The Effects of Elevated Temperatures on the Response of Resins Under Dynamic and Static Loadings

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1. BACKGROUND

The overall objective of the research is to experimentally study the combined effects of temperature and strain rate on the response of two resins that are commonly used for the matrix material in composites. The resins are loaded at various temperatures in shear and in tension over a wide range of strain rates. These two types of loadings provide an opportunity to examine also the effect that temperature might have on the effects of the hydrostatic stress component on the material response.

The experimental data provide the information needed for NASA scientists for the development of a nonlinear, strain rate, and temperature dependent deformation and strength models for composites that can subsequently be used in design. This year effort was directed into the development and testing of the epoxy resin at elevated temperatures. Two types of epoxy resins were tested in shear at high strain rates of about 10^{-4} s^{-1} and elevated temperatures of 50 and 80°C. The results show that the temperature significantly affects the response of epoxy.

2. EXPERIMENTAL SETUP

Torsion and tensile tests were conducted at strain rates of approximately 10^{-4} s^{-1} using an axial/torsional hydraulic Instron machine.

Torsion tests

The specimen in the torsion tests is a short thin-walled tube, shown in Fig.1. The specimen is made by machining a notch in a thick-walled tube. The thick-walled tube is made from an epoxy plate such that the axis of the tube is perpendicular to the plate. The specimen is glued to adapters, also shown in Fig. 1, that are then attached by means of a hexagonal connection and set screws to extension bars that are connected to the grips of the testing machine. To examine the effect of the specimen's thickness on the results, specimens with wall thickness of 0.025 and 0.050 in. were tested. The shear strain is determined from the relative rotation between the specimen's ends. The relative rotation is measured by the rotation of the machine's head and by a special device made of two rings that are attached at the ends of the specimen gage and an LVDT that measure the relative rotation between the rings, Gilat and Krishna (1977). The strain can also be determined from the rotation of the machine's actuator. The shear stress is determined from the torque measured by the load cell of the machine, assuming a uniform state of pure shear in the specimen gage length. The temperature of the specimen is measured with two thermocouples that are touching the specimen thin walled section from the inside.

Tensile tests

The specimen in the tension tests is a short dog-bone shaped coupon, shown in Fig 2(*a*). The specimen is glued to two aluminum adapters, shown in Fig. 2(*b*), and the unit (a specimen glued to two adapters, are pinned to double universal joints that are attached to the grips of the machine. The double universal joints prevent any bending loading that might exist due to misalignments.

The strain is measured with strain gages that are cemented to the specimen. Two strain gages (Measurements Group EA-06-125BZ-350 or EA-06-031DE-350) are cemented on the specimen's surface on opposite sides. The strain can also be determined from the displacement of the machine's head.

The temperature of the specimen is measured with two thermocouples that are glued to the side surface of the specimen.

Elevated temperature tests

Tests at elevated temperatures are done by placing an oven made by ATS Applied Test Systems, Inc., around the specimen. The oven was specially designed, ordered, and manufactured for these tests. The specimen is heated with air that is only slightly higher than the testing temperature. Once the specimen reaches the testing temperature it is maintained in this temperature for about 5 minutes before the loading starts.

4. RESULTS

Tests were conducted with specimens made of E-862, and PR-520 resin materials. The tests are summarized in tables 1. The data that was recorded during the tests (stress and strain as a function of time), and the stress-strain curve, for each test are presented in the Appendix. The data is presented in the order of the listing in table 1. For the torsion tests, the strain that is determined from the rotation of the machine's head is essentially identical to the strain that is measured with the special shear strain-measuring device. For the tension tests, the strain determined from the motion of the actuator is larger than the strain measured by the strain gages on the specimen.

A summary of the results is shown in Figures 3-6. Figures 3 and 4 show the shear stress-strain curves from all the torsion tests together for the PR-520 and E-862 resins, respectively. The figures include also stress-strain curves from previous tests conducted at room temperature. Both resins show a very ductile response at all temperatures with strains reaching at least 40% deformation. Both figures show a significant effect of the temperature on the stiffness (the slope of the stress-strain curve in the initial portion of the curve) and on the maximum stress. Both reduce significantly with temperature. At 80°C both, the stiffness and the maximum stress are about half of those at 25°C. The shear stress-strain curves of the PR-520 resin at all temperatures show a reduction of stress after the stress reaches the maximum. This indicates that localized deformation may be taking place. After the tests the surface of the specimens had a narrow white band that appear to be caused by localized deformation. The shear stress-strain curves of the E-862 resin do not indicate any localization. The stress-strain curves level off at large strains but don't show a reduction in stress.

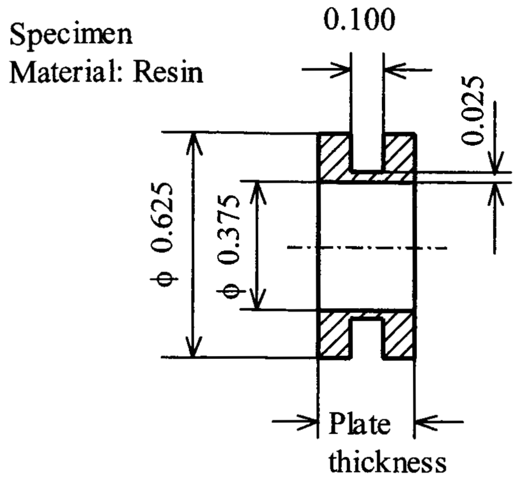
Figures 5 and 6 show the normal stress-strain curves from all the tension tests together for the PR-520 and E-862 resins, respectively. The data set is not yet complete, and the testing continues. From the data that is available so far it appears that in tension at all temperatures the resins are much less ductile than in shear. In addition, compares to shear, the temperature appears to have a larger effect on the maximum stress than on the stiffness. These are only preliminary conclusions that will be evaluated again as more tests are conducted.

REFERENCES

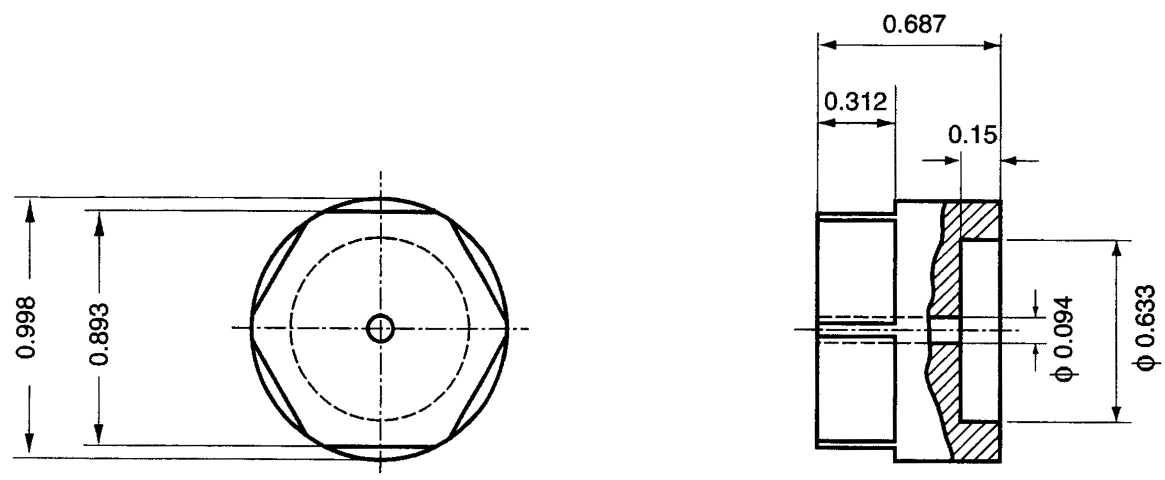
Gilat, A., Krishna, K. (1977) The Effects of Strain Rate and Thickness on the Response of Thin Layers of Solder Loaded in Pure Shear, ASME Journal of Electronic Packaging, Vol. 19, 1977, pp. 81-84.

Table 1: Summary of Tests with epoxy resins, 2004-2005.

TEST NO.	SPECIMEN'S MATERIAL	STRAIN RATE (1/s)	COMMENTS
EXP04-59	Epoxy resin PR-520	$1.36x10^{-4}$	Torsion, T=50°C
EXP04-60	Epoxy resin PR-520	$1.31x10^{-4}$	Torsion, T=50°C
EXP04-61	Epoxy resin PR-520	$1.34x10^{-4}$	Torsion, T=50°C
EXP04-62	Epoxy resin E-862	$1.34x10^{-4}$	Torsion, T=50°C, lower stress
EXP04-63	Epoxy resin E-862	$1.34x10^{-4}$	Torsion, T=50°C
EXP04-64	Epoxy resin E-862	$1.34x10^{-4}$	Torsion, T=50°C
EXP04-65	Epoxy resin PR-520	$1.31x10^{-4}$	Torsion, T=80°C
EXP04-66	Epoxy resin PR-520	$1.39x10^{-4}$	Torsion, T=80°C
EXP04-67	Epoxy resin E-862	$1.43x10^{-4}$	Torsion, T=80°C
EXP04-68	Epoxy resin PR-520	$4.44x10^{-4}$	Torsion, T=80°C (Higher strain rate)
EXP04-69	Epoxy resin E-862	$1.5x10^{-4}$	Torsion, T=80°C
EXP04-70	Epoxy resin PR-520	$1.43x10^{-4}$	Torsion, T=80°C
EXP04-71	Epoxy resin E-862	$1.4x10^{-4}$	Torsion, T=80°C
EXP04-72	Epoxy resin PR-520	$1.39x10^{-4}$	Torsion, T=80°C
EXP04-73	Epoxy resin E-862	$1.39x10^{-4}$	Torsion, T=50°C
EXP04-74	Epoxy resin PR-520	$3.59\ x10^{-4}$	Tension, T=50°C
EXP04-75	Epoxy resin PR-520	$3.25\ x10^{-4}$	Tension, T=50°C
EXP04-76	Epoxy resin PR-520	$5.24\ x10^{-4}$	Tension, T=50°C
EXP04-77	Epoxy resin PR-520	$5.24\ x10^{-4}$	Tension, T=80°C
EXP05-1	Epoxy resin E-862	$4\ x10^{-5}$	Tension, T=50°C



(*a*)



(*b*)

All dimensions are in inches.

Fig. 1: Torsion test specimen and adapter.
(*a*) specimen, (*b*) adapter

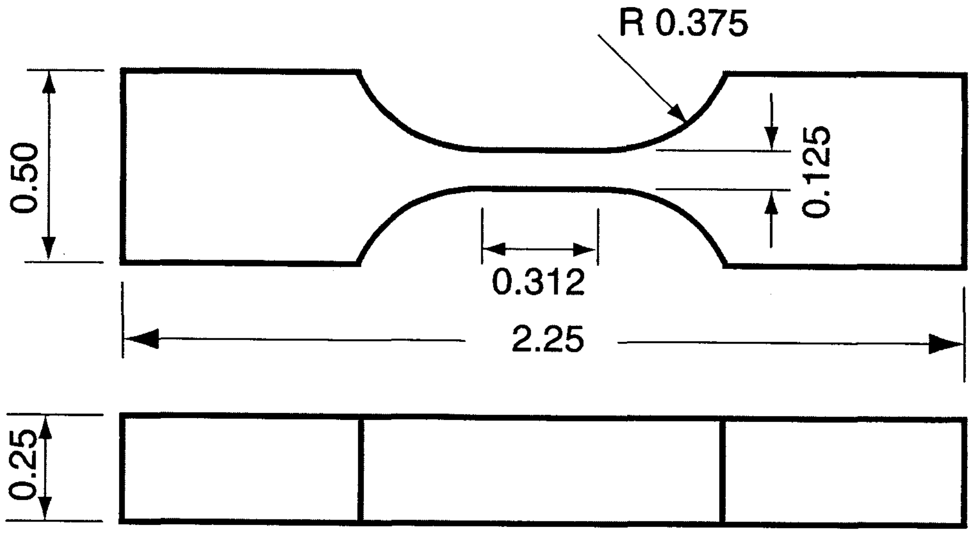


Fig. 2 (*a*): Tensile test specimen.

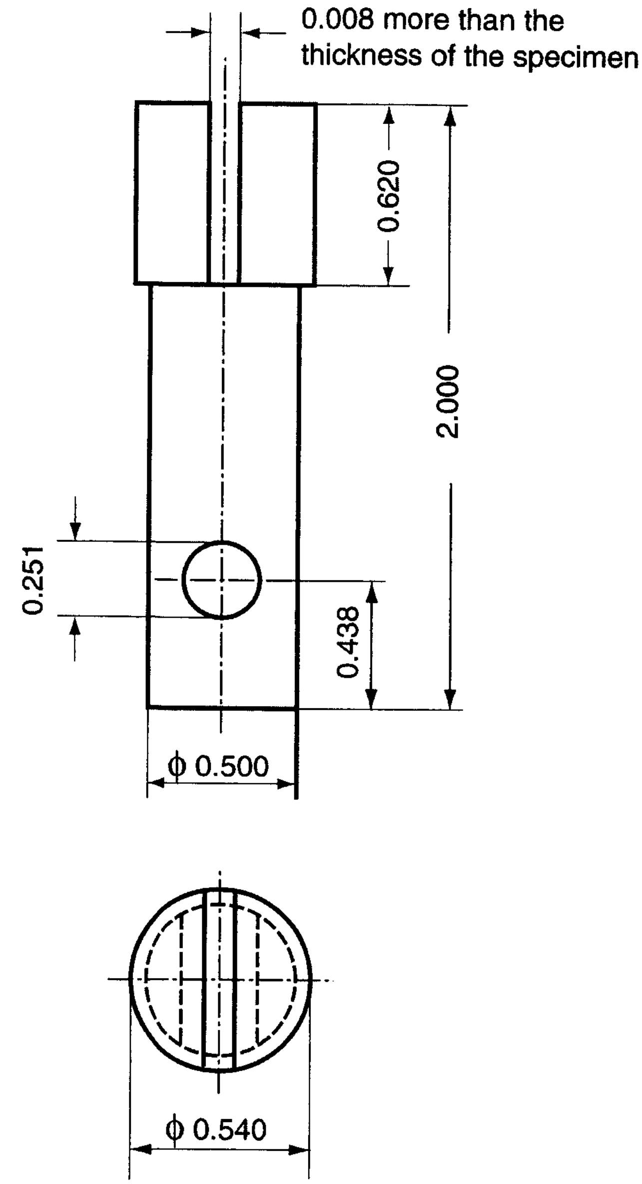


Fig. 2 (*b*): Adapter for tensile test specimen.

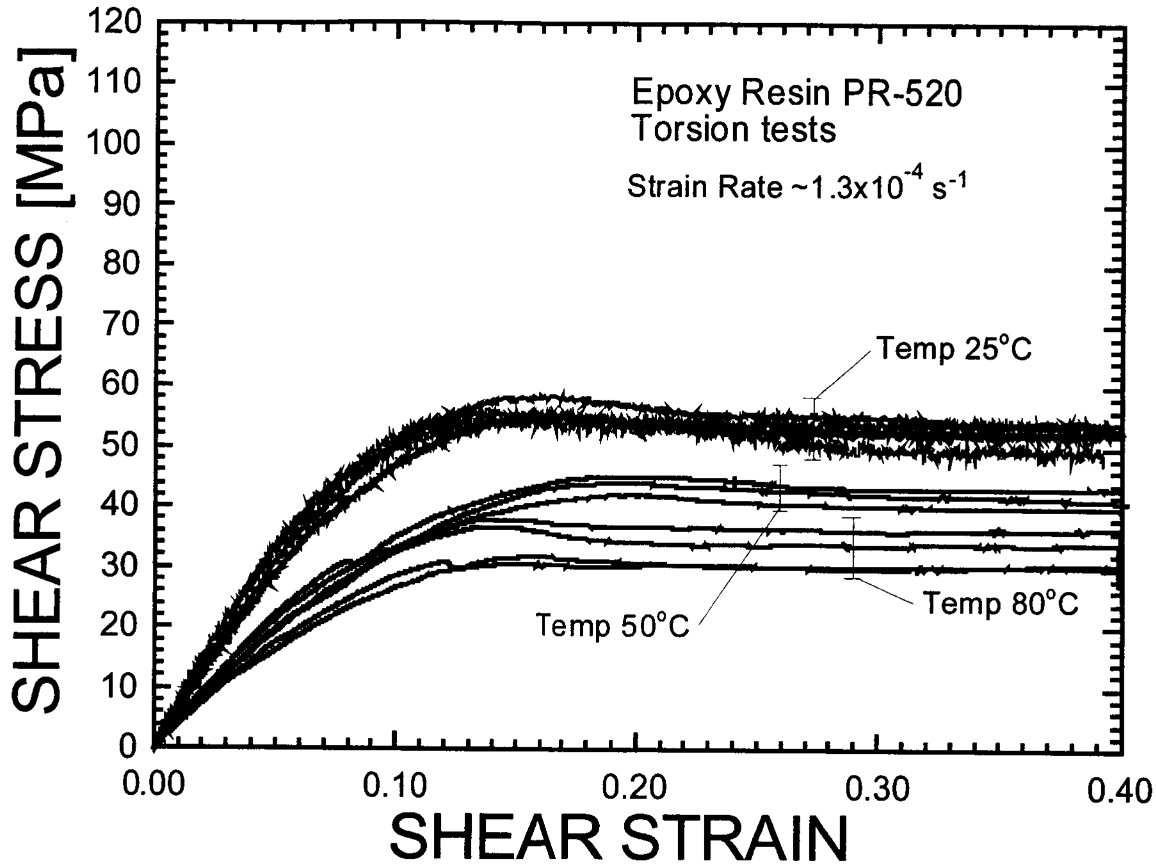


Fig. 3: Shear stress strain curves for PR-520 epoxy at low rate and various temperatures.

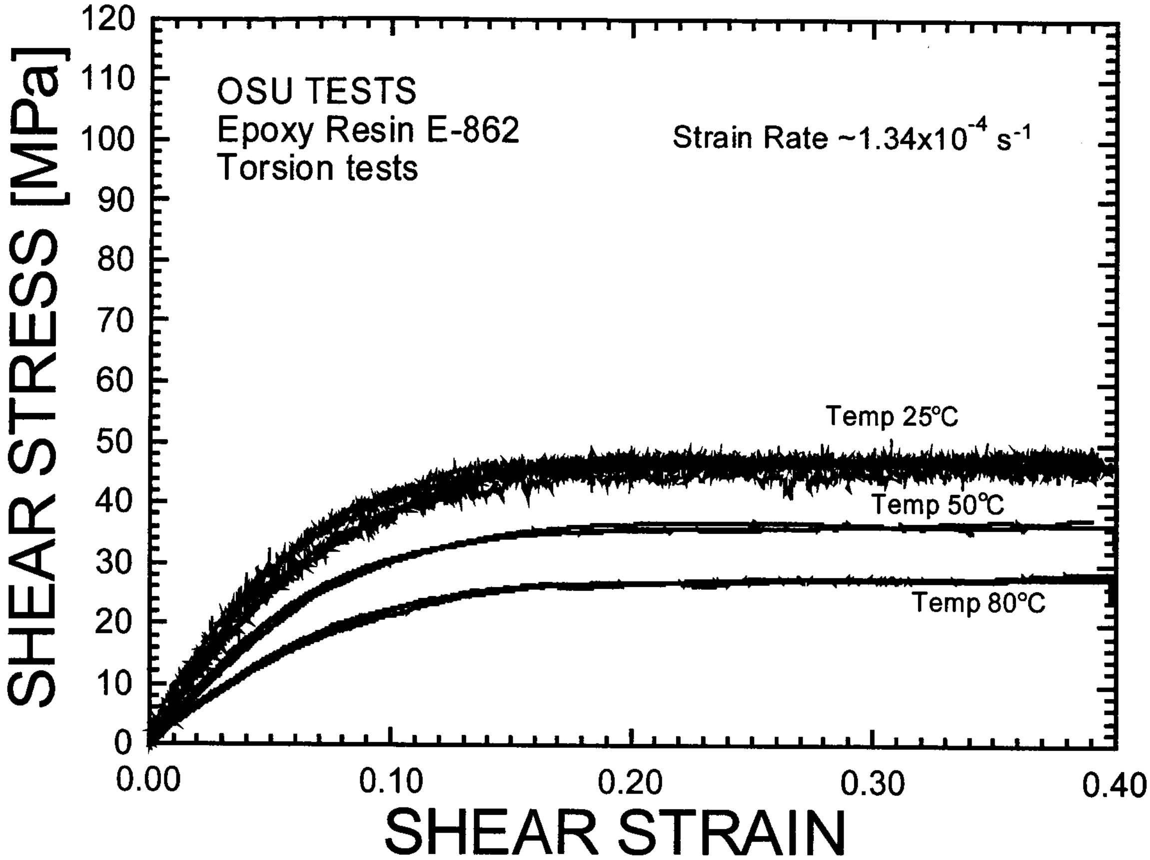


Fig. 4: Shear stress strain curves for E-862 epoxy at low rate and various temperatures.

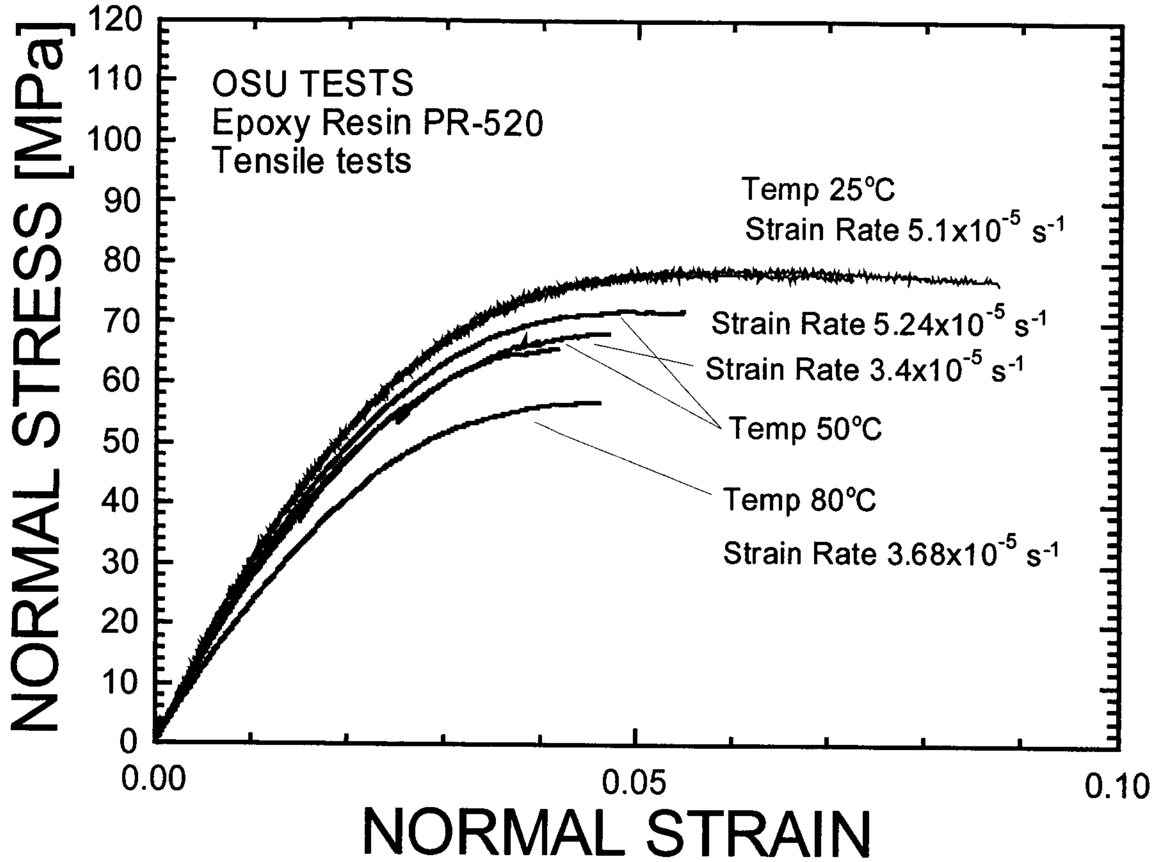


Fig. 5: Normal stress strain curves for PR-520 epoxy at low rate and various temperatures.

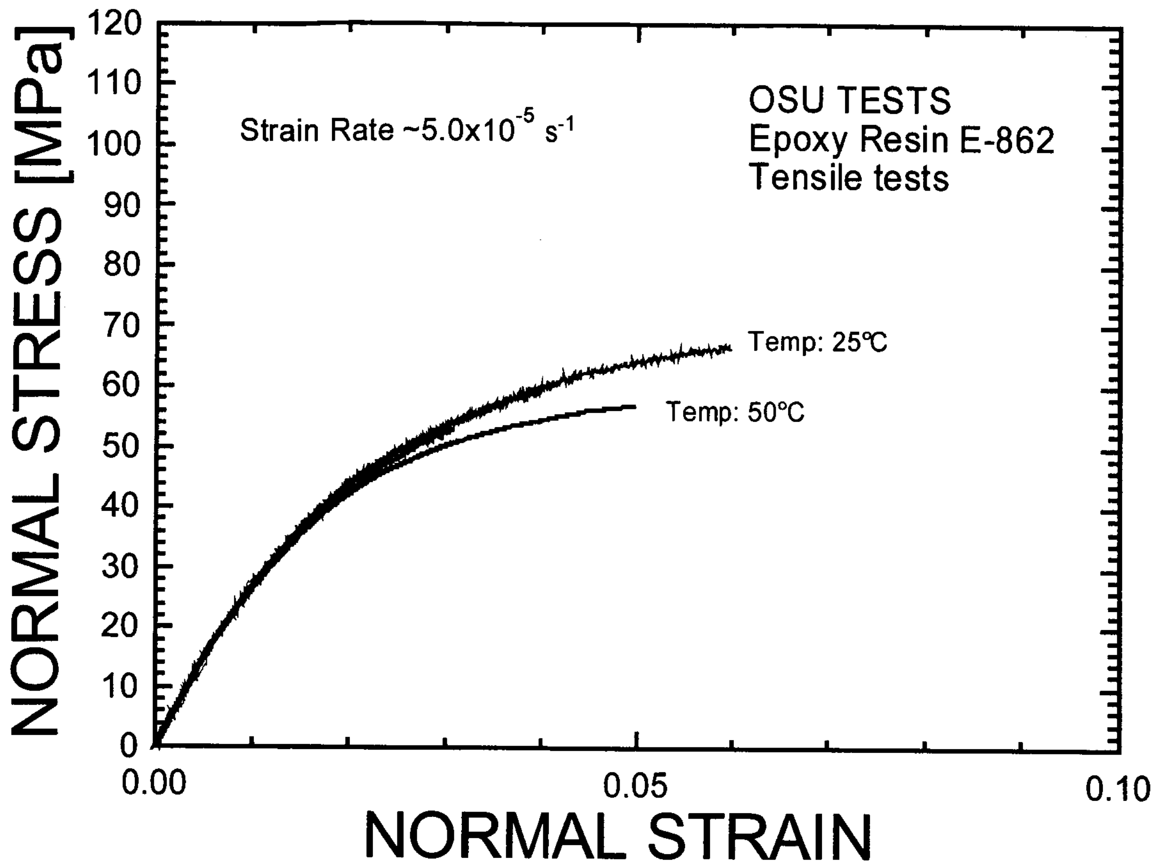
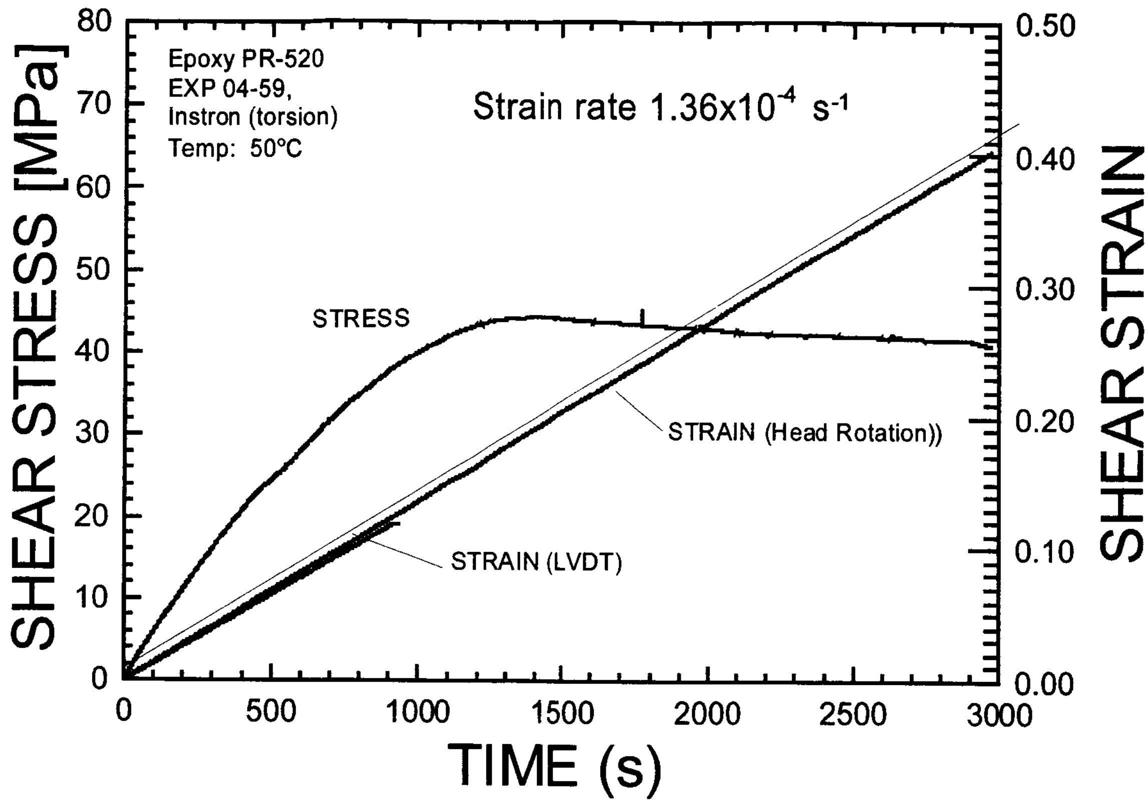


Fig. 5: Normal stress strain curves for E-862 epoxy at low rate and various temperatures.

APPENDIX

For each test two plots are presented. In the first (top) plot the stress and strain are plotted as a function of time. The second (bottom) plot shows the stress-strain curve for the test.

The plots are in the order listed in Table 1.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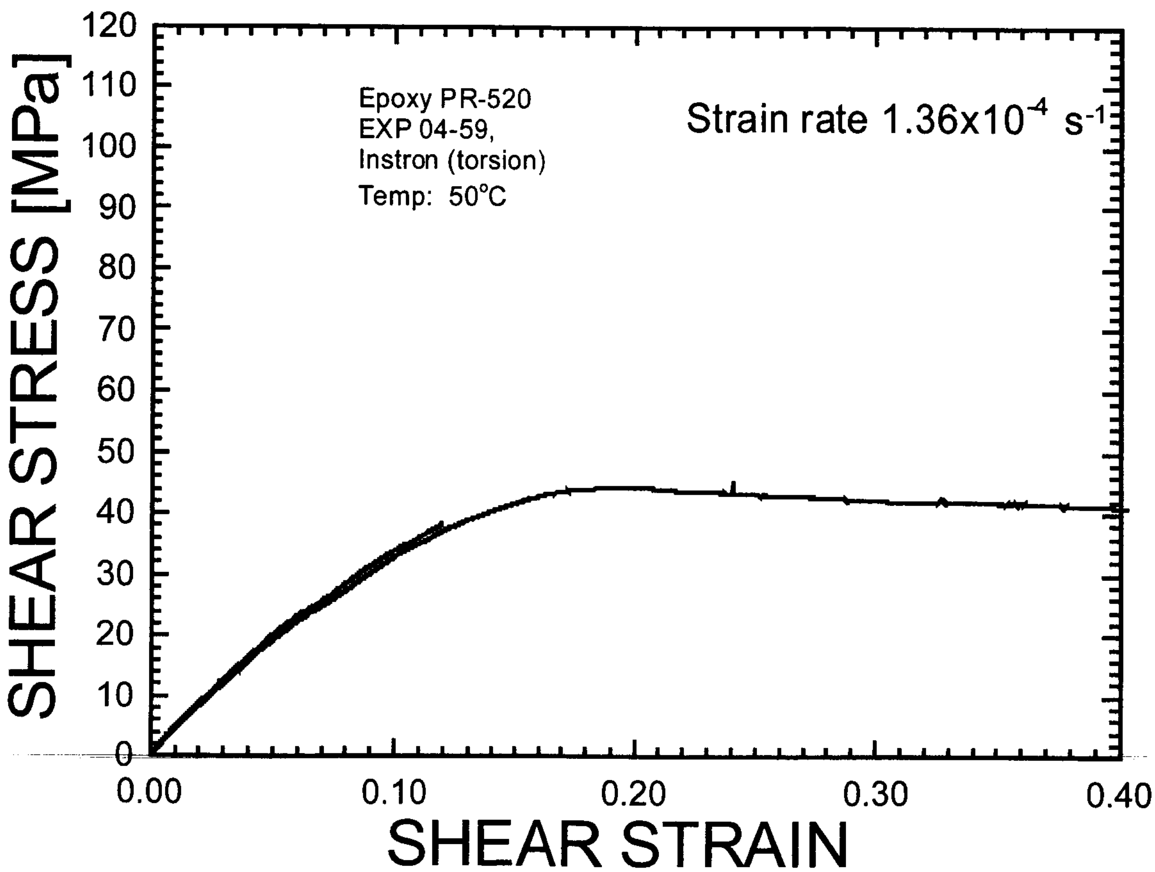
Instron (torsion)
Temp: 50°C
Strain rate 1.36x10-4 s-1
STRESS
STRAIN (Head Rotation))
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)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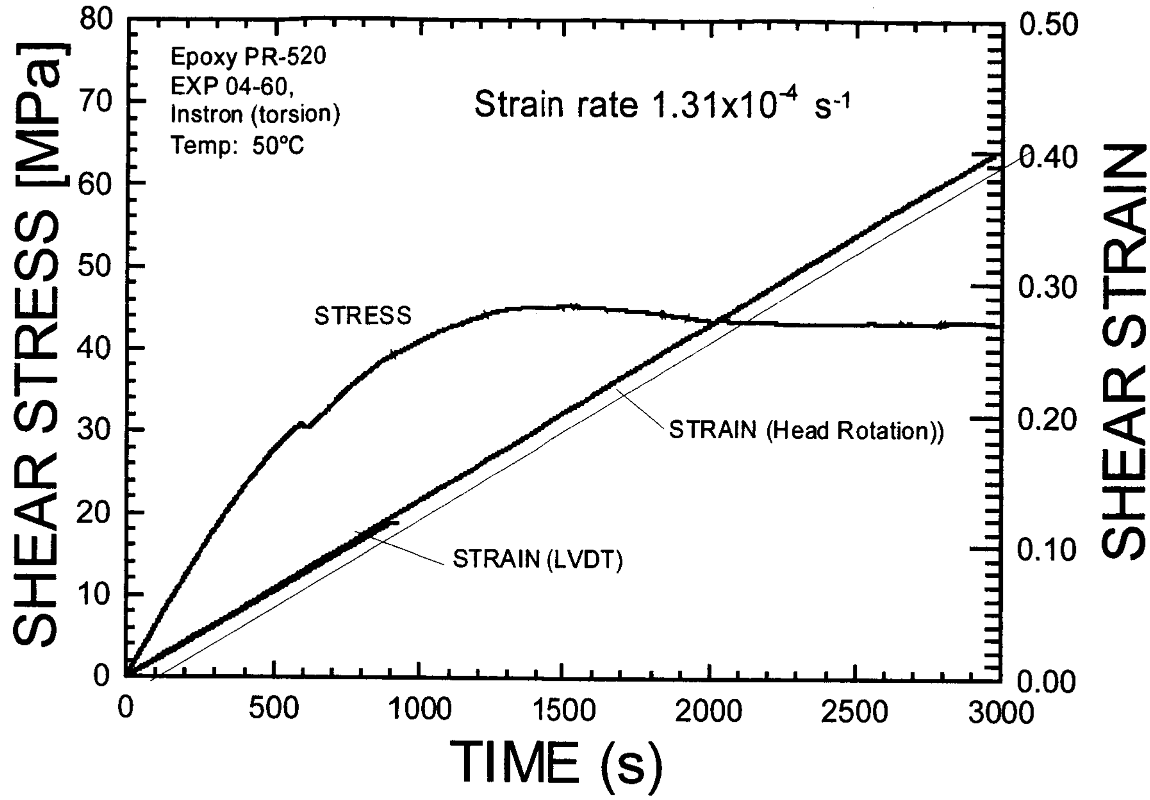
Strain rate 1.36x10-4 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN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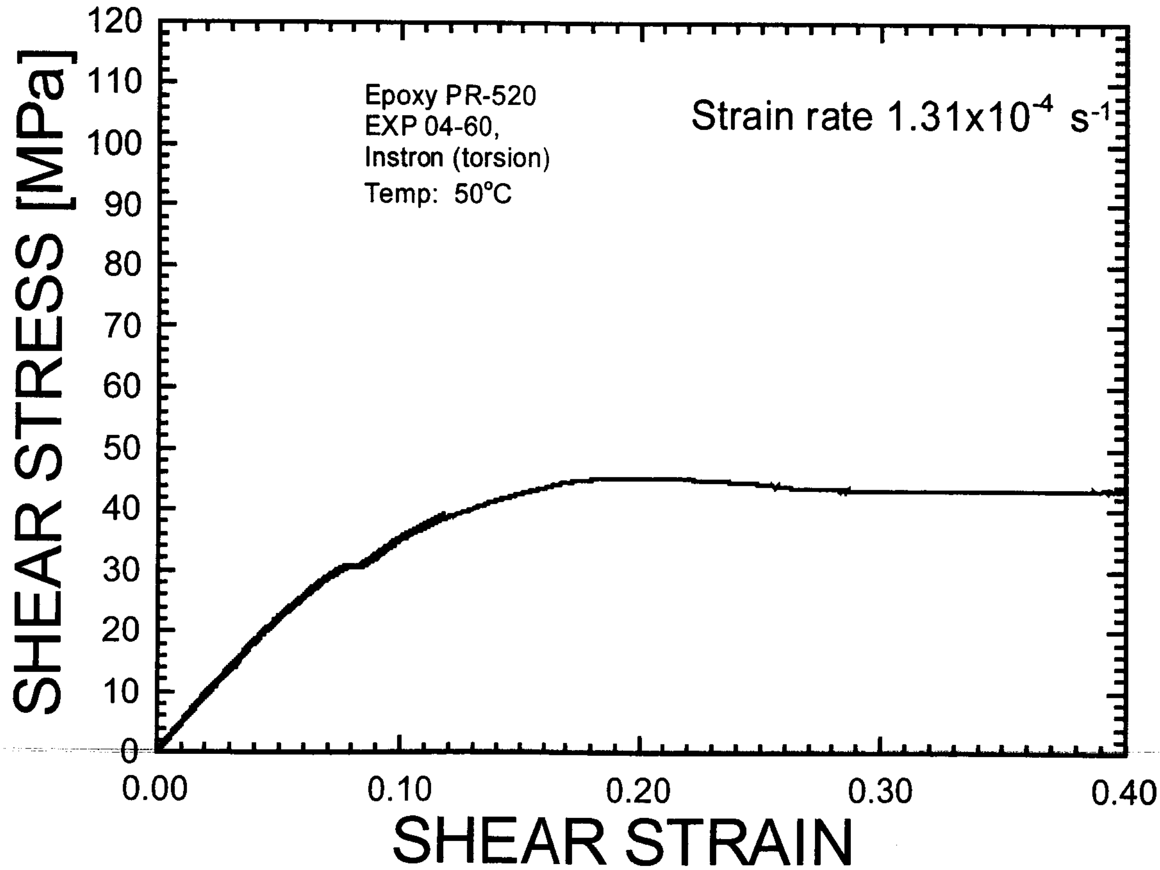
EXP 04-60,
Instron (torsion)
Temp: 50°C
Strain rate 1.31x10-4 s-1
STRESS
STRAIN (Head Rotation))
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
80
70
60
50
40
30
20
10
0
0.50
0.40
0.30
0.20
0.10
0.00
0
500
1000
1500
2000
2500
3000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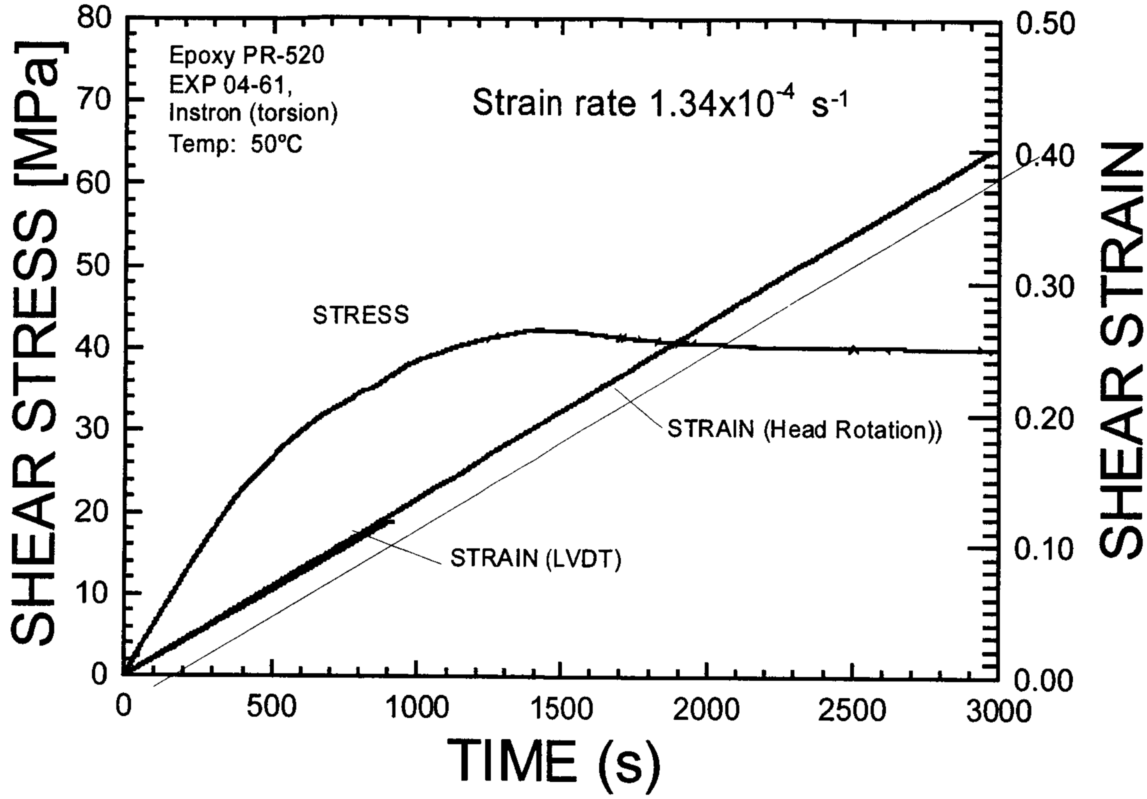
EXP 04-60,
Instron (torsion)
Temp: 50°C
Strain rate 1.31x10-4 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN
120
110
100
90
80
70
60
50
40
30
20
10
0
0.00
0.10
0.20
0.30
0.40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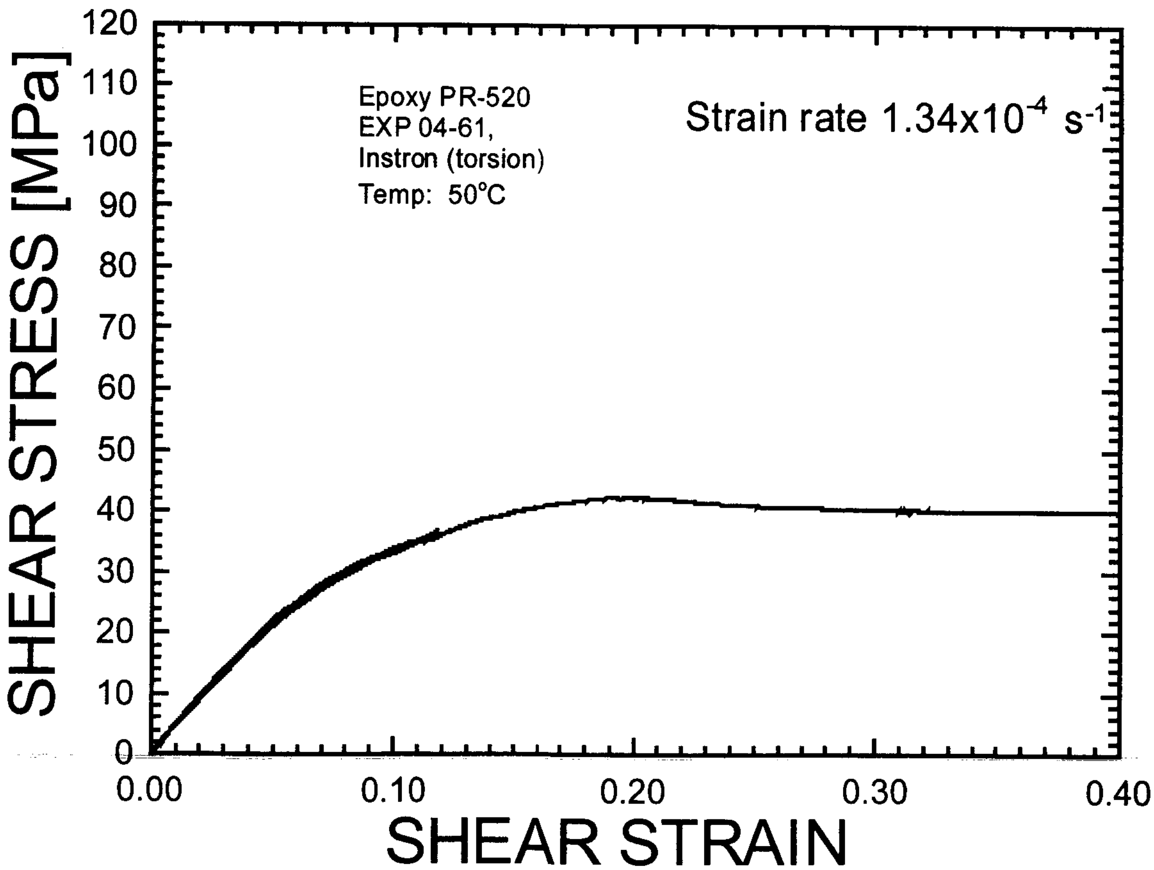
Instron (torsion)
Temp: 50°C
Strain rate 1.34x10-4 s-1
STRESS
STRAIN (Head Rotation))
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)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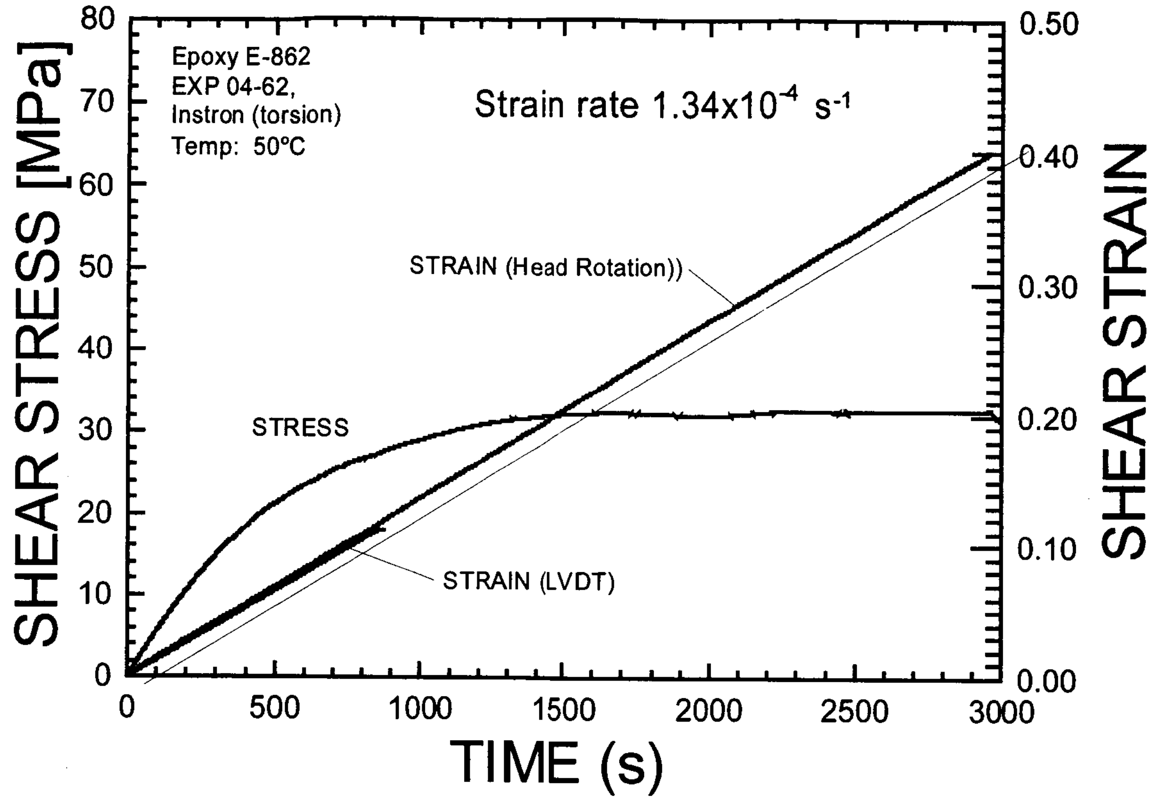
SHEAR STRAIN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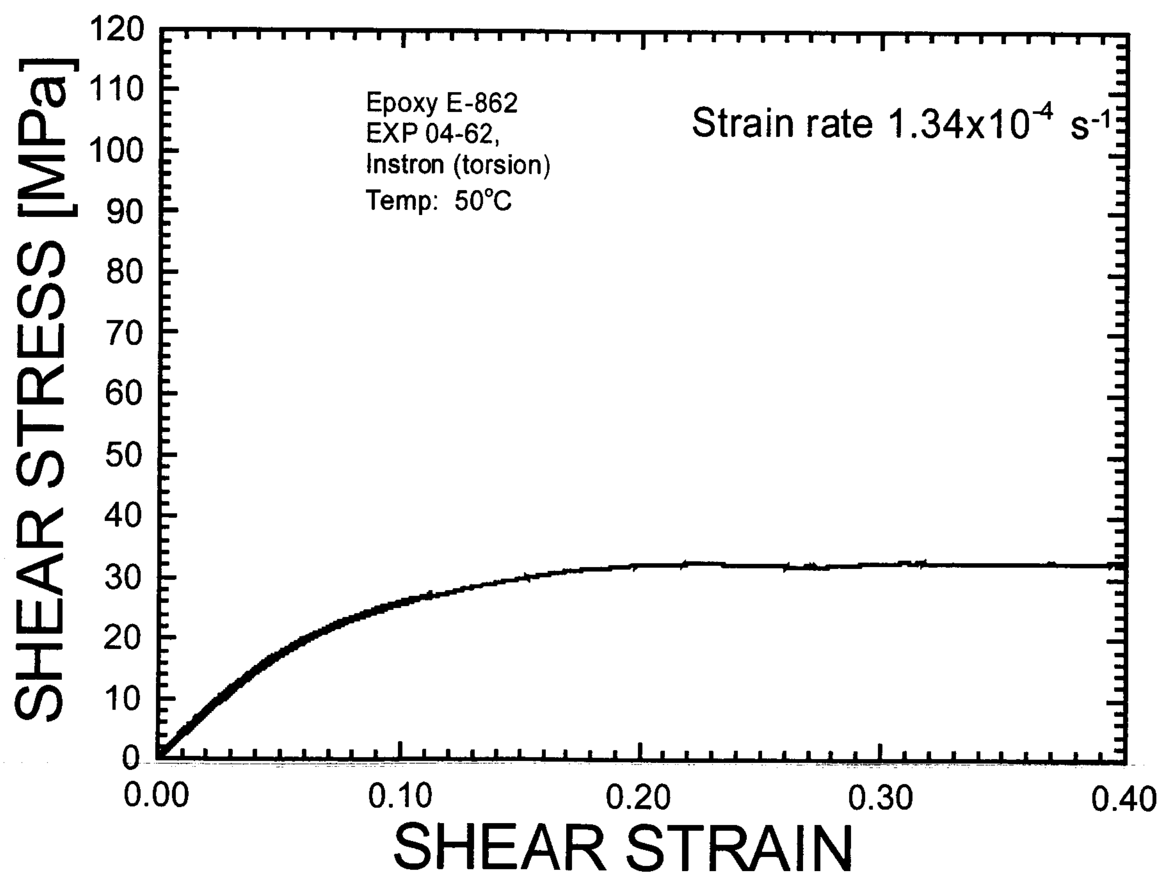
Instron (torsion)
Temp: 50°C
Strain rate 1.34x10-4 s-1
STRAIN (Head Rotation))
STRESS
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)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Instron (torsion)
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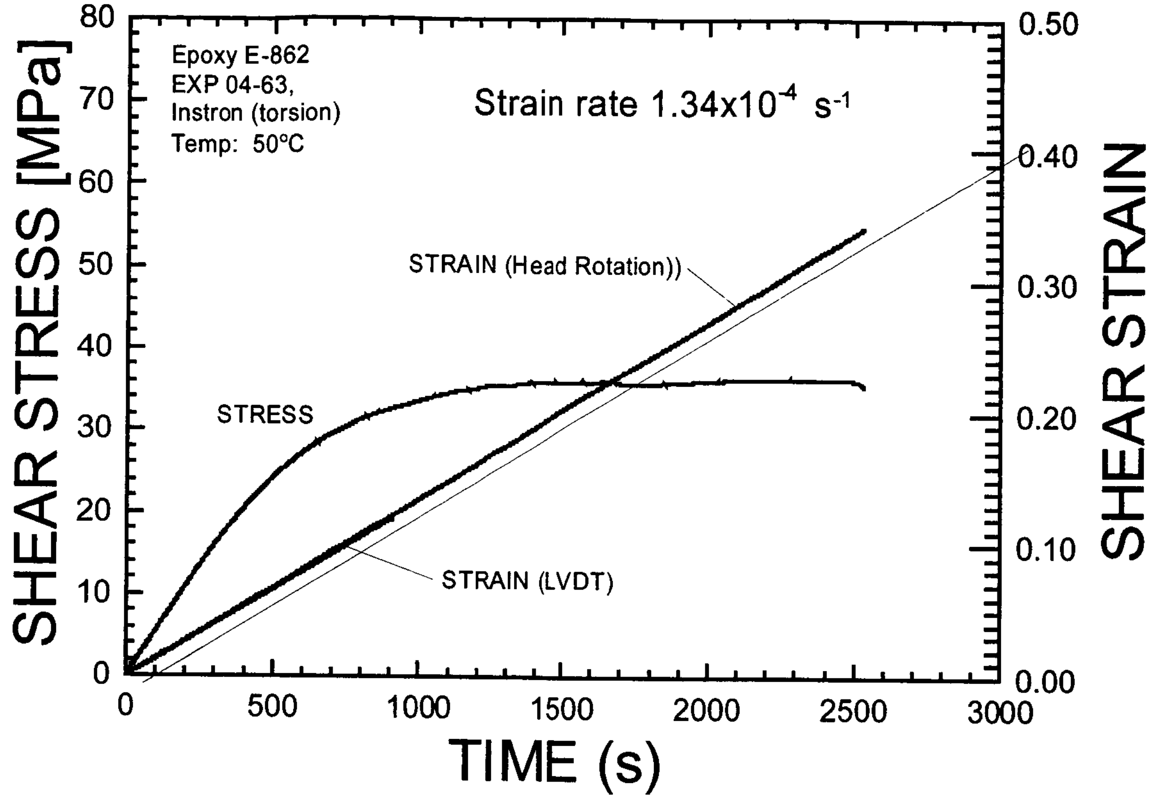
Strain rate 1.34x10-4 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN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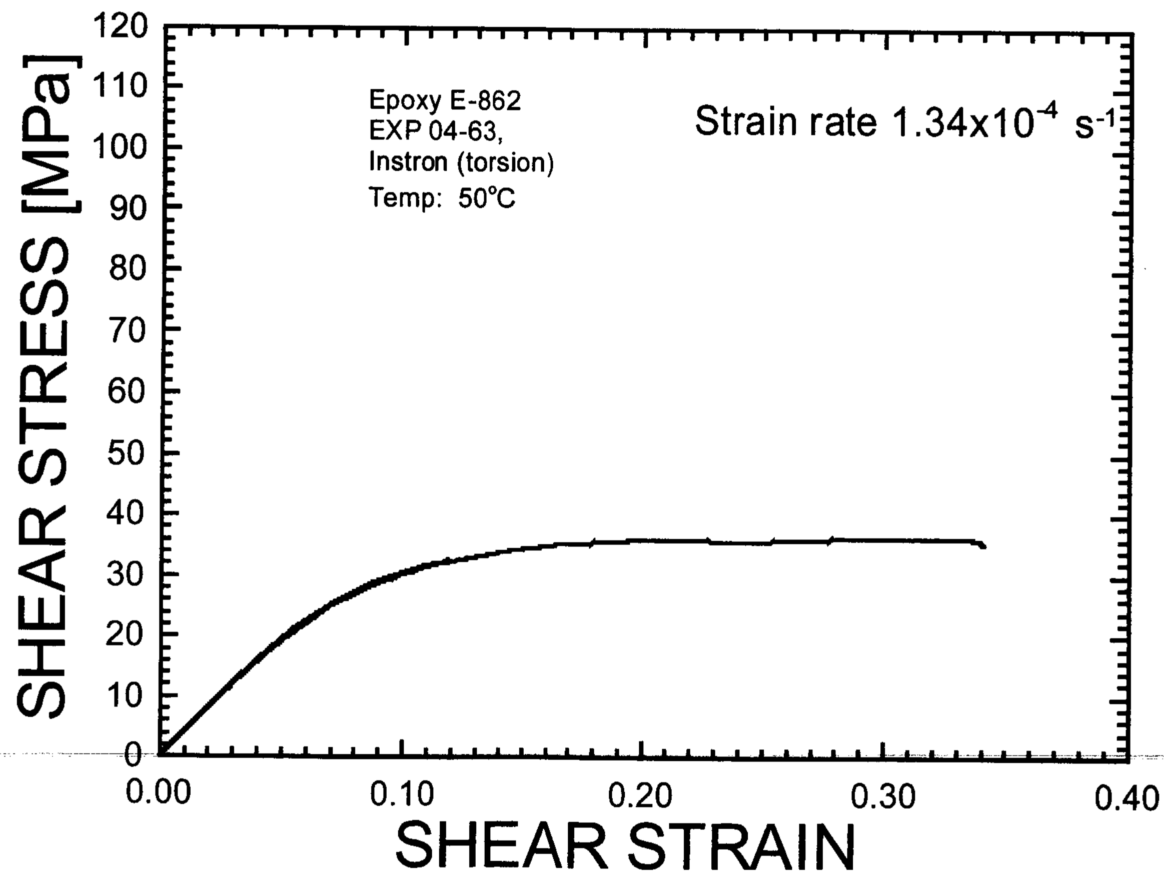
EXP 04-63,
Instron (torsion)
Temp: 50°C
Strain rate 1.34x10-4 s-1
STRAIN (Head Rotation))
STRESS
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)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Instron (torsion)
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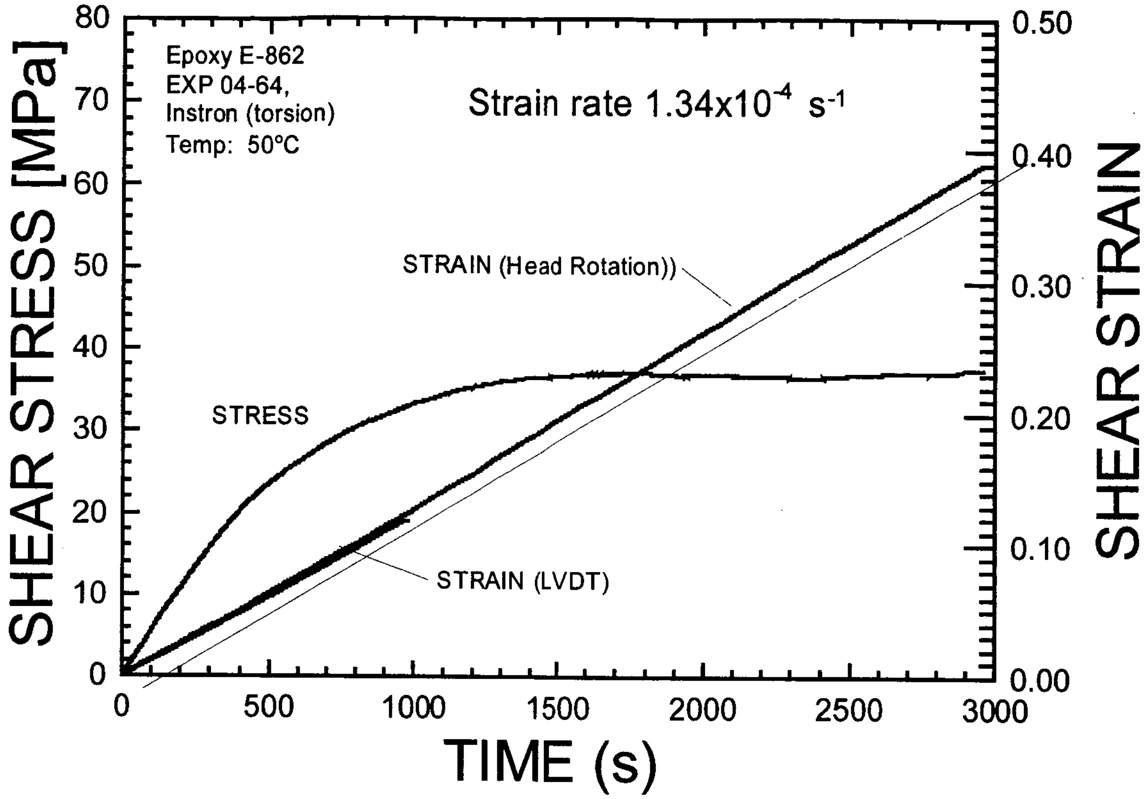
Strain rate 1.34x10-4 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN



Epoxy E-862
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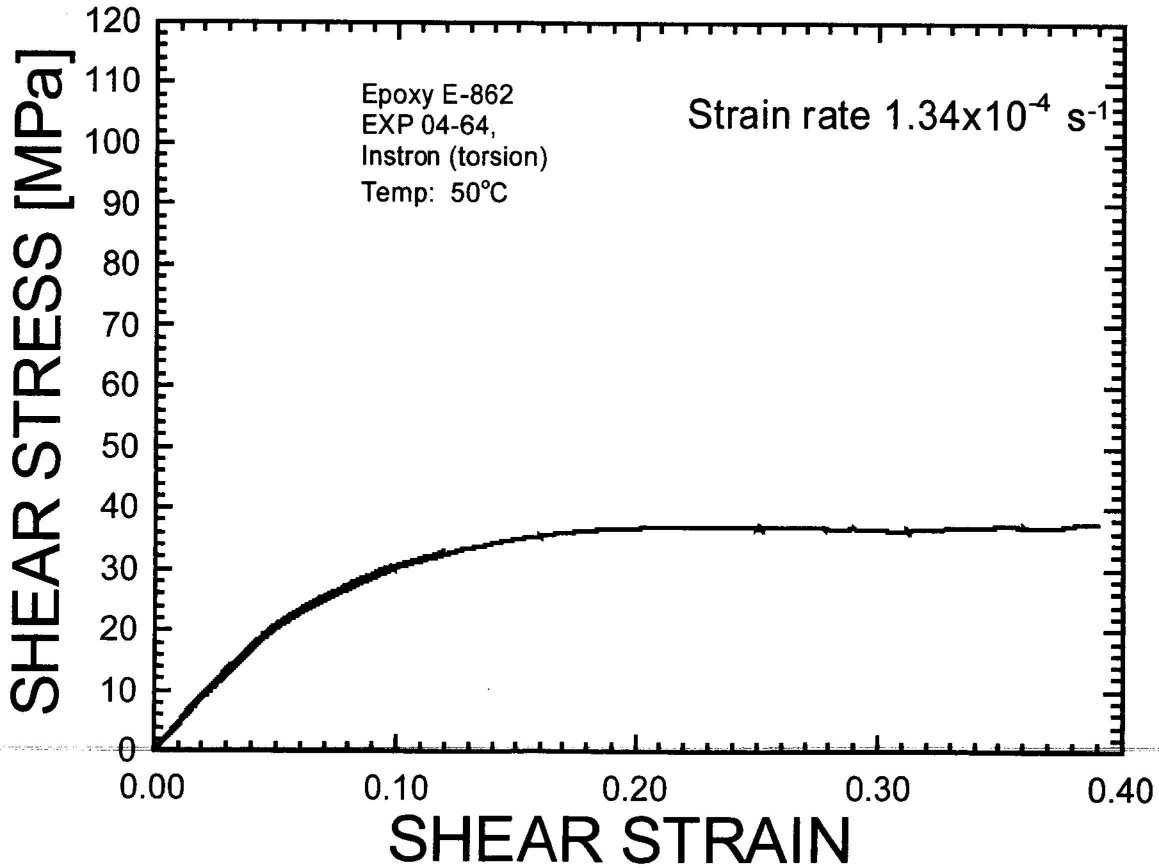
Instron (torsion)
Temp: 50°C
Strain rate 1.34x10-4 s-1
STRAIN (Head Rotation))
STRESS
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)



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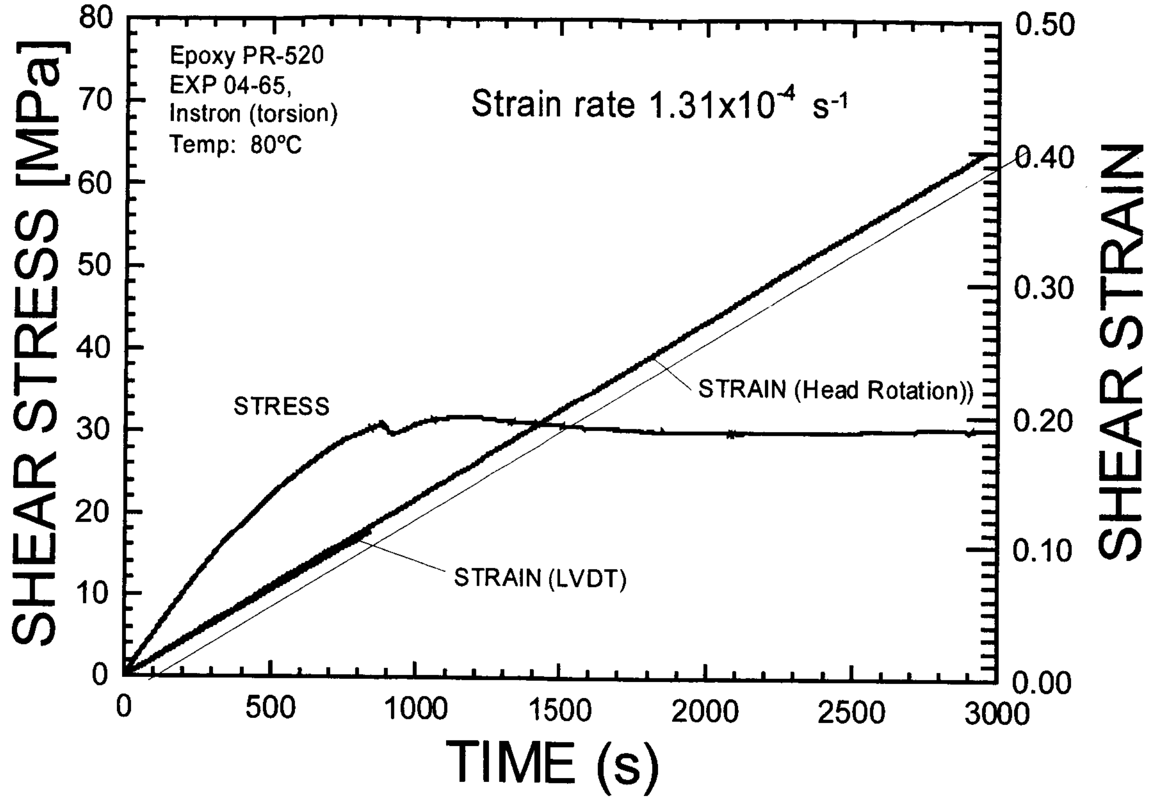
Strain rate 1.34x10-4 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN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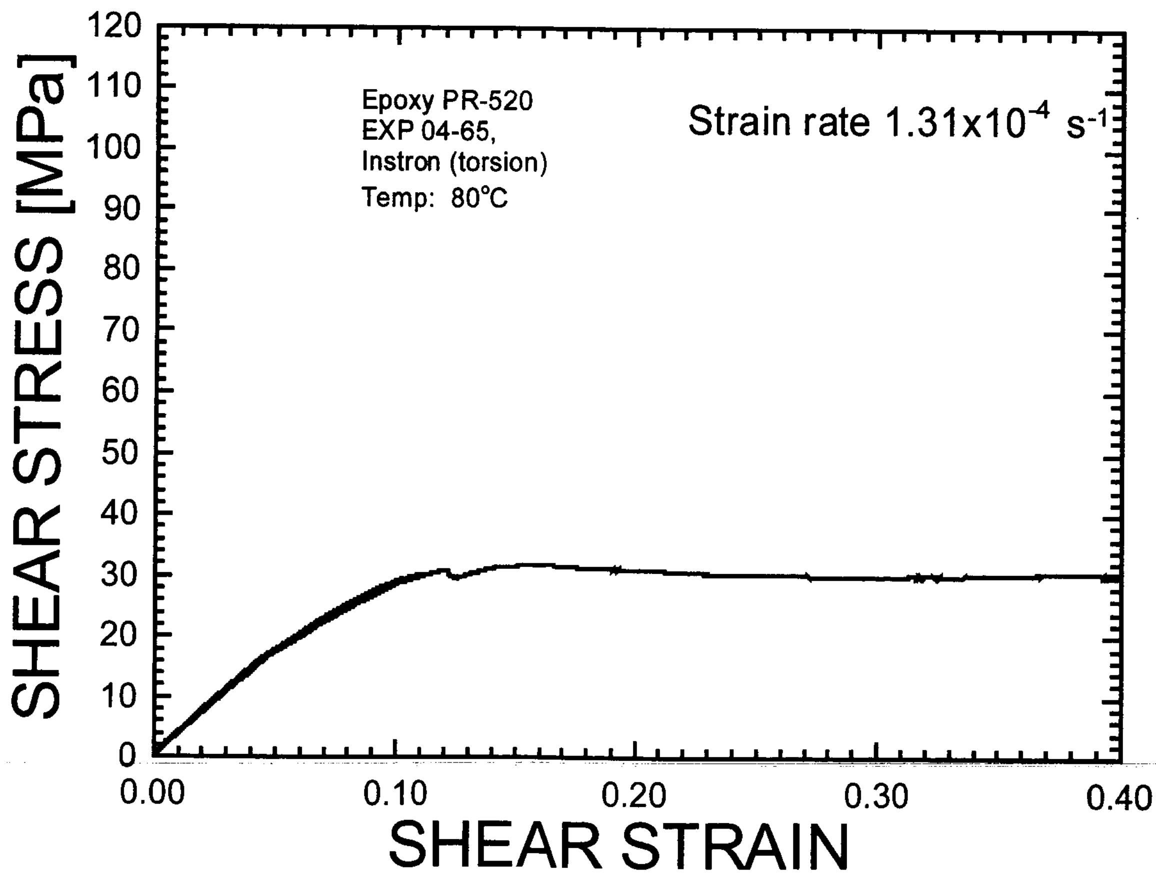
Temp: 80°C
Strain rate 1.31x10-4 s-1
STRESS
STRAIN (Head Rotation))
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0
10
20
30
40
50
60
70
80
0.00
0.10
0.20
0.30
0.40
0.50
500
1000
1500
2000
2500
3000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SHEAR STRAIN
0
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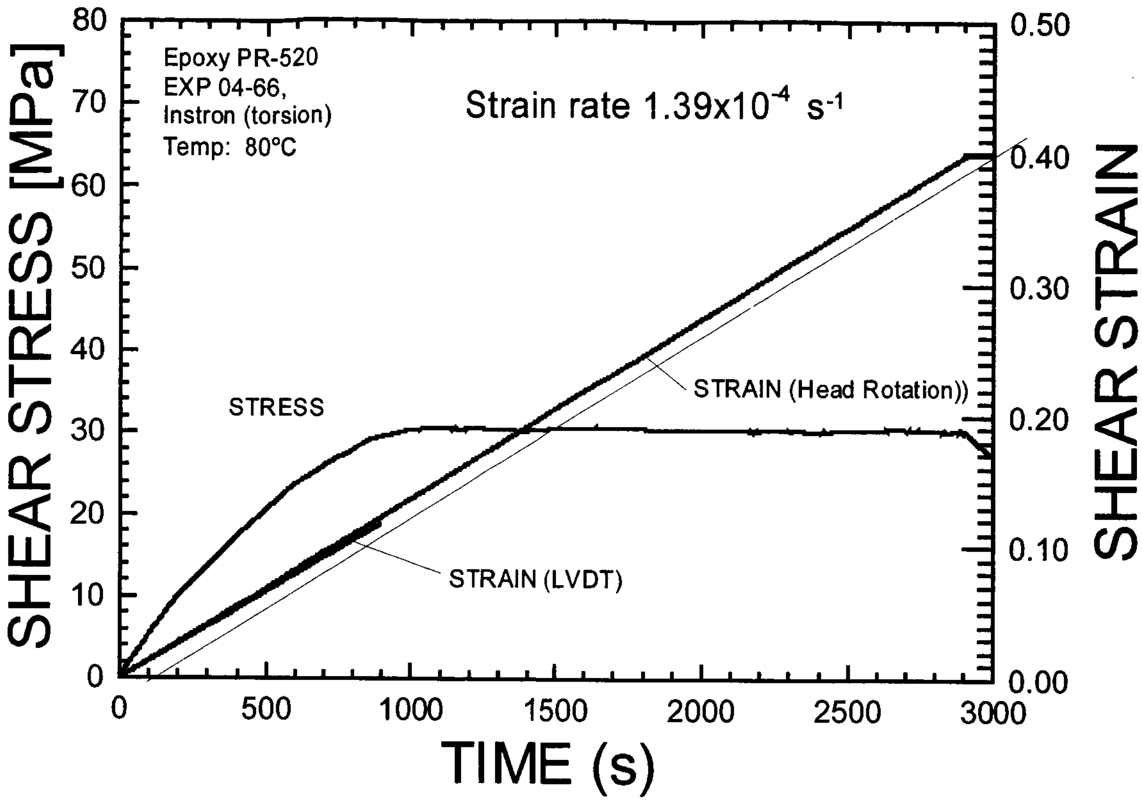
0.40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Temp: 80°C
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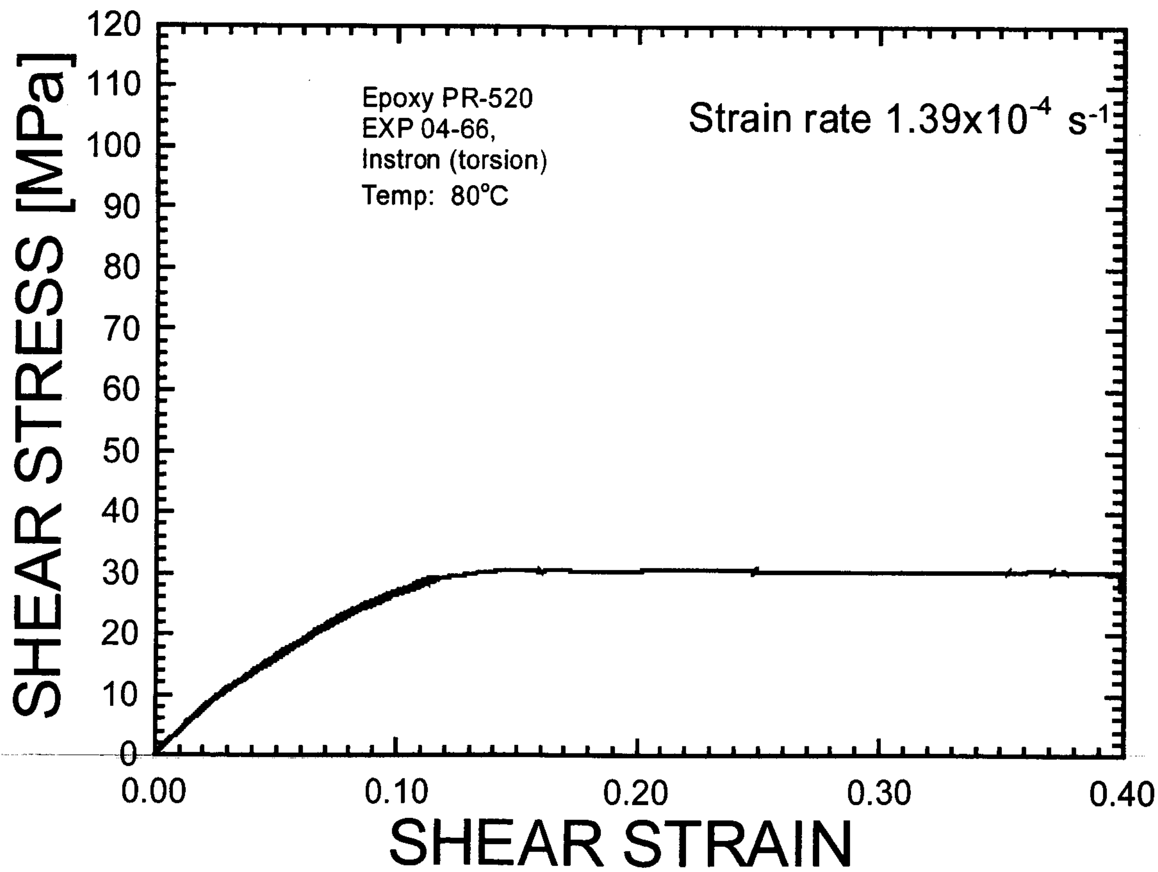
STRESS
STRAIN (Head Rotation))
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)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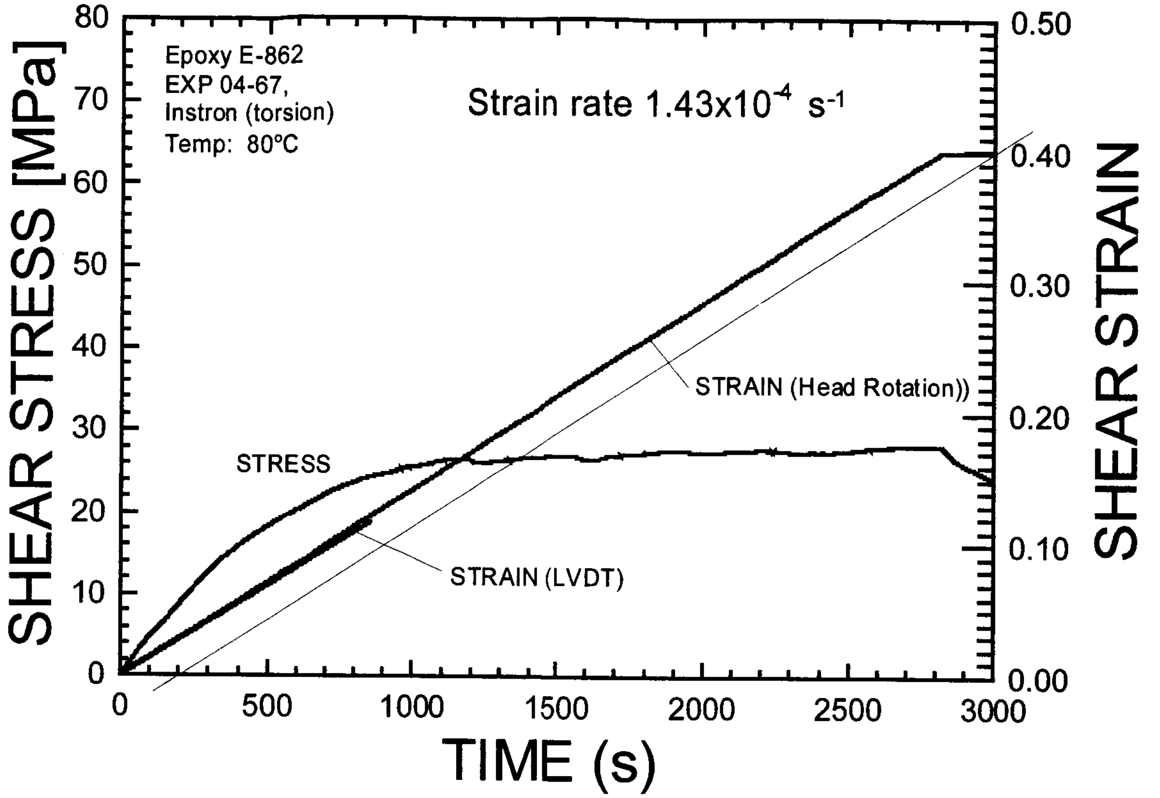
Strain rate 1.39x10-4 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN



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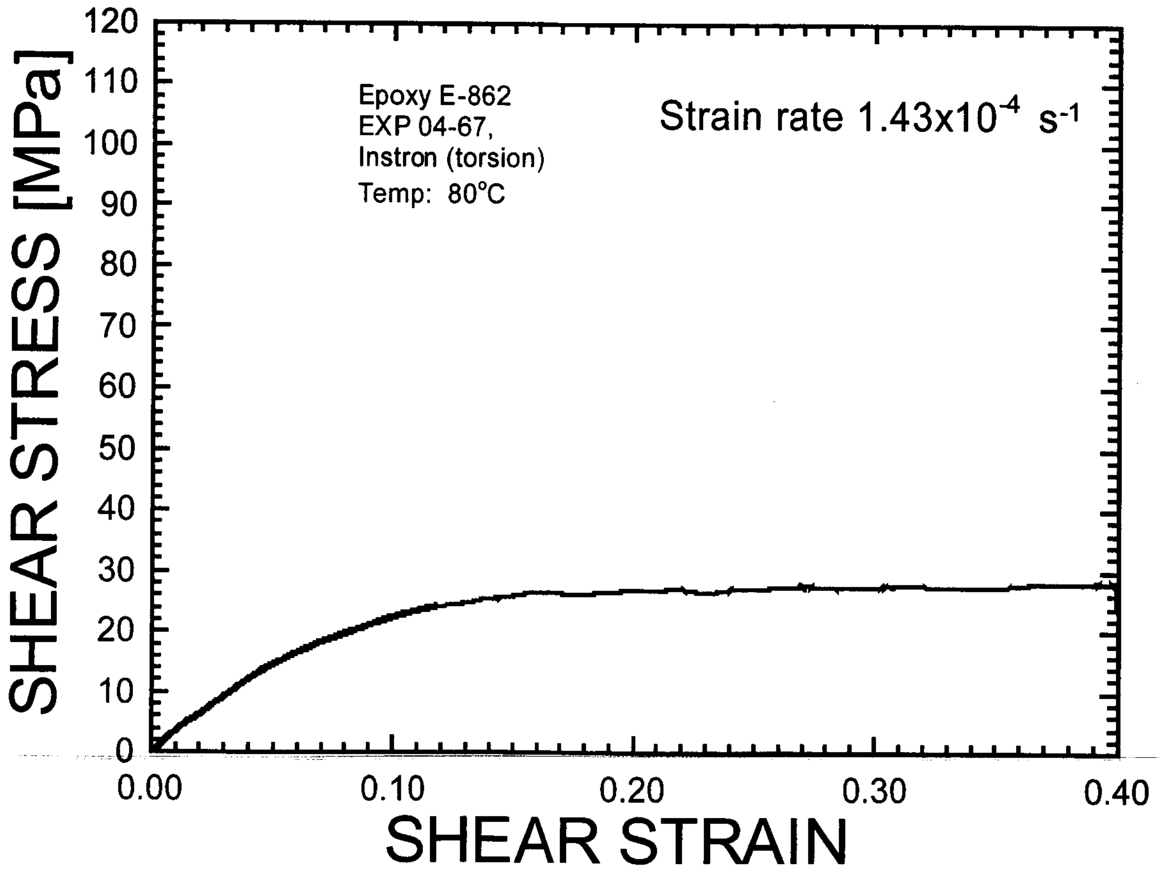
STRESS
STRAIN (LVDT)
STRAIN (Head Rotation))
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)



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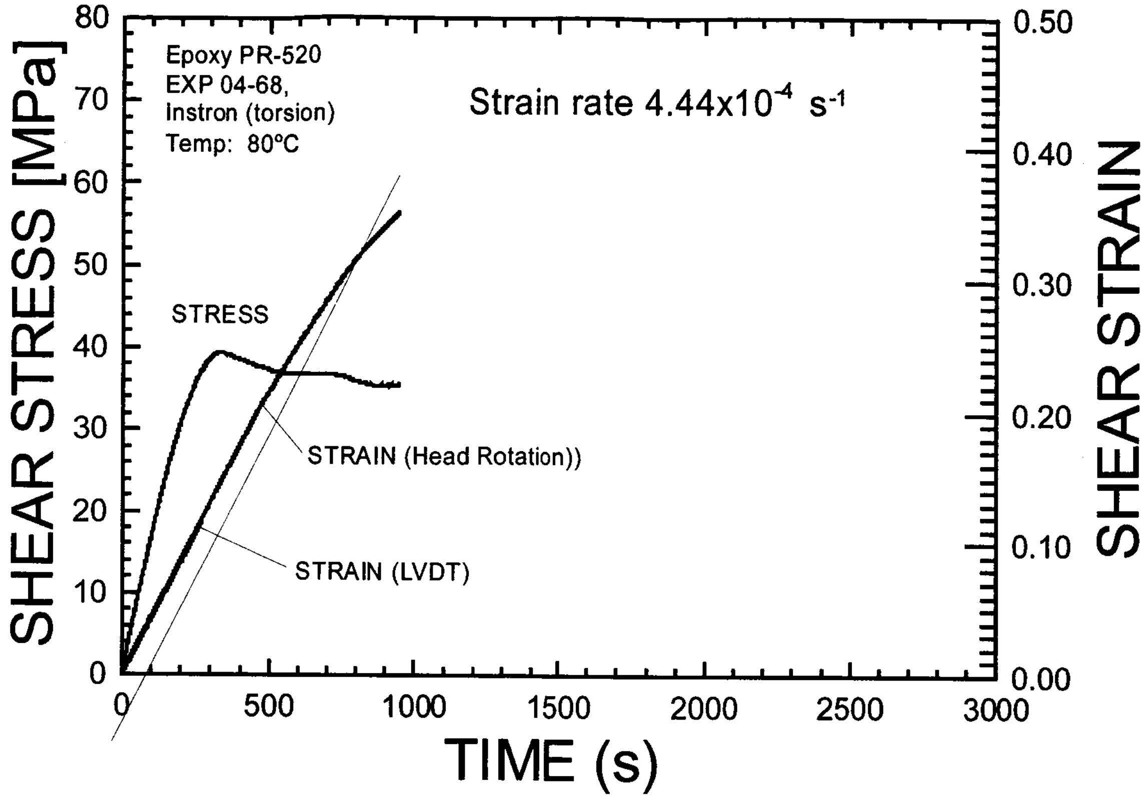
Temp: 80°C
Strain rate 1.43x10^-4 s^-1
SHEAR STRESS [MPa]
SHEAR STRAIN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Strain rate 4.44x10^-4 s^-1
STRESS
STRAIN (Head Rotation))
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0
10
20
30
40
50
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70
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2500
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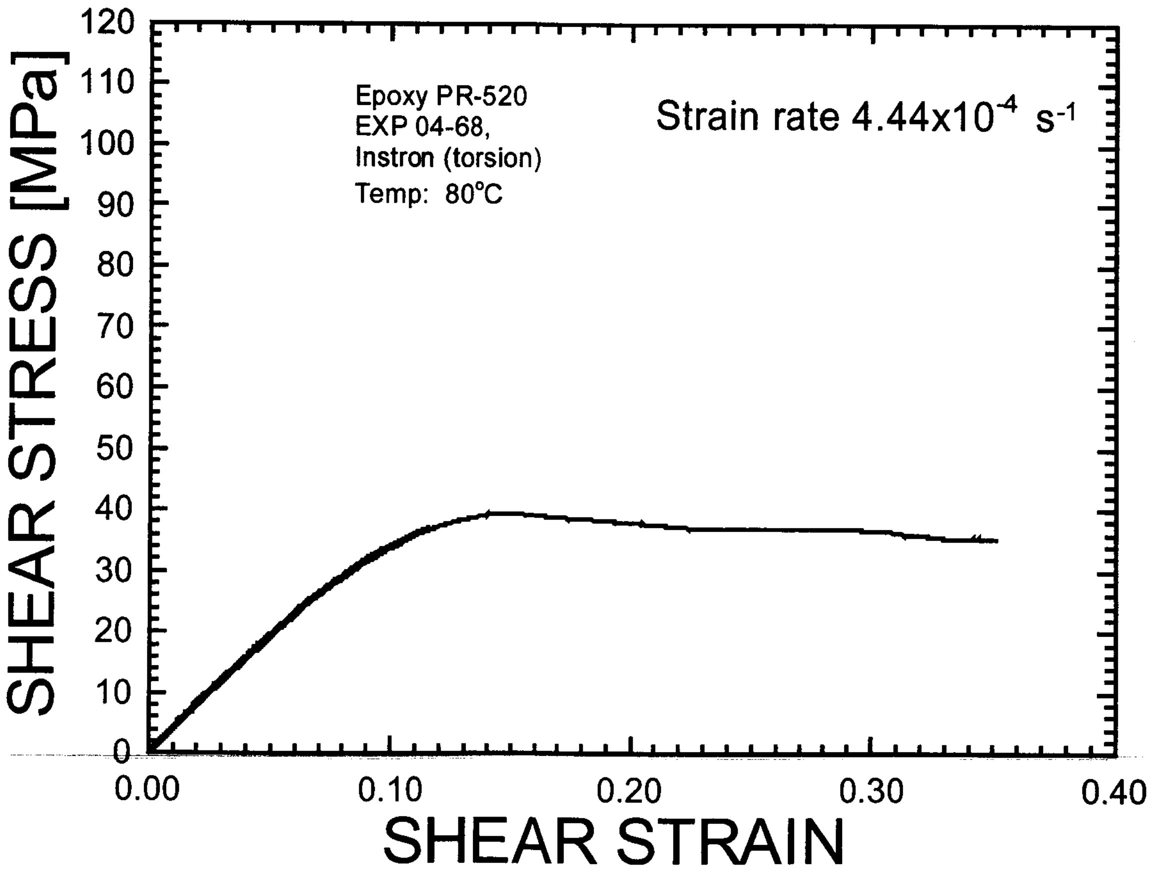
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Instron (torsion)
Temp: 80°C
Strain rate 4.44x10^-4 s^-1
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SHEAR STRAIN
0
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0.10
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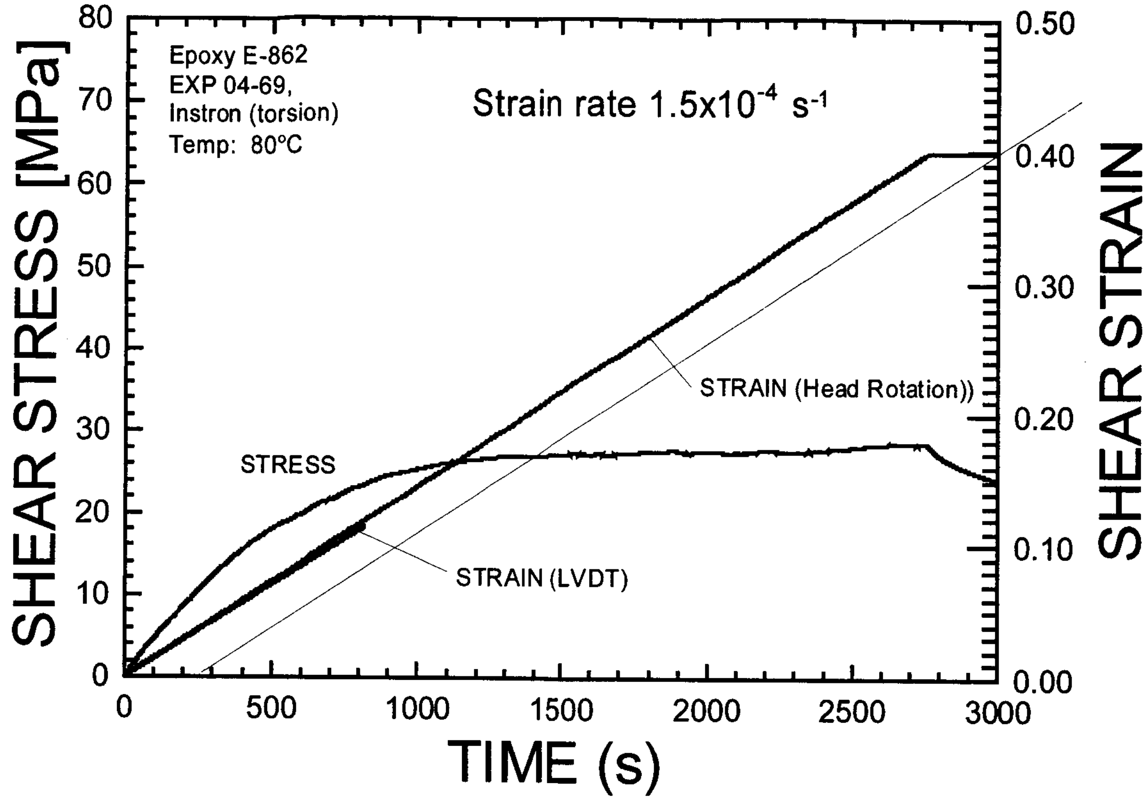
0.30
0.40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Instron (torsion)
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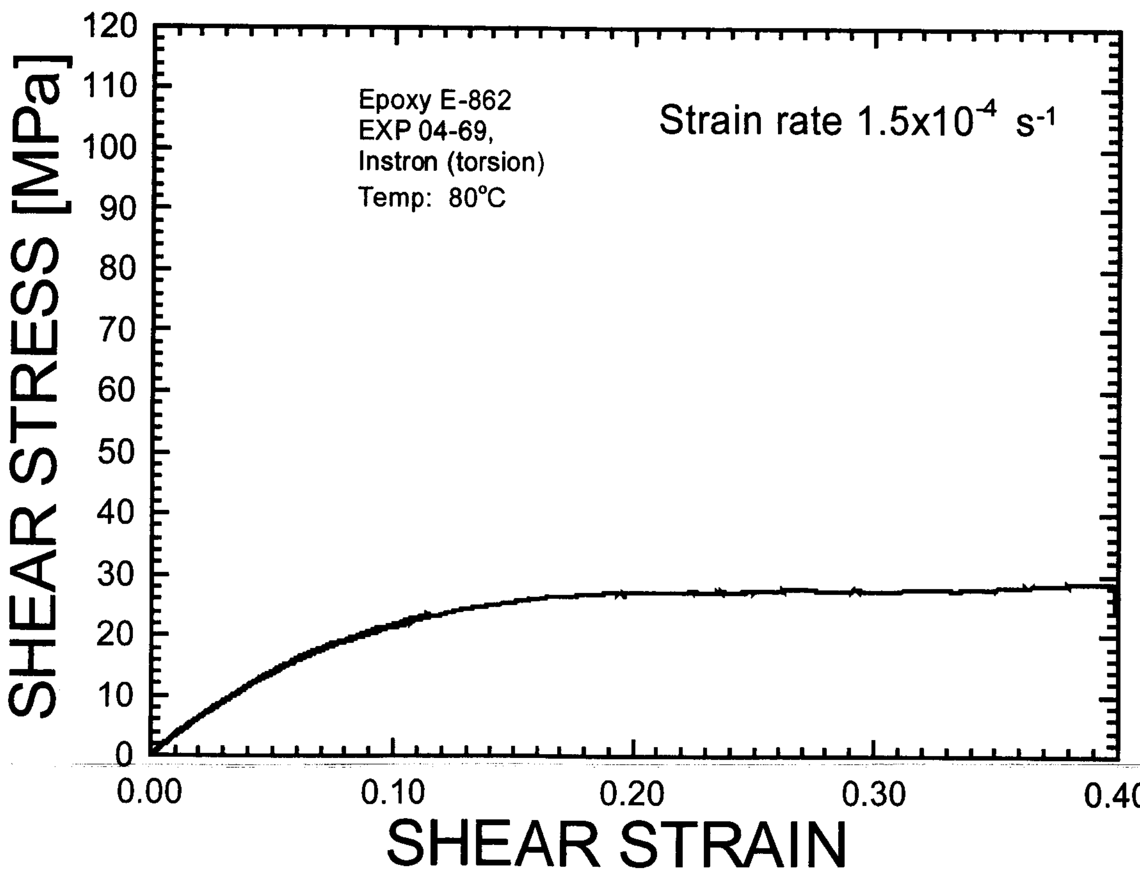
Strain rate 1.5x10-4 s-1
STRESS
STRAIN (Head Rotation))
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0 10 20 30 40 50 60 70 80
0.00 0.10 0.20 0.30 0.40 0.50
0 500 1000 1500 2000 2500 3000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Strain rate 1.5x10-4 s-1
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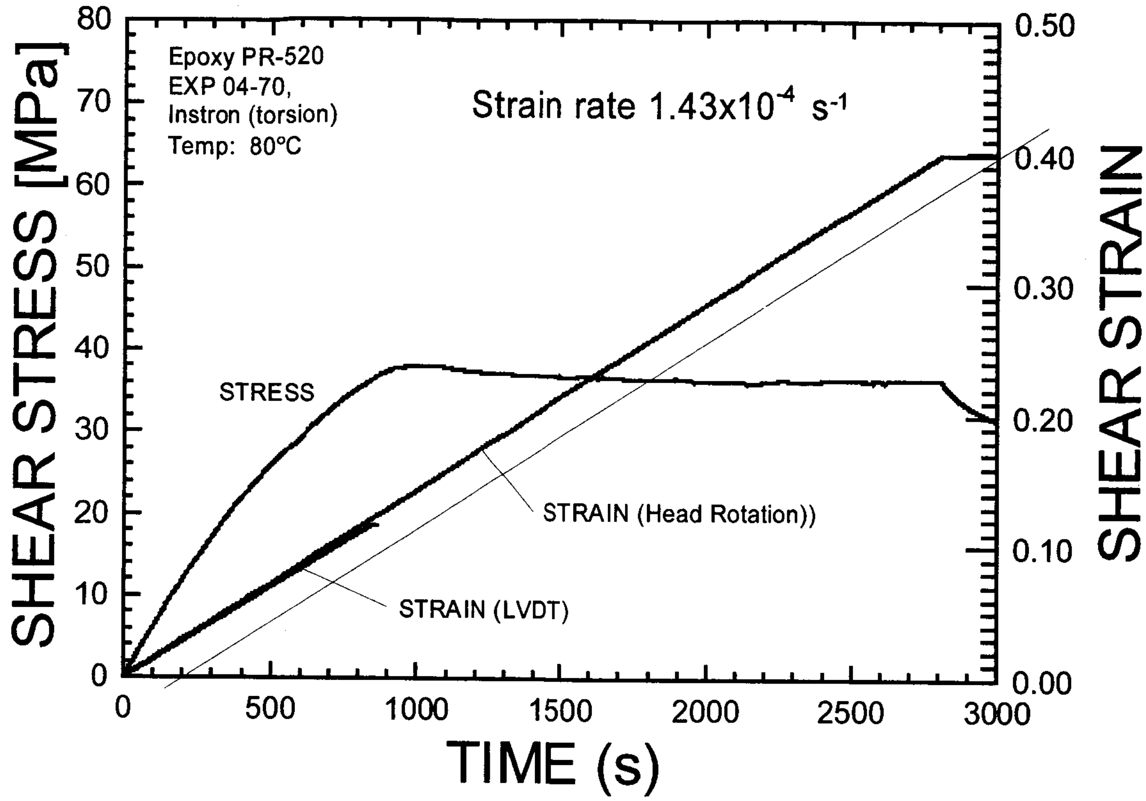
0 10 20 30 40 50 60 70 80 90 100 110 120
0.00 0.10 0.20 0.30 0.40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Temp: 80°C
Strain rate 1.43x10^-4 s^-1
STRESS
STRAIN (Head Rotation))
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0
10
20
30
40
50
60
70
80
0.00
0.10
0.20
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0.40
0.50
0
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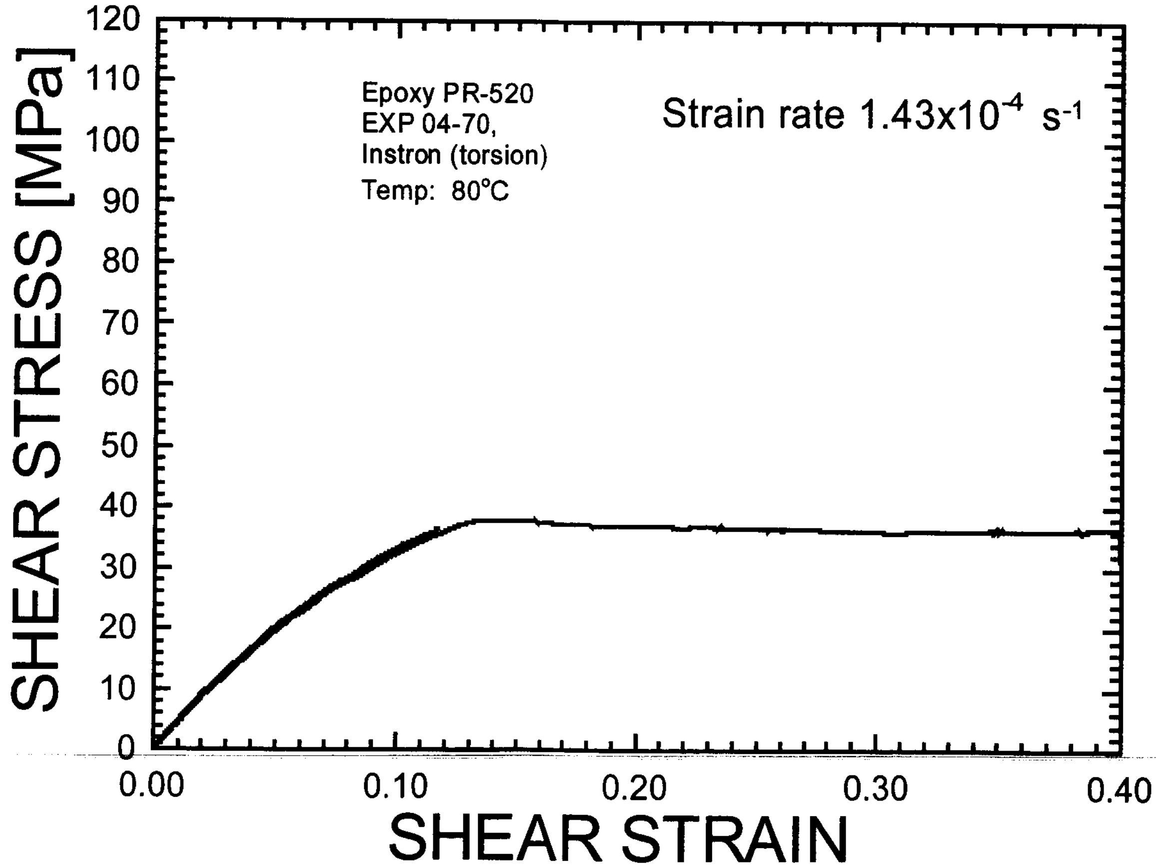
2500
3000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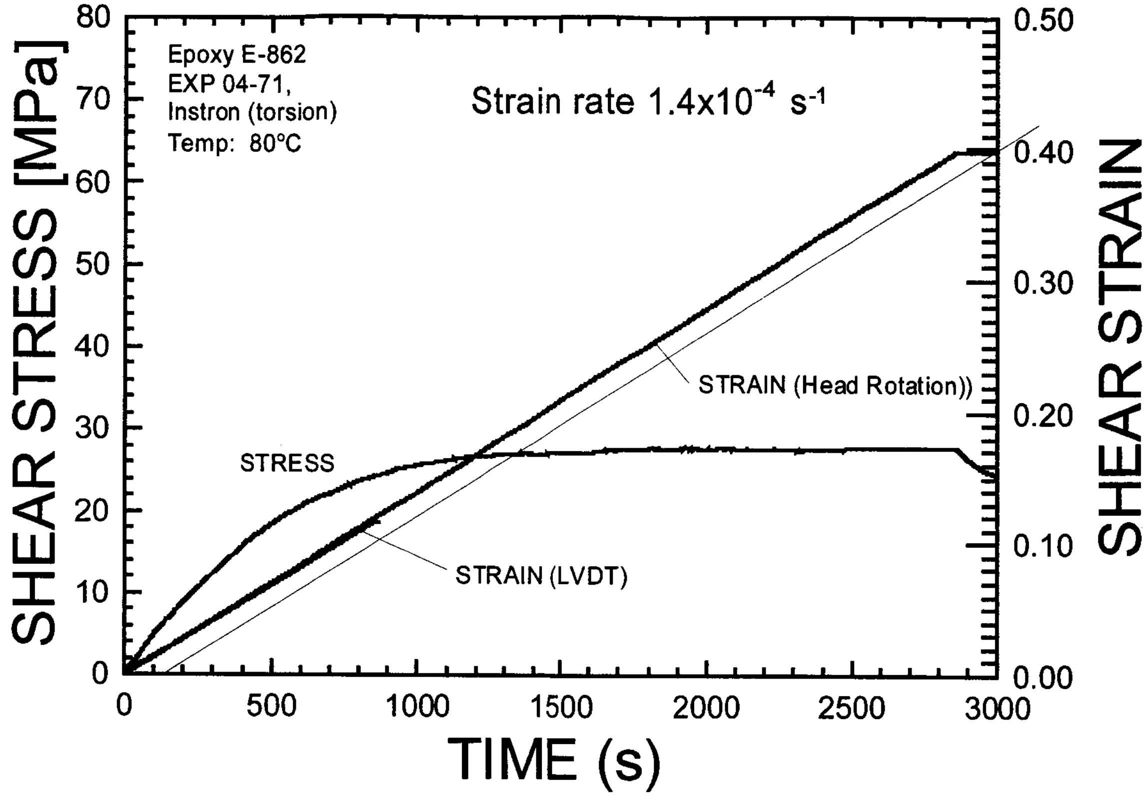
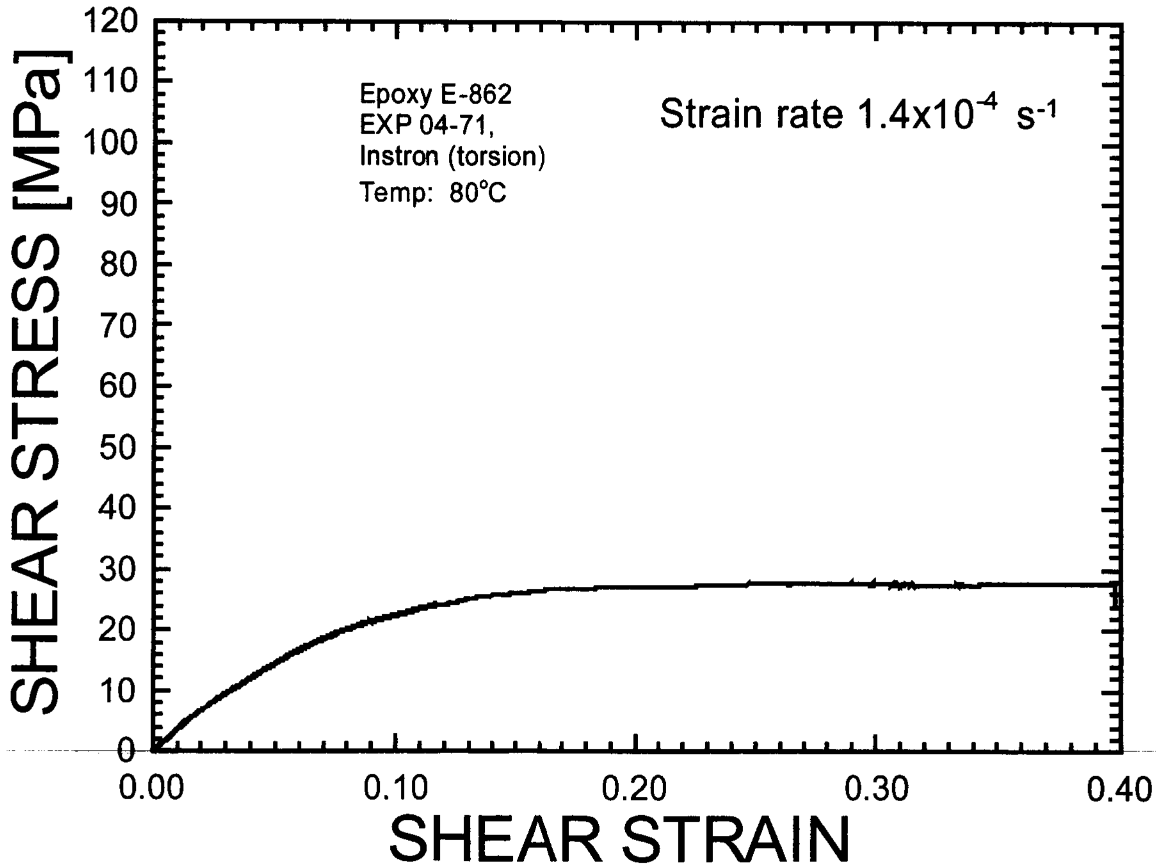
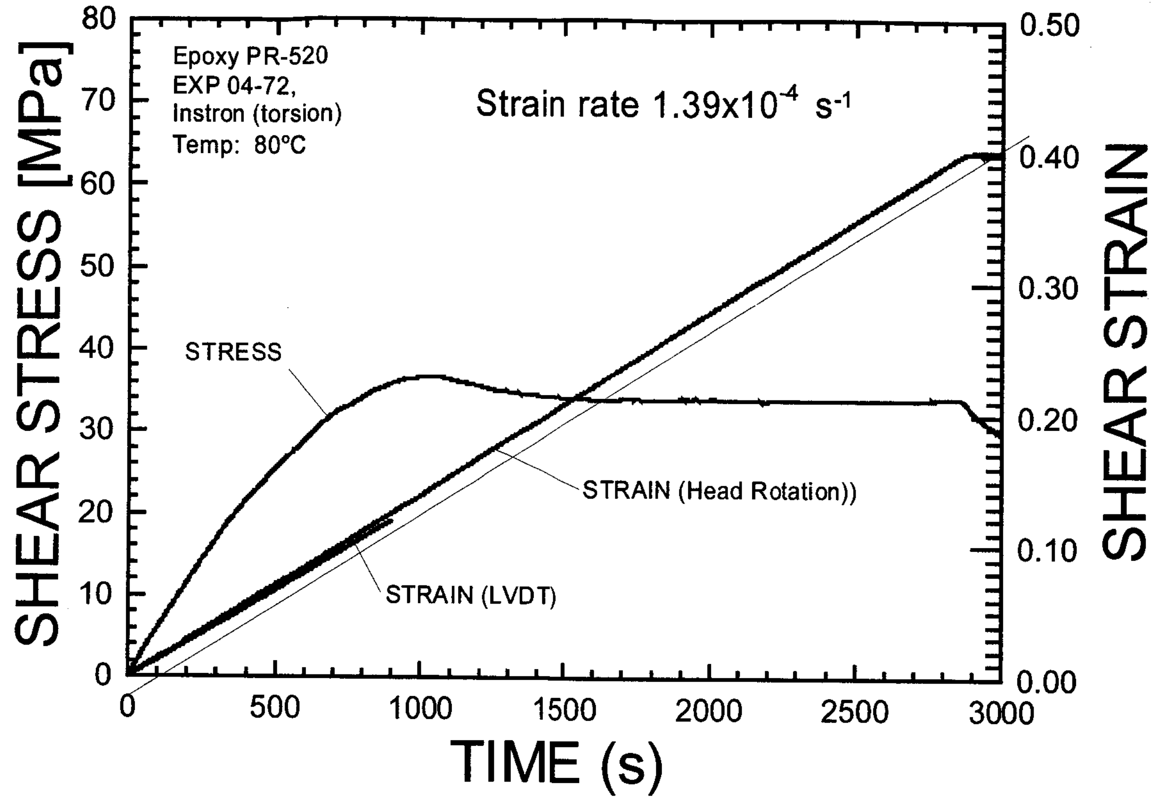
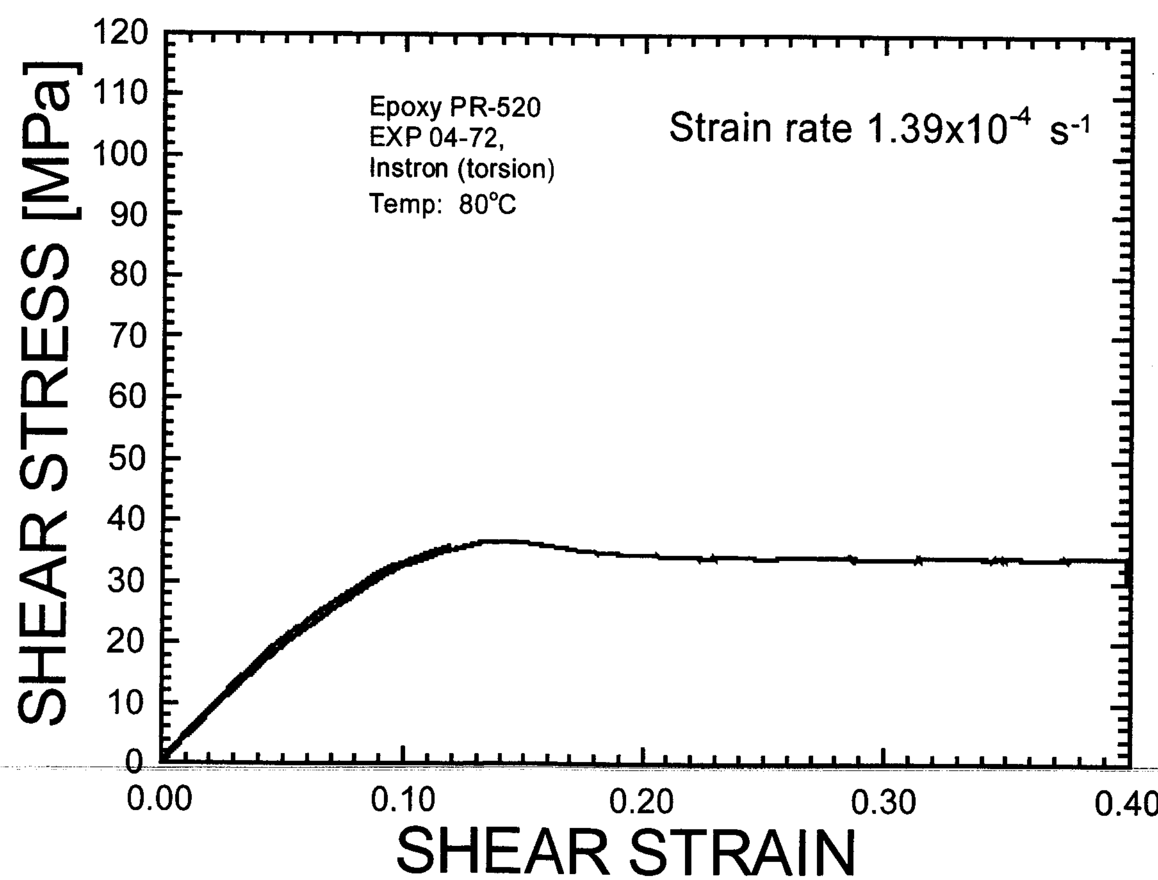
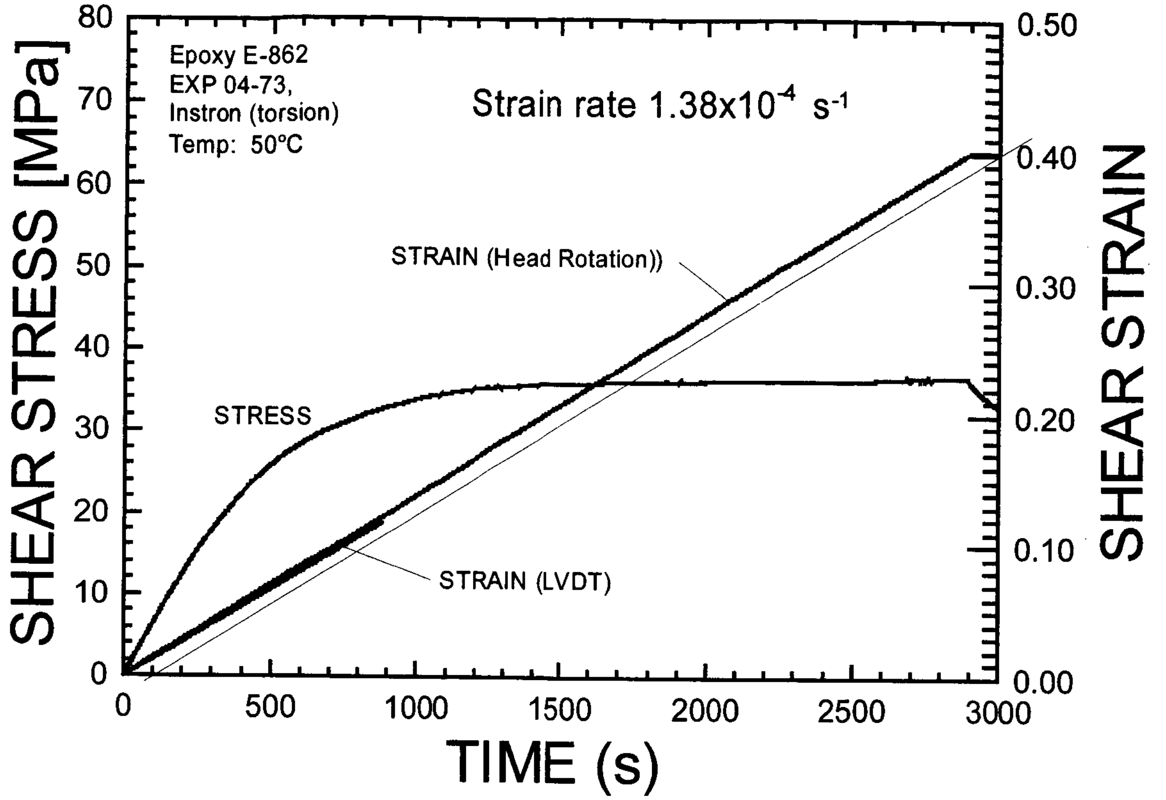
Instron (torsion)
Temp: 80°C
Strain rate 1.43x10^-4 s^-1
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40

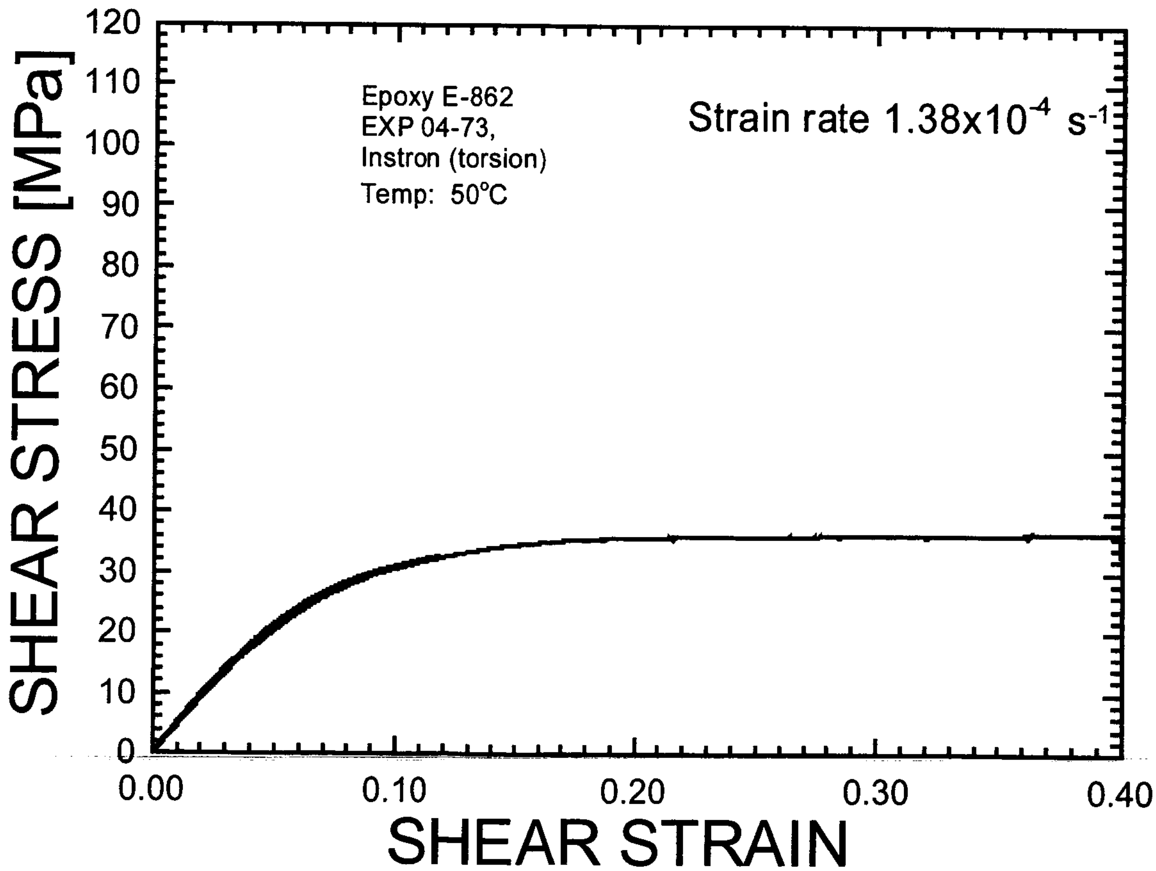

SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
Epoxy E-862
EXP 04-71,
Instron (torsion)
Temp: 80°C
Strain rate 1.4x10⁻⁴ s⁻¹
STRESS
STRAIN (LVDT)
STRAIN (Head Rotation))
0 10 20 30 40 50 60 70 80
0.00 0.10 0.20 0.30 0.40 0.50
0 500 1000 1500 2000 2500 3000

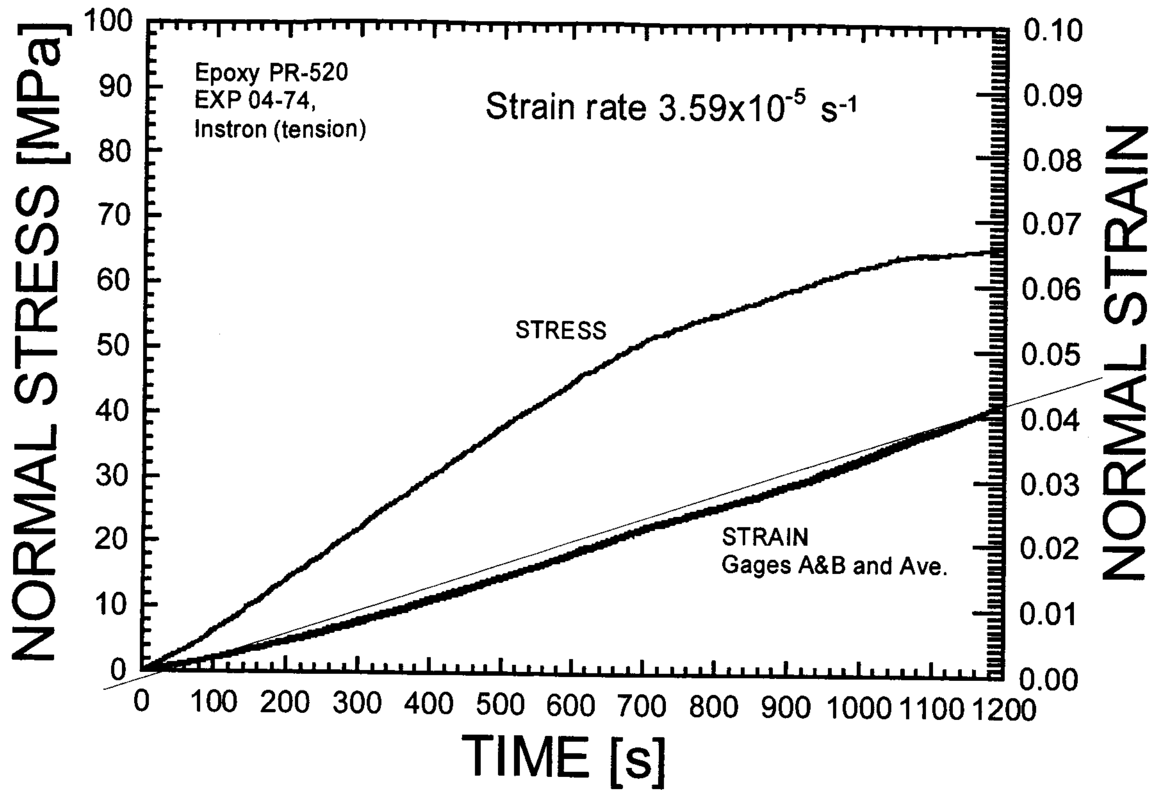

SHEAR STRESS [MPa]
SHEAR STRAIN
Epoxy E-862
EXP 04-71,
Instron (torsion)
Temp: 80°C
Strain rate 1.4x10⁻⁴ s⁻¹
0 10 20 30 40 50 60 70 80 90 100 110 120
0.00 0.10 0.20 0.30 0.40


Epoxy PR-520
EXP 04-72,
Instron (torsion)
Temp: 80°C
Strain rate 1.39x10^{-4} s^{-1}
STRESS
STRAIN (Head Rotation))
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)

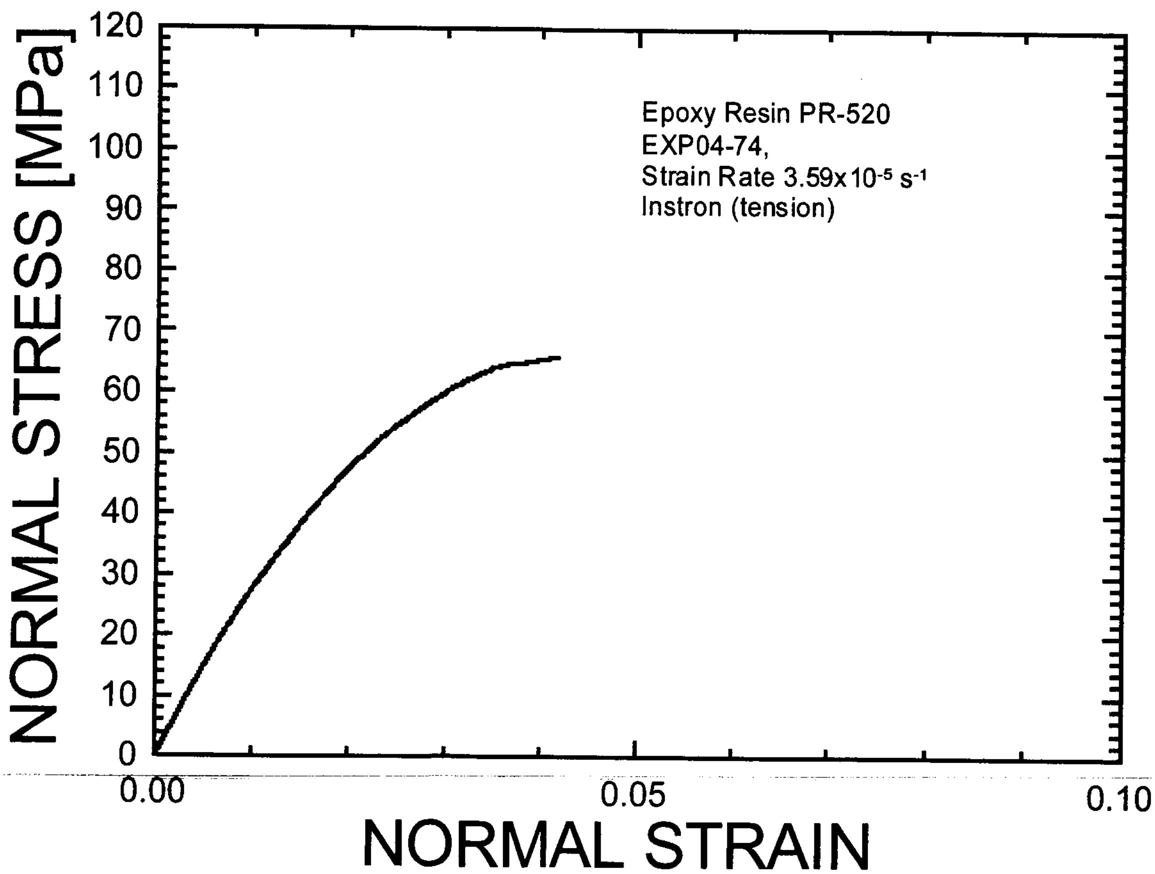

Epoxy PR-520
EXP 04-72,
Instron (torsion)
Temp: 80°C
Strain rate 1.39x10^{-4} s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN


Epoxy E-862
EXP 04-73,
Instron (torsion)
Temp: 50°C
Strain rate 1.38x10^{-4} s^{-1}
STRAIN (Head Rotation))
STRESS
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0
10
20
30
40
50
60
70
80
0.00
0.10
0.20
0.30
0.40
0.50
0
500
1000
1500
2000
2500
3000

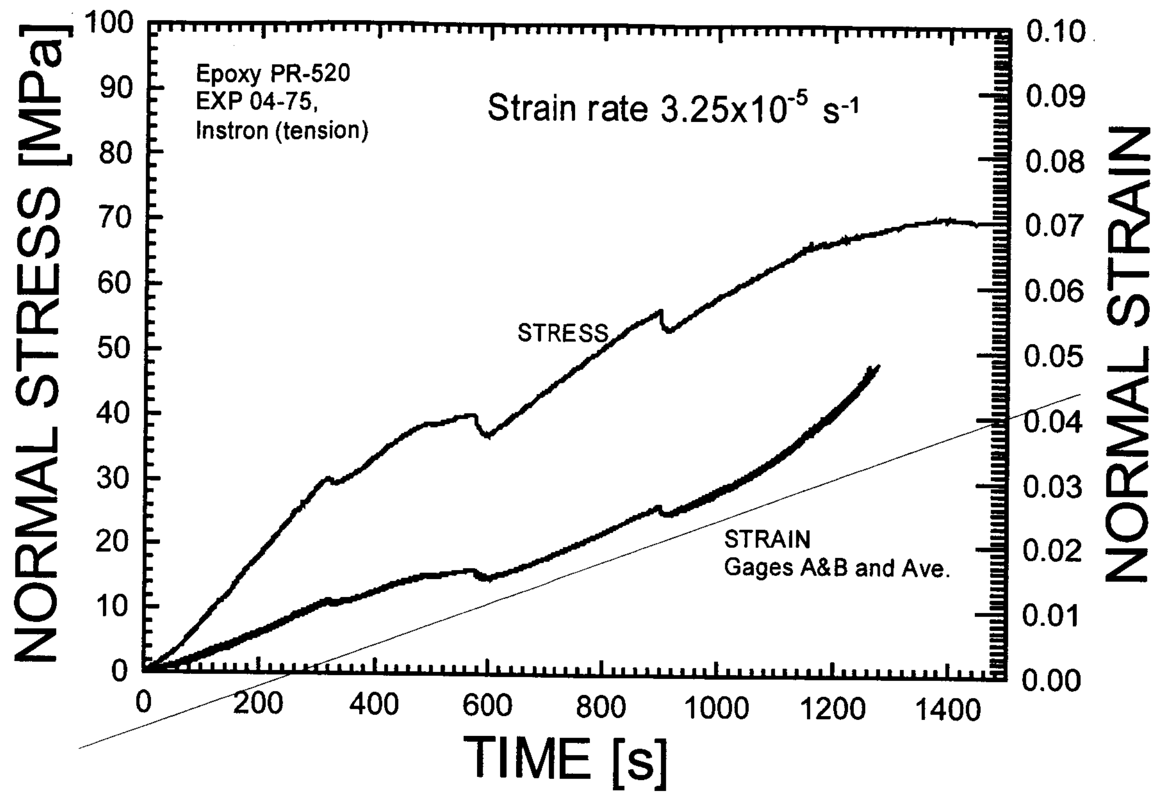

Epoxy E-862
EXP 04-73,
Instron (torsion)
Temp: 50°C
Strain rate 1.38x10^{-4} s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40

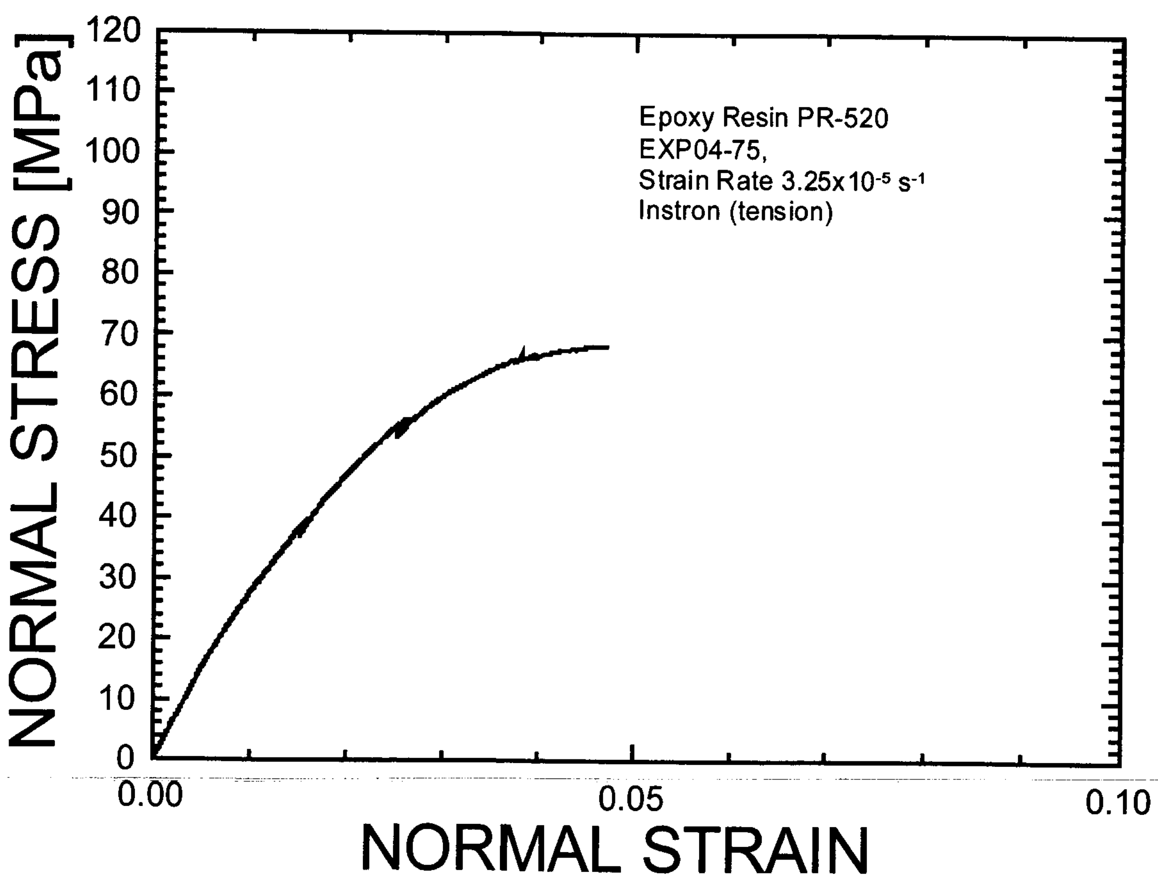


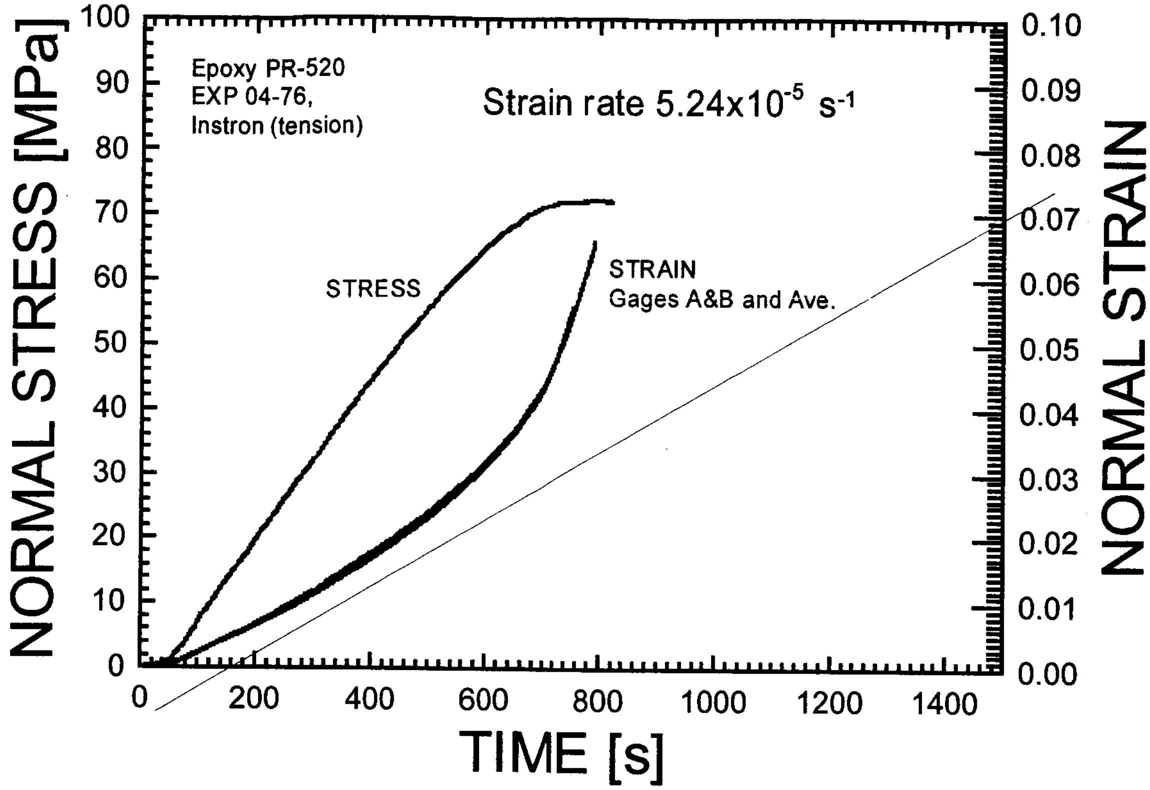
Epoxy PR-520
EXP 04-74,
Instron (tension)
Strain rate 3.59x10-5 s-1
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]

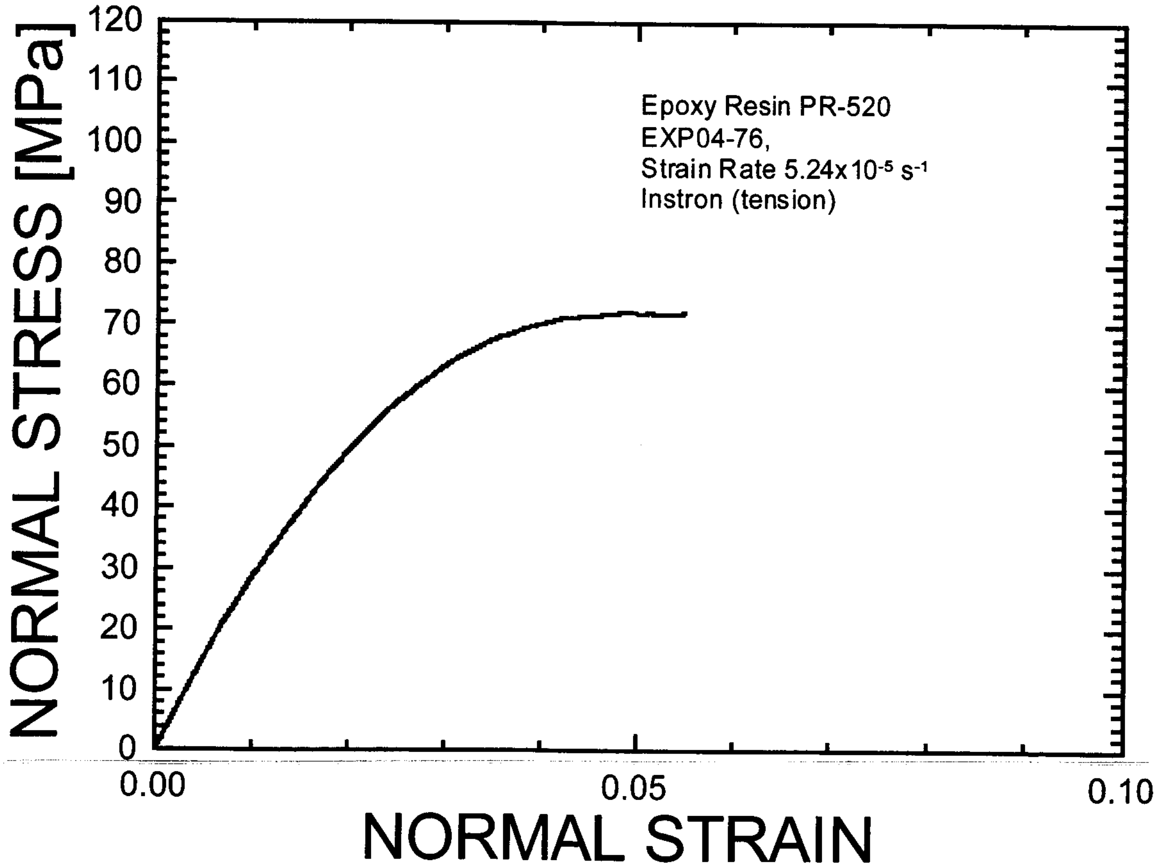


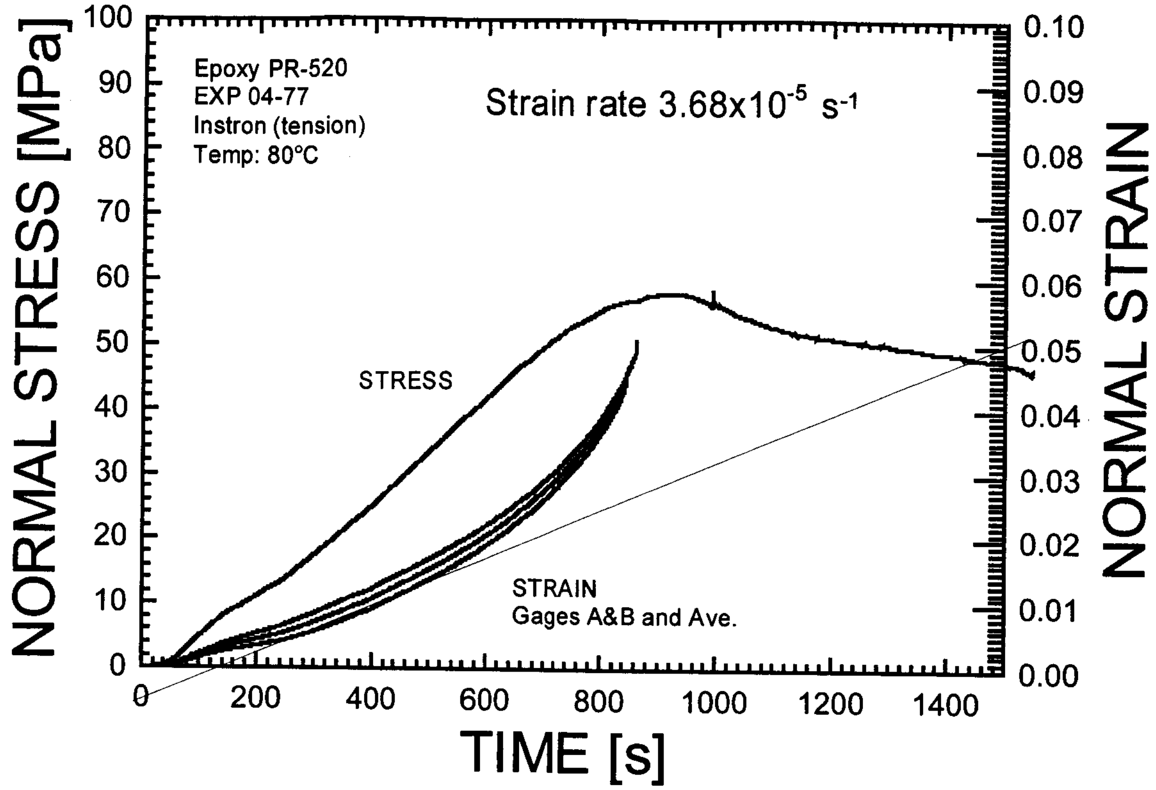
Epoxy Resin PR-520
EXP04-74,
Strain Rate 3.59x10-5 s-1
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN


NORMAL STRESS [MPa]
Epoxy PR-520
EXP 04-75,
Instron (tension)
Strain rate 3.25x10-5 s-1
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRAIN
TIME [s]

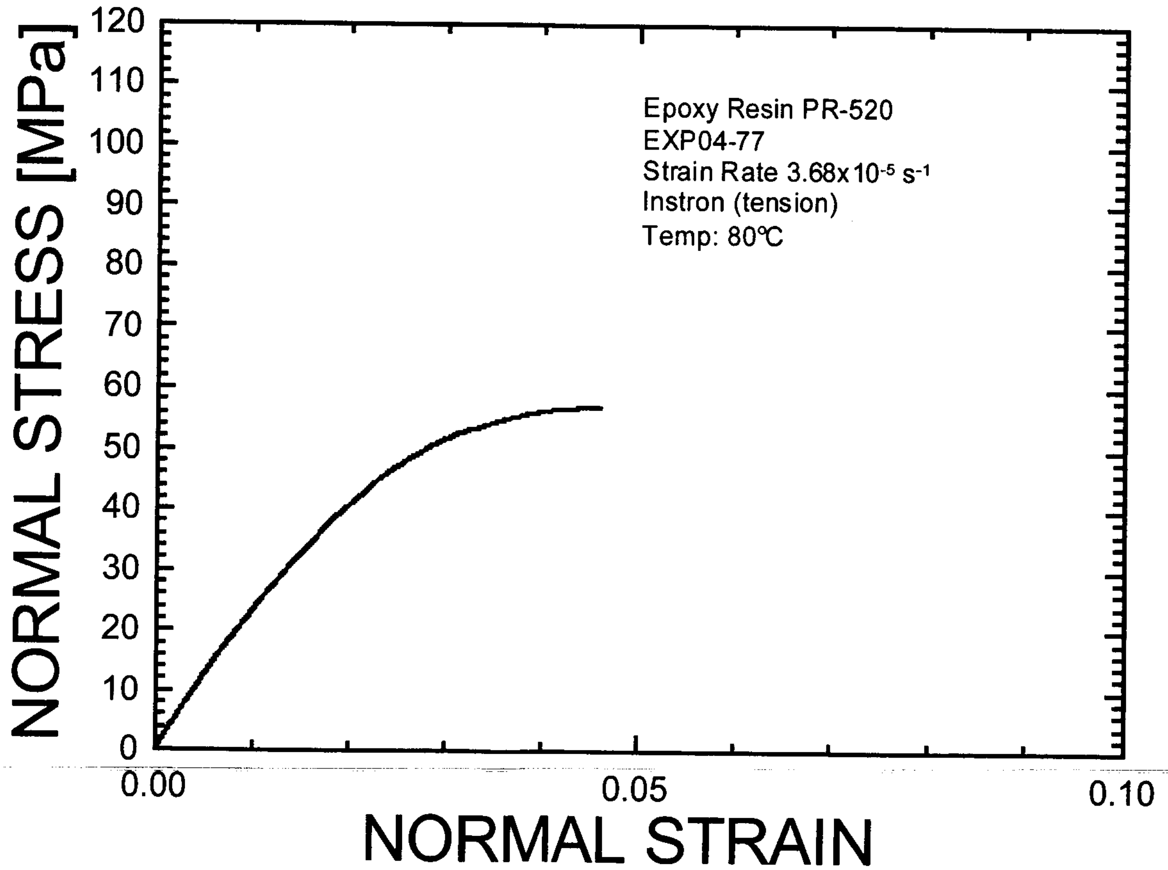

NORMAL STRESS [MPa]
Epoxy Resin PR-520
EXP04-75,
Strain Rate 3.25x10-5 s-1
Instron (tension)
NORMAL STRAIN


Epoxy PR-520
EXP 04-76,
Instron (tension)
Strain rate 5.24x10^{-5} s^{-1}
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]
0
10
20
30
40
50
60
70
80
90
100
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
200
400
600
800
1000
1200
1400

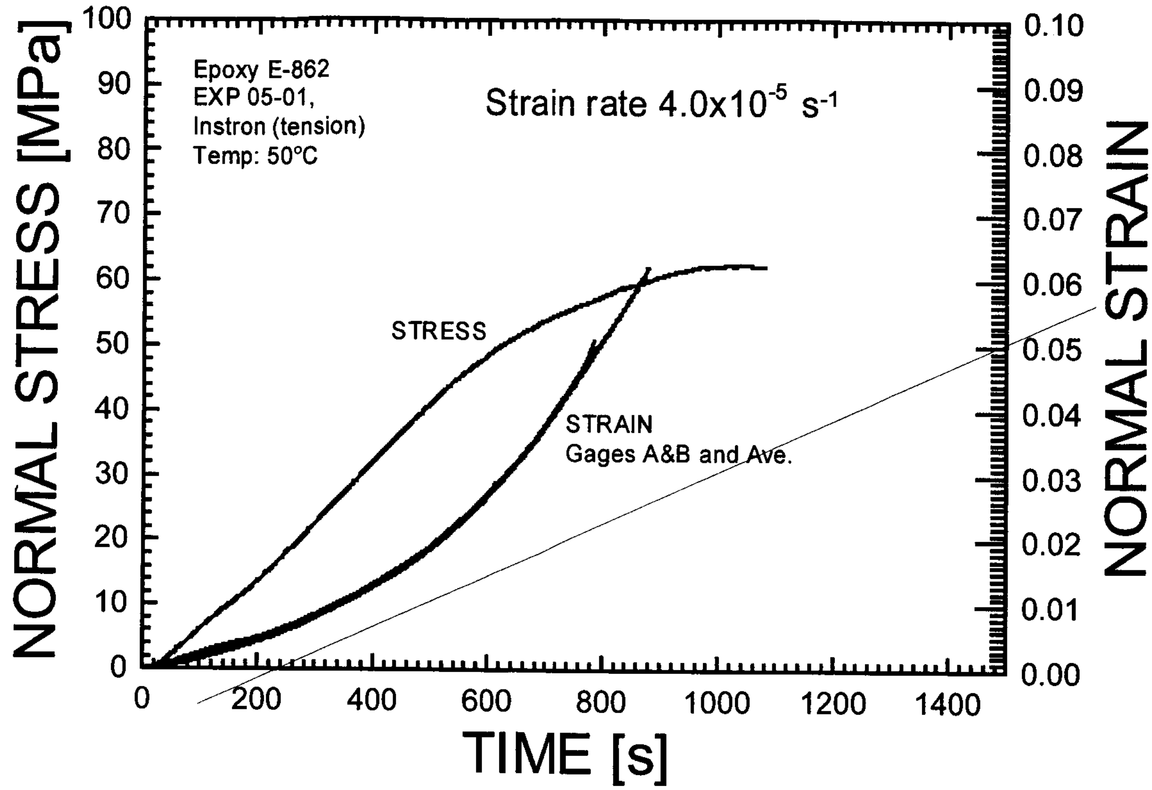

Epoxy Resin PR-520
EXP04-76,
Strain Rate 5.24x10^{-5} s^{-1}
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.05
0.10

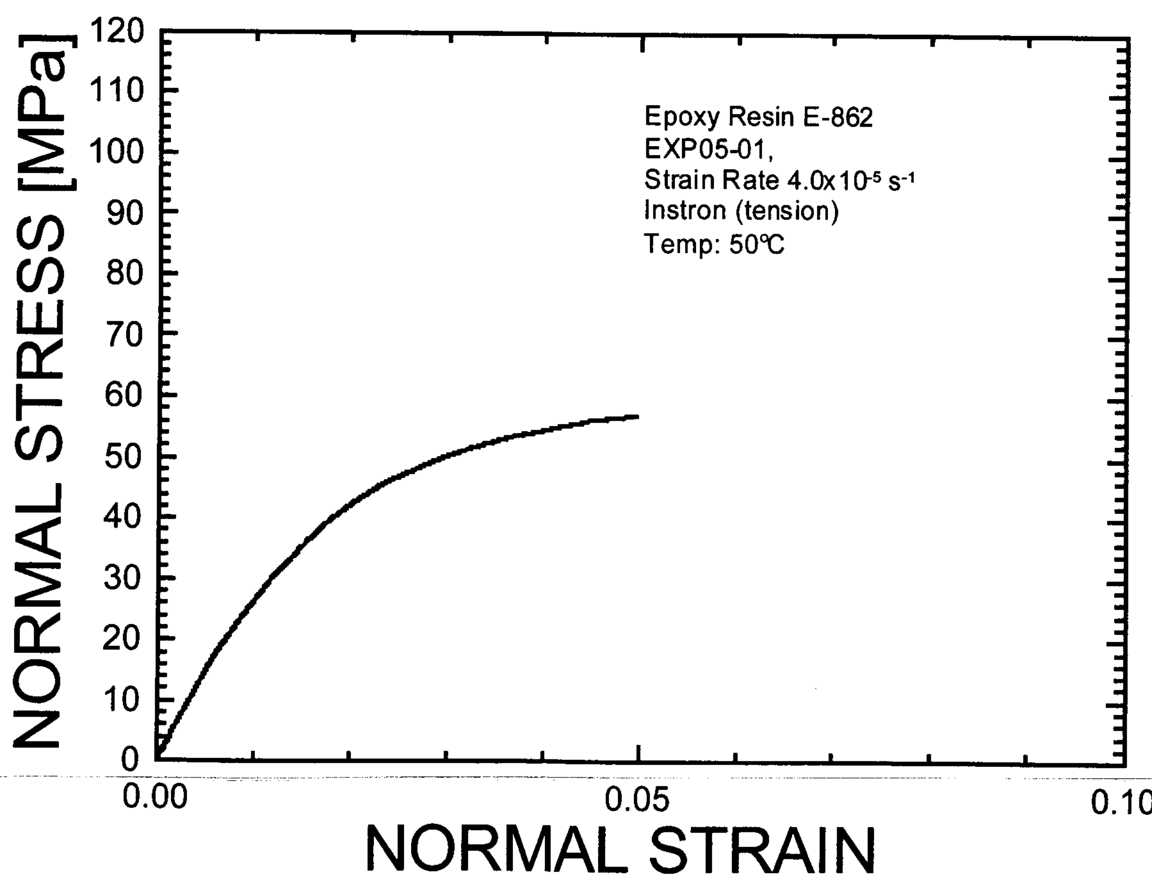


Epoxy PR-520
EXP 04-77
Instron (tension)
Temp: 80°C
Strain rate 3.68x10^{-5} s^{-1}
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]
0
200
400
600
800
1000
1200
1400
10
20
30
40
50
60
70
80
90
100
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10



Epoxy Resin PR-520
EXP04-77
Strain Rate 3.68x10^{-5} s^{-1}
Instron (tension)
Temp: 80°C
NORMAL STRESS [MPa]
NORMAL STRAIN
0.00
0.05
0.10
0
10
20
30
40
50
60
70
80
90
100
110
120


NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]
Epoxy E-862
EXP 05-01,
Instron (tension)
Temp: 50°C
Strain rate 4.0x10-5 s-1
STRESS
STRAIN
Gages A&B and Ave.


NORMAL STRESS [MPa]
NORMAL STRAIN
Epoxy Resin E-862
EXP05-01,
Strain Rate 4.0x10-5 s-1
Instron (tension)
Temp: 50°C