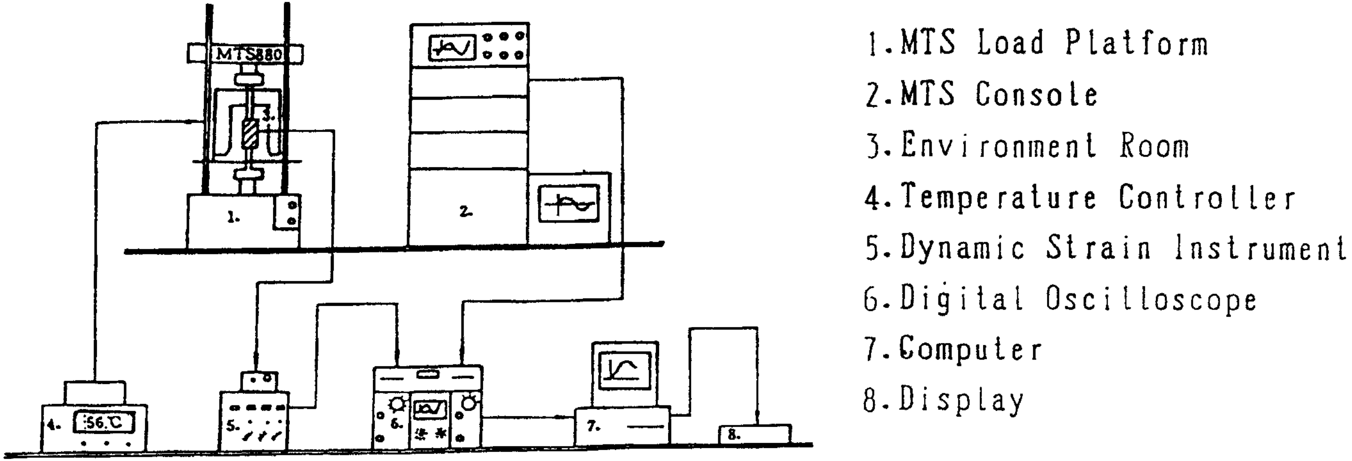

Fig. 1 Schematic diagram of the experimental set-up

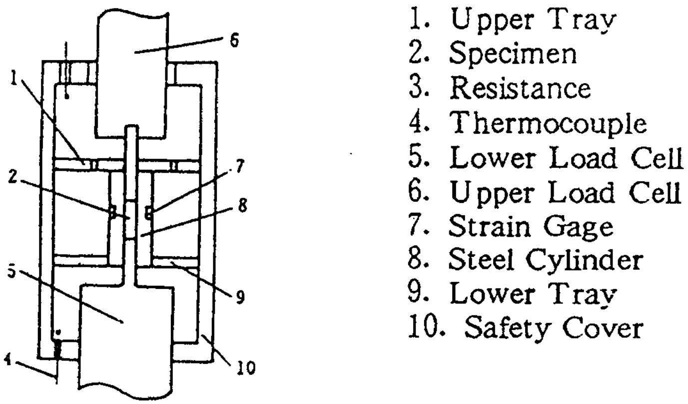

Fig. 2 Environmental room of triaxial compression

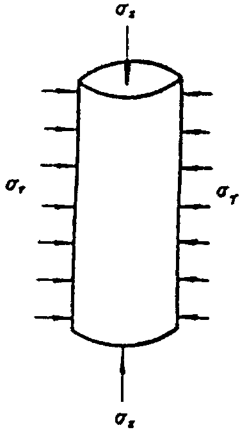

Fig. 3 Loading illustration

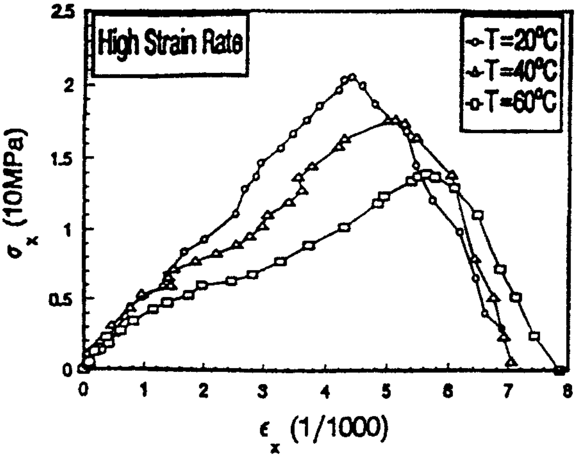

Fig. 4 Curve of axial stress versus axial strain for Comp. B

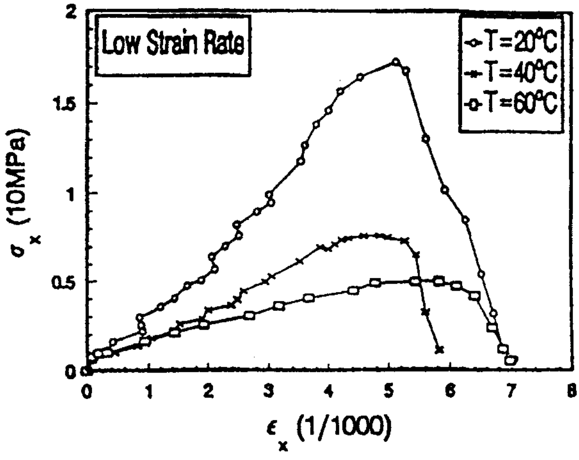

Fig. 5 Curve of axial stress versus axial strain for Comp. B

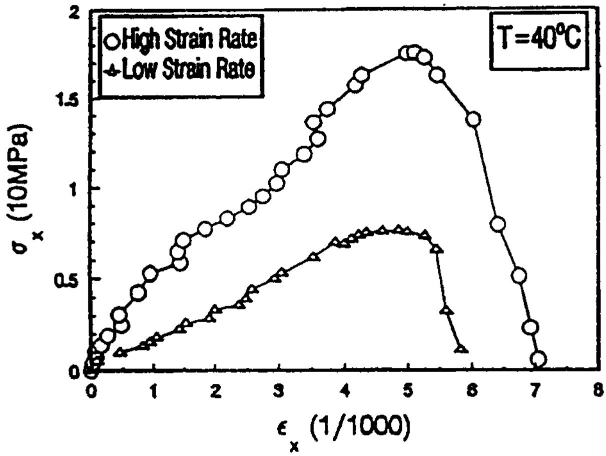

Fig. 6 Curve of axial stress versus axial strain for Comp. B

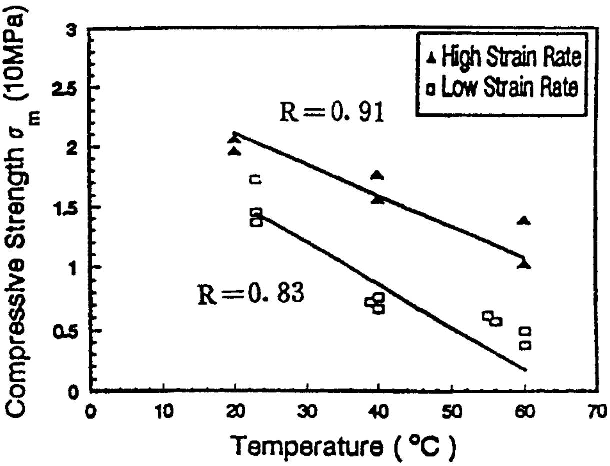

Fig. 7 Curve of compressive strength versus temperature for Comp. B

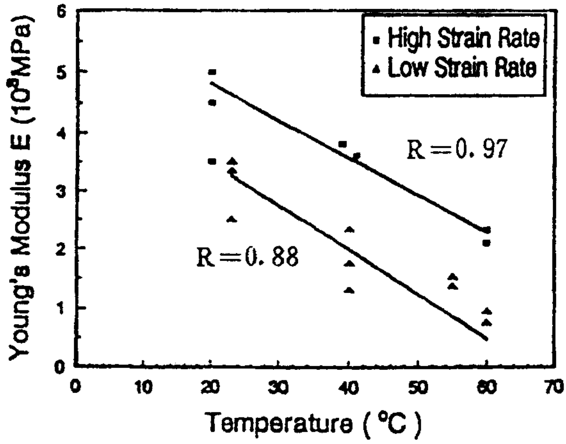

Fig. 8 Curve of Young's modulus versus temperature for Comp. B

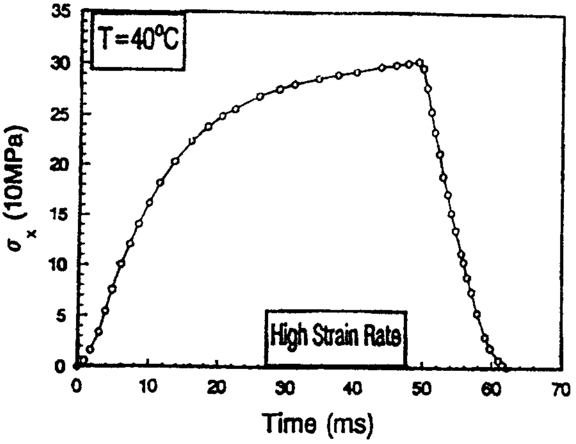

Fig. 9 Curve of axial stress versus time for Comp. B

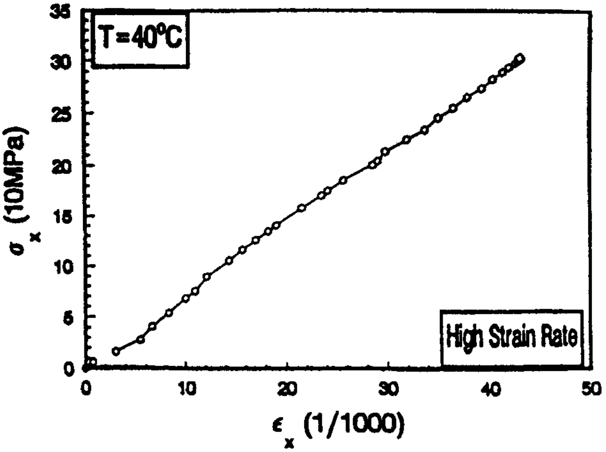

Fig. 10 curve of axial stress versus axial strain for Comp. B

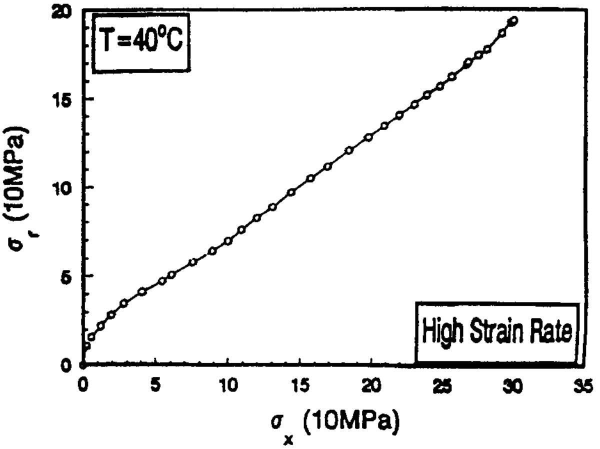

Fig. 11 curve of radial stress versus axial stress for Comp. B

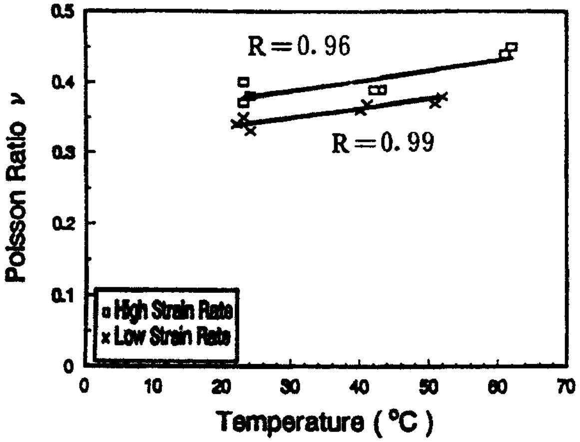

Fig. 12 Curve of Poisson's ratio versus temperatures for Comp. B

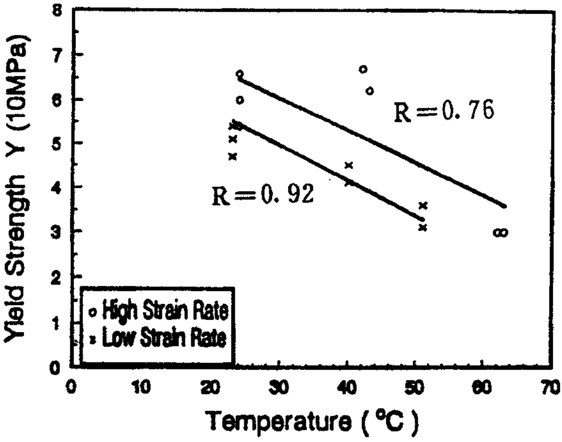

Fig. 13 Curve of Yield strength versus temperatures for Comp. B

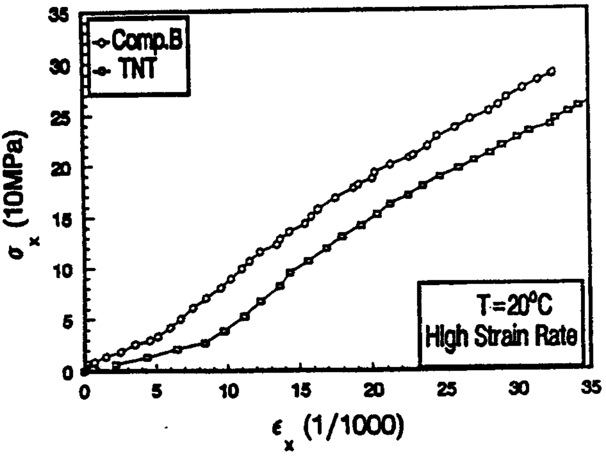

Fig. 14 Comparison of the experimental data for Comp. B and TNT

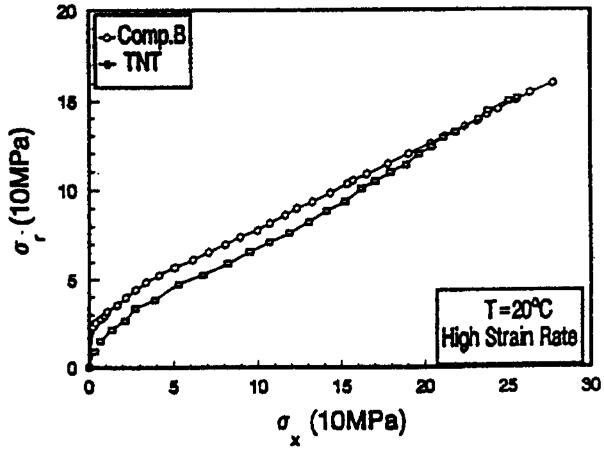

Fig. 15 Comparison of the experimental data for Comp. B and TNT