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Characterization of Composites Response at High Rates of Loading

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Final Report

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By

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1. BACKGROUND

The objective of the proposed research is to experimentally study the effect of strain rate on mechanical response (deformation and failure) carbon fiber/epoxy matrix composites. The experimental data provide the information needed for the development of a nonlinear, rate dependent deformation and strength models that can subsequently be used in design. This year effort was directed into testing the epoxy resin. Two types of epoxy were tested each in tension and shear at various strain rate that ranges from 5×10^{-5}, to 700 s^{-1}. The results show that both, the strain rate and the mode of loading affect the epoxy response.

2. EXPERIMENTAL SETUP

Tension and torsion tests were conducted at strain rates of approximately 5×10^{-5}, 1, and 400 s^{-1}. The low strain rate tests (5×10^{-5} and 1 s^{-1}) were done on a hydraulic Instron machine, and the high strain rate tests were done using the tensile split Hopkinson bar apparatus. The Instron machine is bi-axial (tension/torsion) and loading can be tensile, torsion, or a combination of the two. In tests with the Instron machine, force or torque is measured by the load cell of the machine. In the tensile tests strain is measured with strain gages cemented to the specimen. In each test two strain gages (Measurements Group EA-06-125BZ-350) were cemented on the specimen's surface on opposite sides. In the torsion tests the shear strain is determined from the relative rotation of the specimen's ends that is measured by a special rotation extensometer.

The split Hopkinson bar apparatus, shown schematically in Fig. 1, is made up of two aluminum bars. The specimen is placed (cemented) between the bars. The specimen is loaded by a wave that is generated in the incident bar by clamping a tensile force in the tensile bar (and a torque in the torsion bar) in the end section of the bar, and then releasing the clamp. Upon loading, part of the loading wave reflects back to the incident bar, and part propagates on to the transmitter bar. The incident and transmitter bars remain elastic throughout the test. In the standard technique, the history of stress and strain in the specimen is determined from the recorded elastic waves in the bars. In this determination it is assumed that the specimen is under a state of uniform uniaxial tension stress and deformation in the tensile bar (and pure shear in the torsion bar). In the present research the tensile split Hopkinson bar technique was also modified such that strain is also be measured directly on the specimen. This was done by attaching two strain gages on opposite sides of the specimen, as in the low rate tests.

3. SPECIMENS

The specimen in the tensile tests is a short dog-bone shape coupon cut from a plate. The coupon is glued to two slotted cylindrical adapters. The specimen's geometry and the adapters are shown in Fig. 2. For use in the split Hopkinson bar the unit is cemented between the input and output bars. For use in the hydraulic testing machine the assembly is pinned to double universal joints, which are connected to the grips of the machine. The double universal joint connection reduces the possibility of introducing a bending moment resulting from a possible eccentric load line in the testing machine.

In the torsion tests the specimen is a short thin-walled tube. The specimen is obtained 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 that are then attached to the testing machine. The specimen and adapters are shown in Fig. 3. In a torsional split Hopkinson bar test the adapters are cemented to the bars. In a test with the Instron machine, the adapters have a hexagonal end that is attached mechanically to a hexagonal grip.

4. RESULTS

Tests were conducted with specimens made of E-862 and PR-520 resin material. Each type of specimen was tested in tension and shear at strain rates of approximately $5x10^{-5}$, 1, and 400 s^{-1}.

The tests are summarized in table 1. For each test, the stress, strain, and strain rate (in the split Hopkinson bar tests), all as a function of time, and the stress-strain curve for the test are given in the Appendix (in the order listed in table 1). The stress-strain curves from all the tests for each material tested are given in Figs. 4 – 7. The results show that the material is very sensitive to the strain rate. In all of the specimens tested the initial modulus and the maximum stress increases with strain rate.

TABLE 1: OSU TESTS FOR NASA
SUMMARY OF TESTS 2001-2002

TEST NO.	SPECIMEN'S MATERIAL	STRAIN RATE (1/s)	COMMENTS
EXP01-1	Epoxy resin E-862	700	Torsion
EXP01-2	Epoxy resin E-862	700	Torsion
EXP01-3	Epoxy resin PR-520	700	Torsion
EXP01-4	Epoxy resin PR-520	700	Torsion
EXP01-5	Epoxy resin E-862	1.3×10^{-4}	Torsion
EXP01-6	Epoxy resin PR-520	1.3×10^{-4}	Torsion
EXP01-7	Epoxy resin E-862	2.6	Torsion
EXP01-8	Epoxy resin PR-520	2.6	Torsion
EXP01-9	Epoxy resin PR-520	455	Tension
EXP01-10	Epoxy resin PR-520	476	Tension, stepped adapter
EXP01-11	Epoxy resin E-862	No data	Clamp broke at pin.
EXP01-12	Epoxy resin E-862	470	Tension
EXP01-13	Epoxy resin PR-520	476	Tension
EXP01-14	Epoxy resin E-862	455	Tension
EXP01-15	Epoxy resin E-862	455	Tension
EXP01-16	Epoxy resin PR-520	445	Tension
EXP01-17	Epoxy resin PR-520	5×10^{-5}	Tension
EXP01-18	Epoxy resin PR-520	5.1×10^{-5}	Tension
EXP01-19	Epoxy resin E-862	5.7×10^{-5}	Tension
EXP01-20	Epoxy resin E-862	5.7×10^{-5}	Tension
EXP01-21	Epoxy resin PR-520	5.3×10^{-5}	Tension
EXP01-22	Epoxy resin PR-520	1.4	Tension
EXP01-23	Epoxy resin PR-862	5.4×10^{-5}	Tension
EXP01-24	Epoxy resin E-862	1.2	Tension
EXP01-25	Epoxy resin PR-520	4.7×10^{-5}	Tension
EXP01-26	Epoxy resin PR-520	1.7	Tension
EXP01-27	Epoxy resin PR-862	1.2	Tension
EXP01-28	Epoxy resin PR-862	1.4	Tension

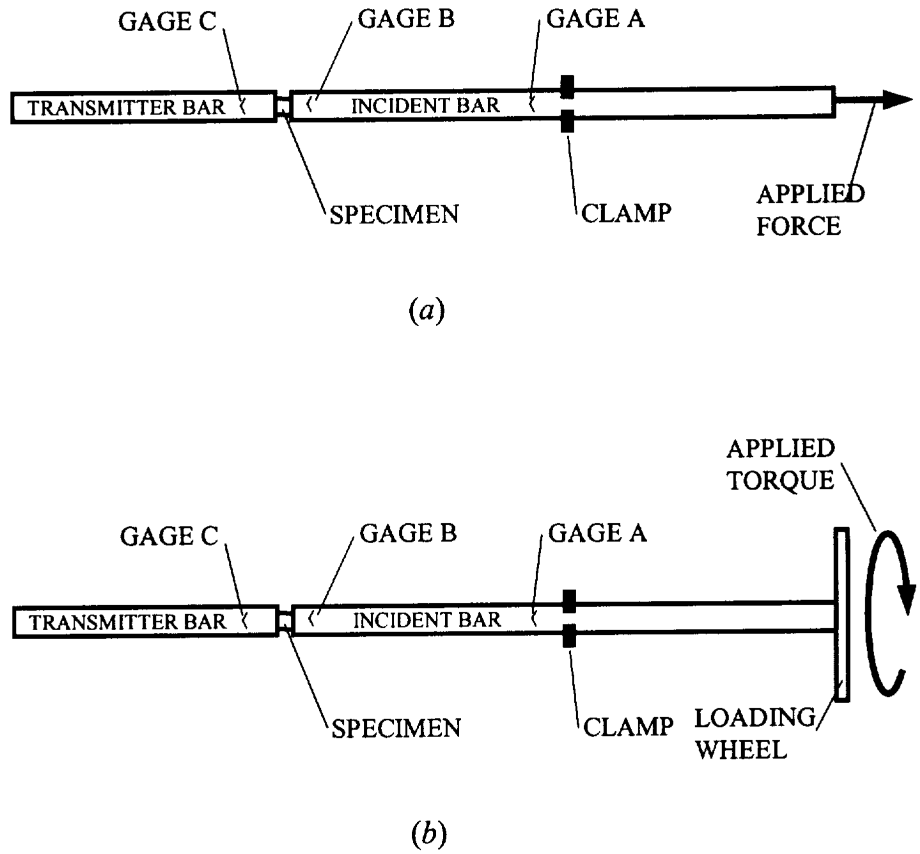


Fig. 1: Schematic of the tensile split Hopkinson bar apparatus,
(*a*) tensile, (*b*) torsion.

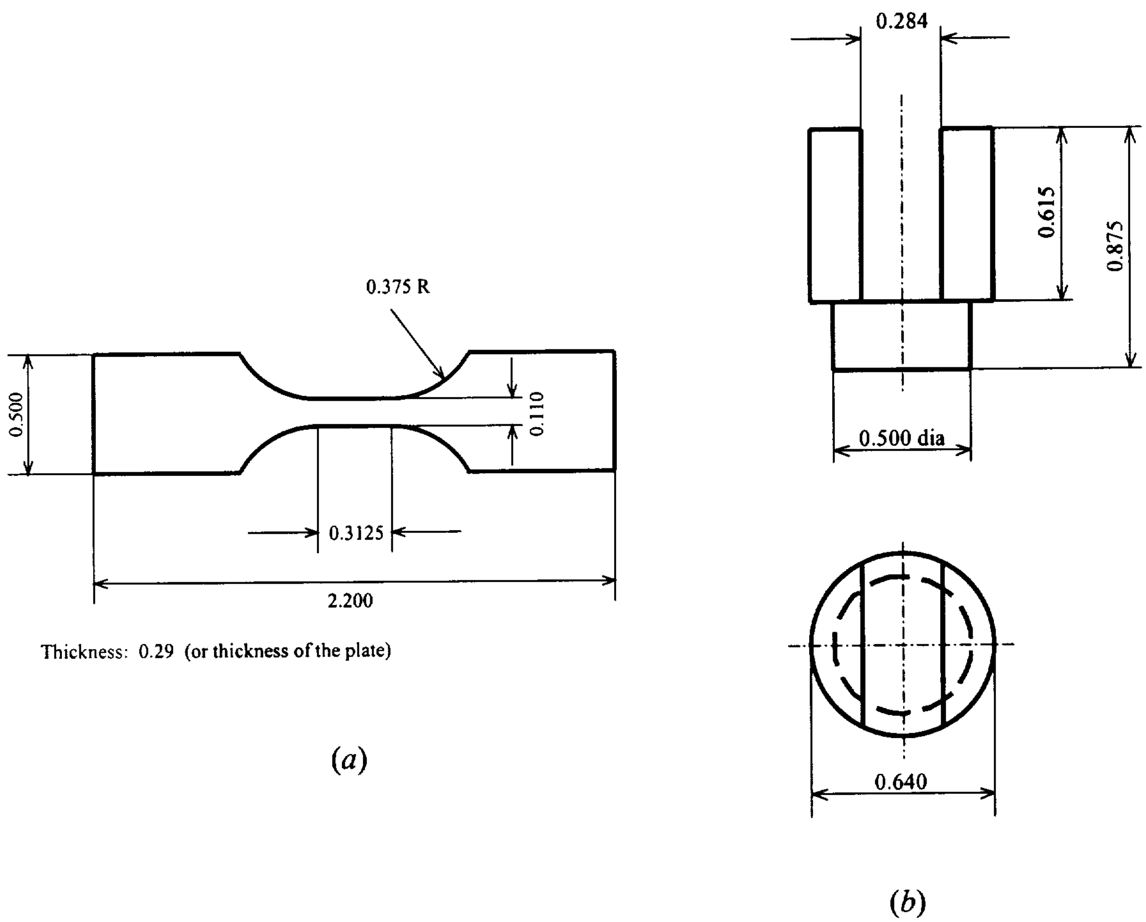


Fig. 2 Tensile test specimen and adapters.
(*a*) specimen, (*b*) adapter.

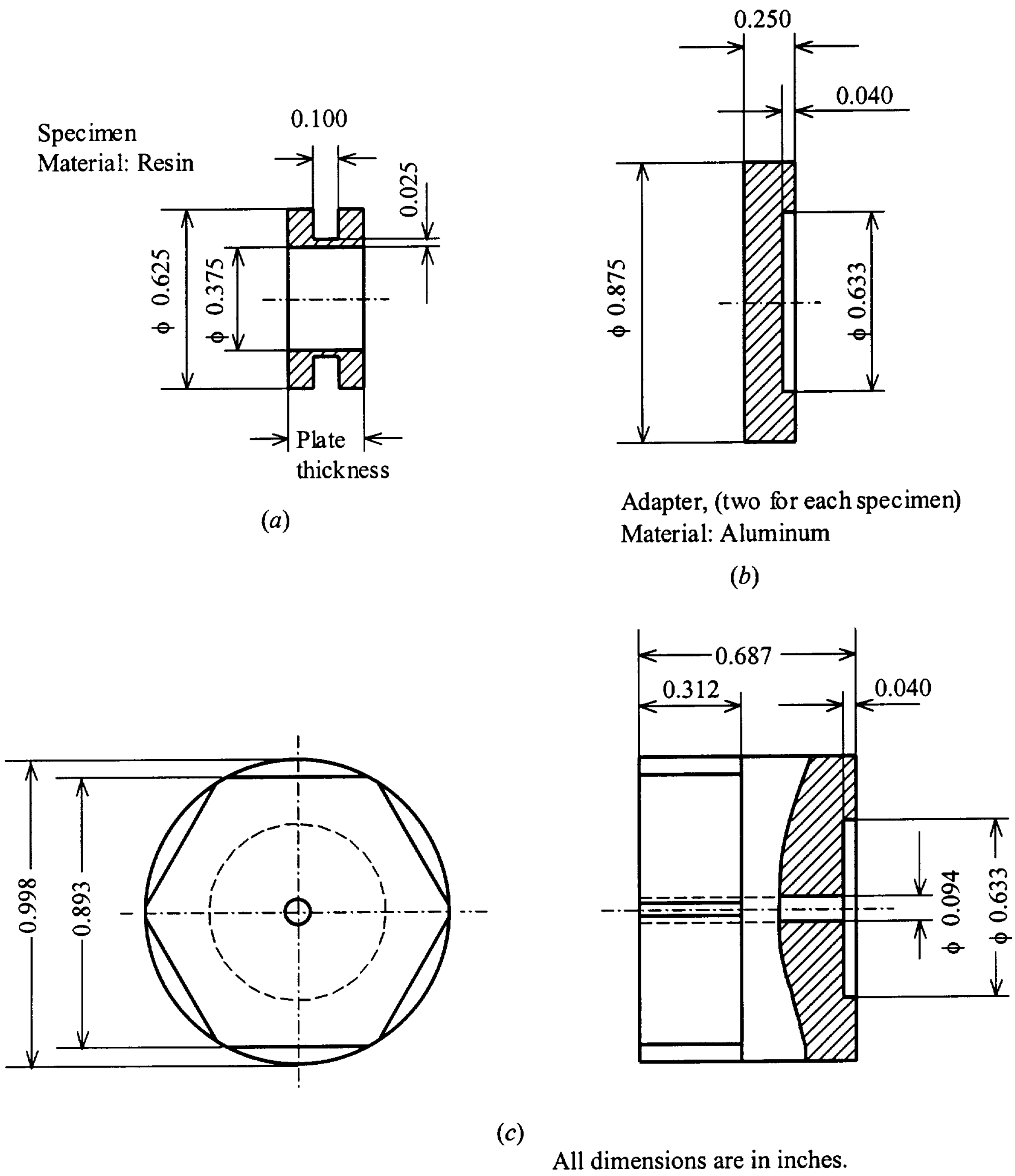


Fig. 3 Torsion test specimen and adapters.
(*a*) specimen, (*b*) adapter for SHB test,
(*c*) adapter for stastic test.

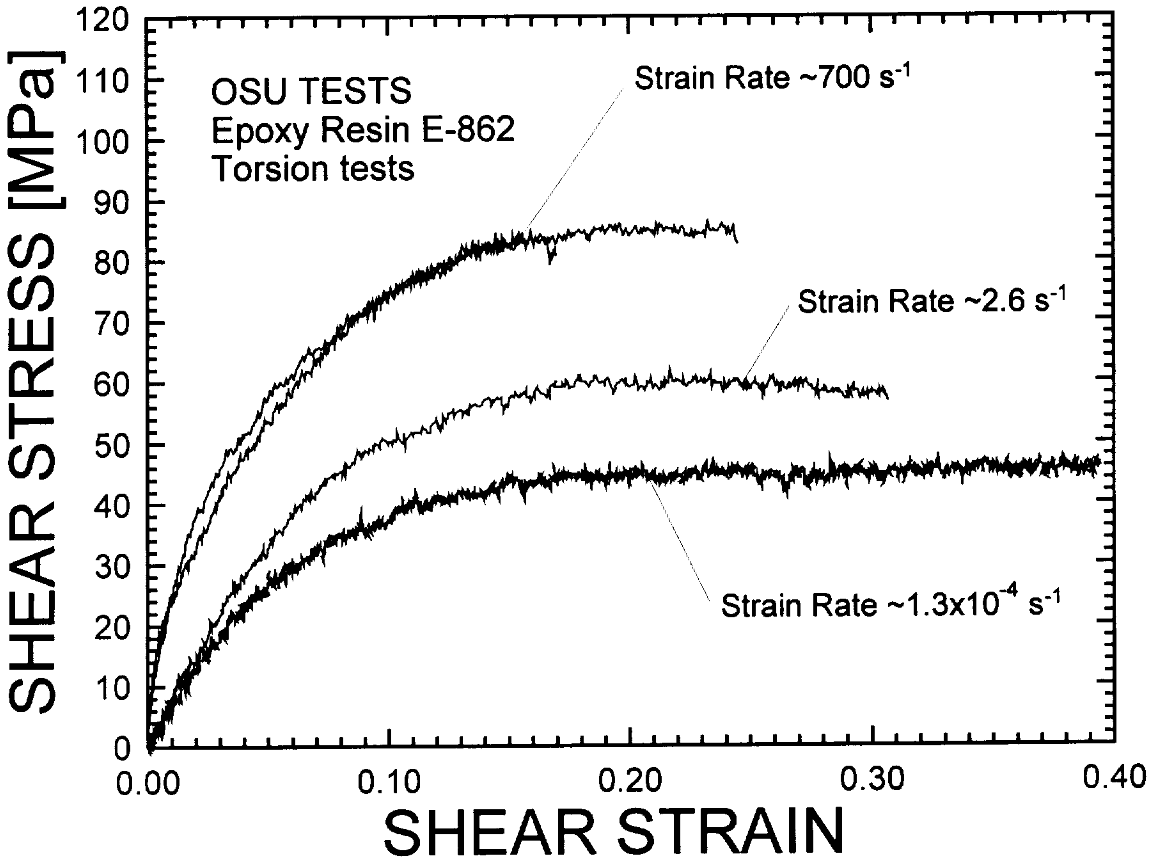


Fig. 4 Shear stress strain curves for E-862 epoxy at different strain rates.

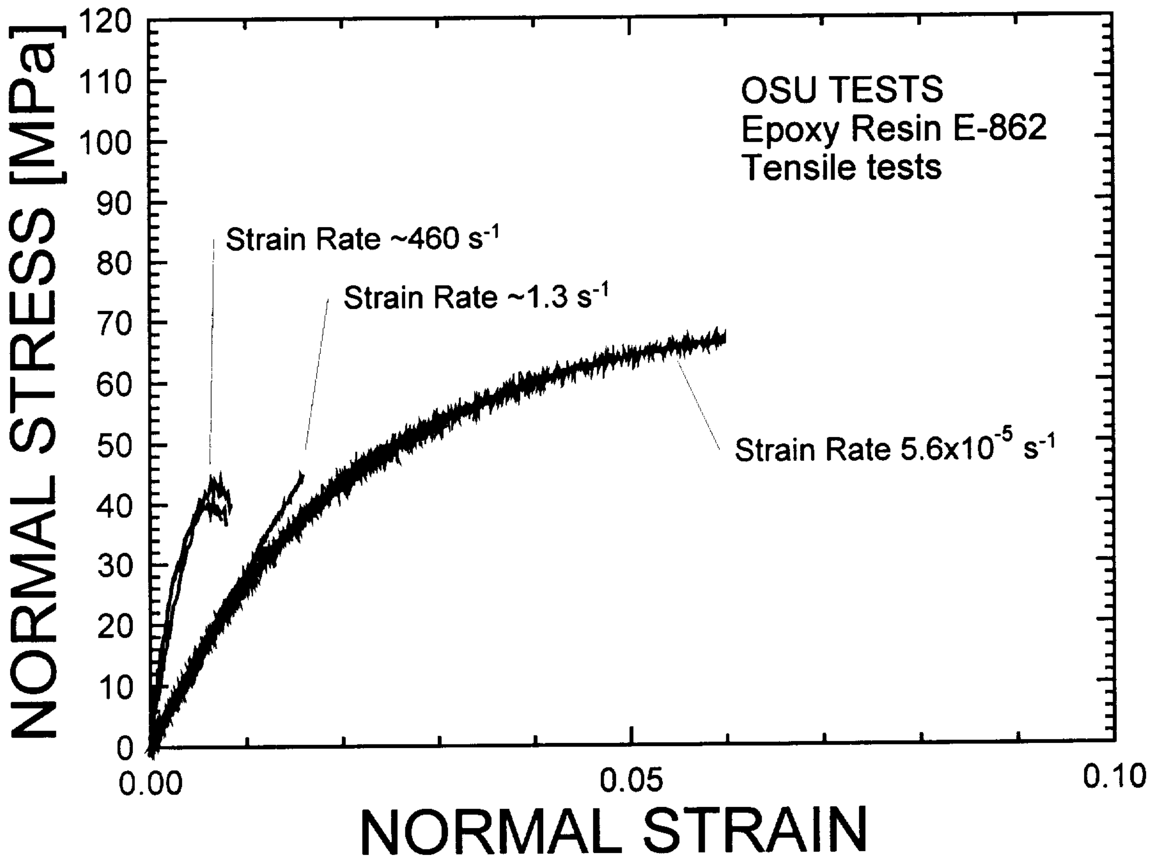


Fig. 5 Tensile stress strain curves for E-862 epoxy at different strain rates.

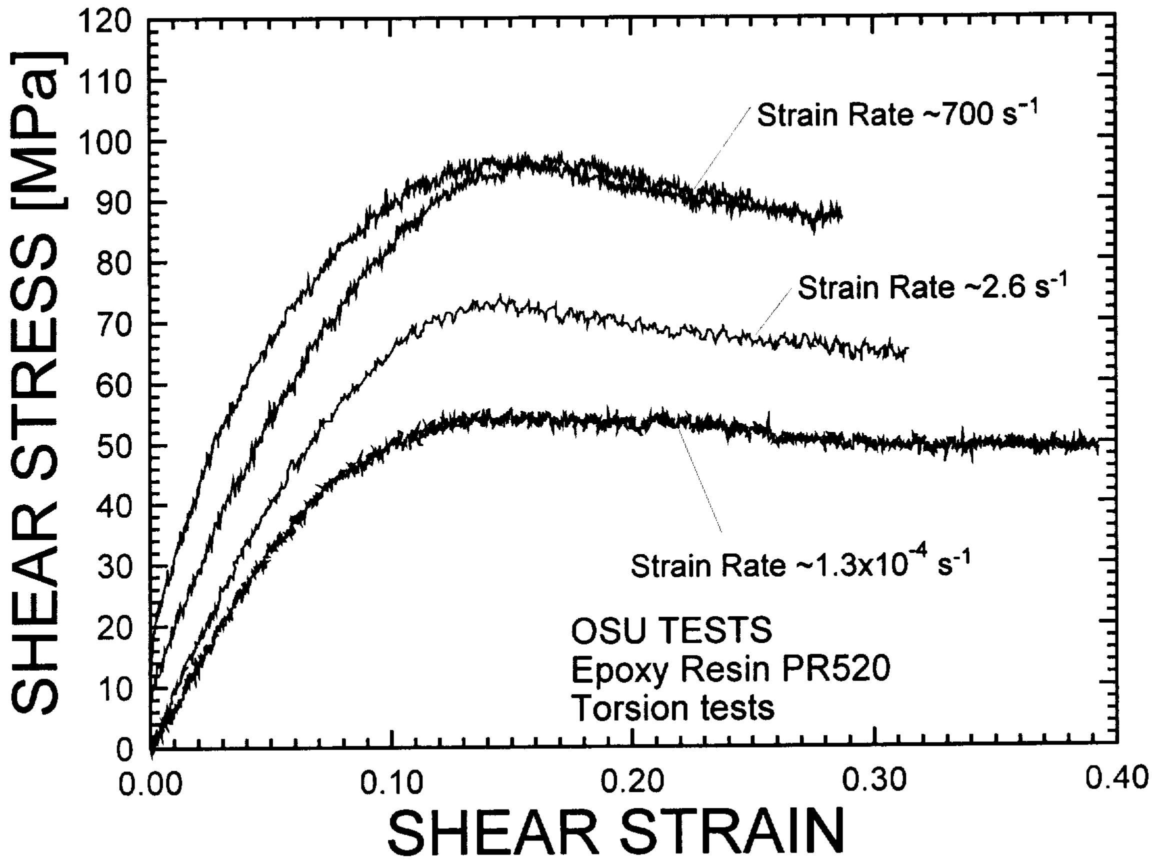


Fig. 6 Shear stress strain curves for PR-520 epoxy at different strain rates.

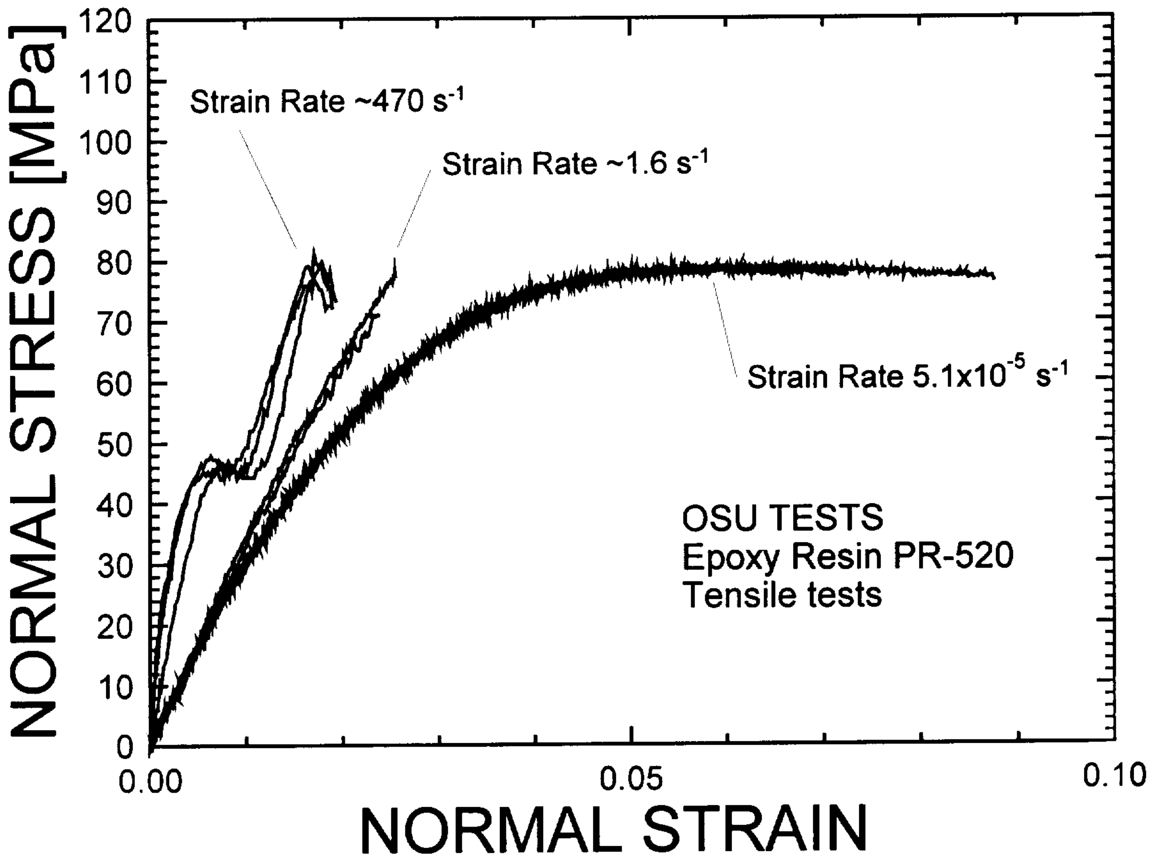
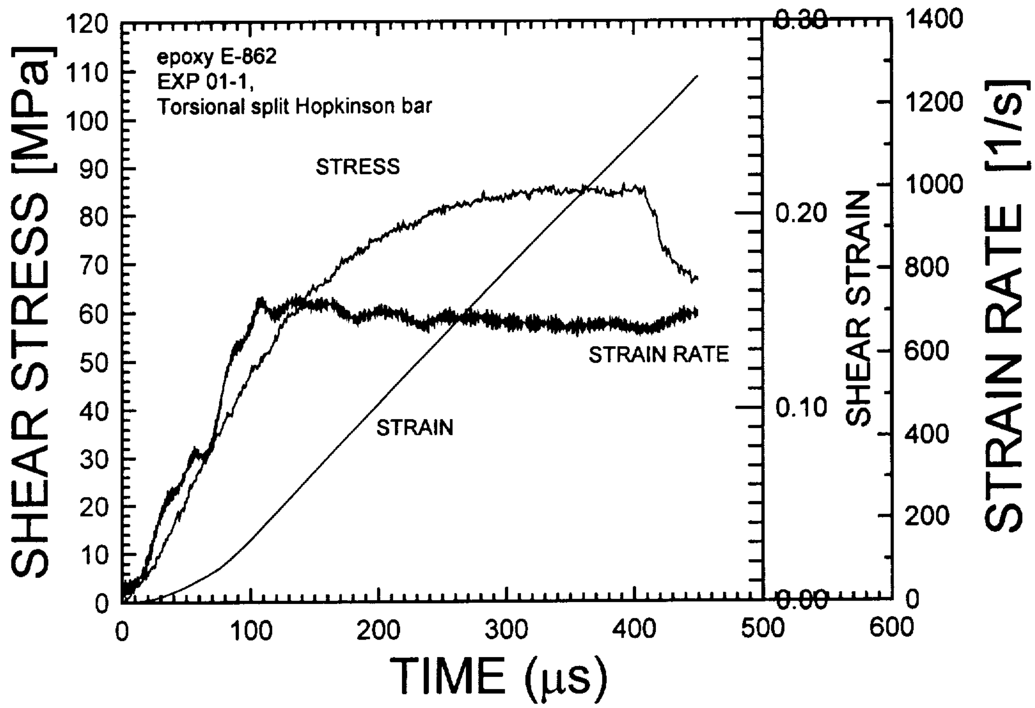


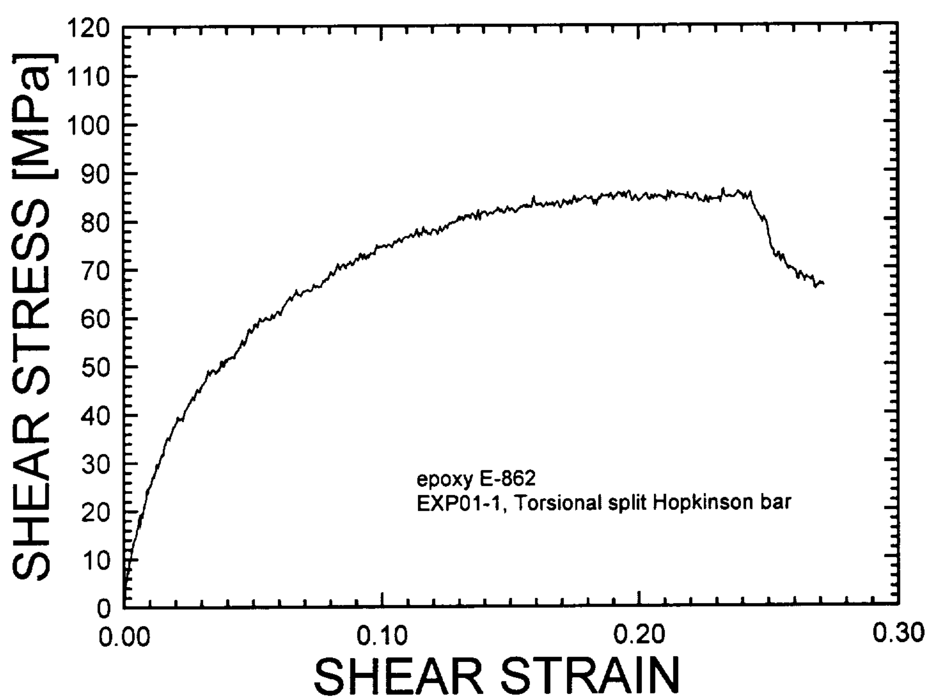
Fig. 7 Tensile stress strain curves for PR-520 epoxy at different strain rates.

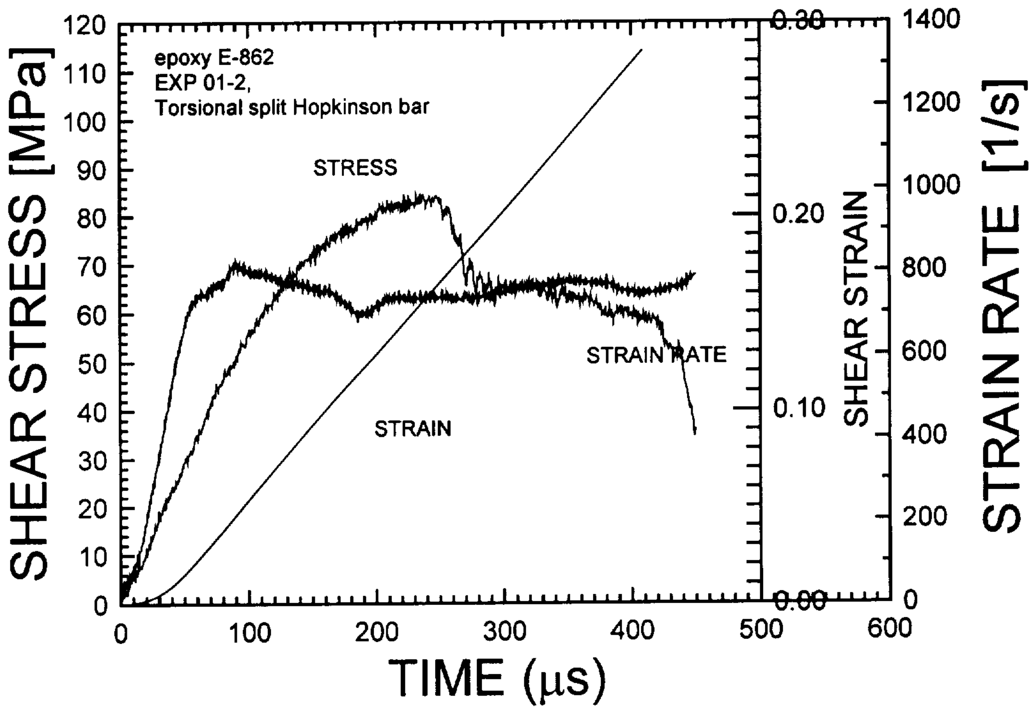
APPENDIX

For each test two plots are presented. In one the stress, strain (measured by the strain gages when gages were attached to the specimen, and/or determined by the SHB analysis), and strain rate (in the split Hopkinson bar tests), all as a function of time. The other plot contains the stress-strain curve for the test.

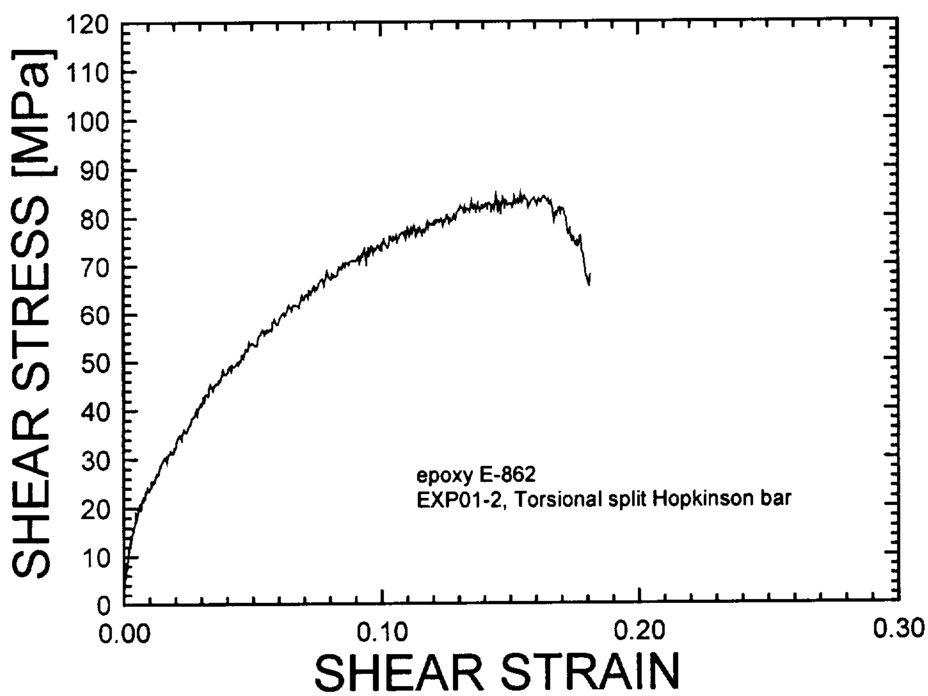
The plots are in the order listed in Table 1.


epoxy E-862
EXP 01-1,
Torsional split Hopkinson bar
STRESS
STRAIN RATE
STRAIN
SHEAR STRESS [MPa]
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

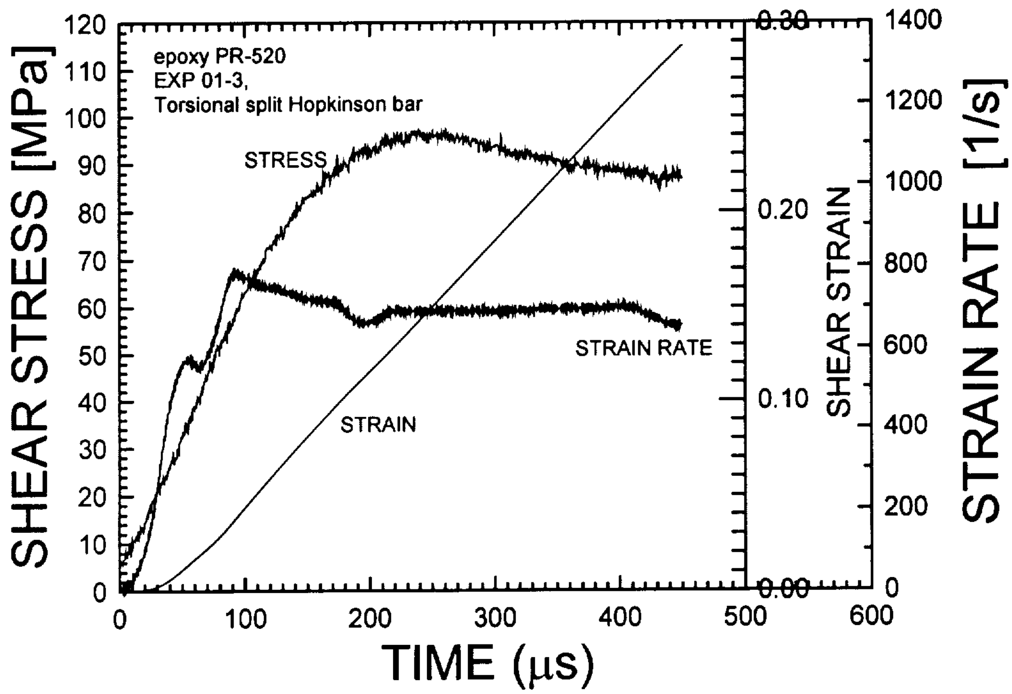

epoxy E-862
EXP01-1, Torsional split Hopkinson bar
SHEAR STRESS [MPa]
SHEAR STRAIN

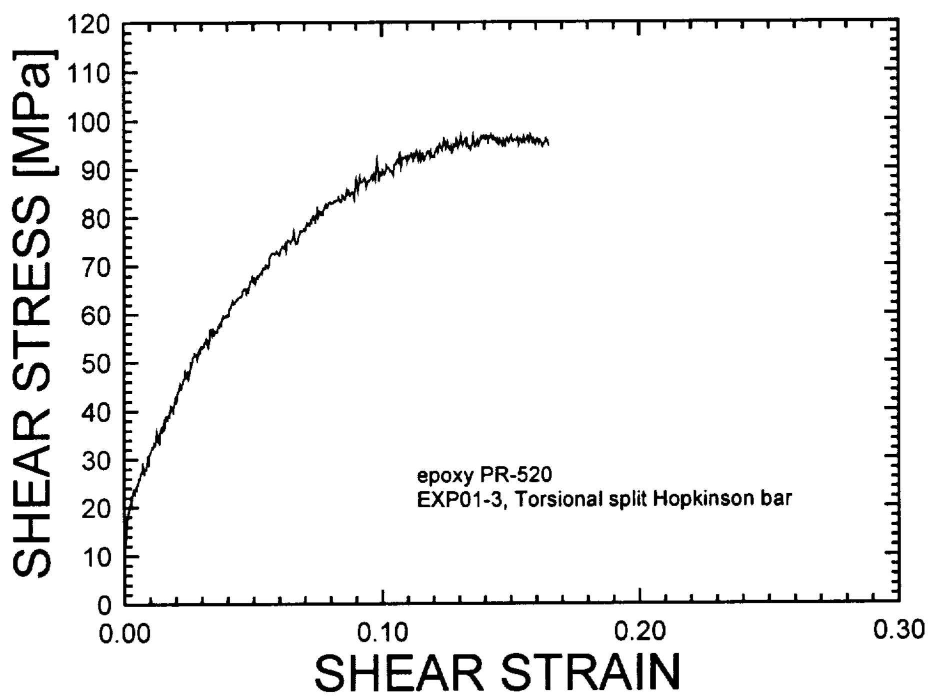


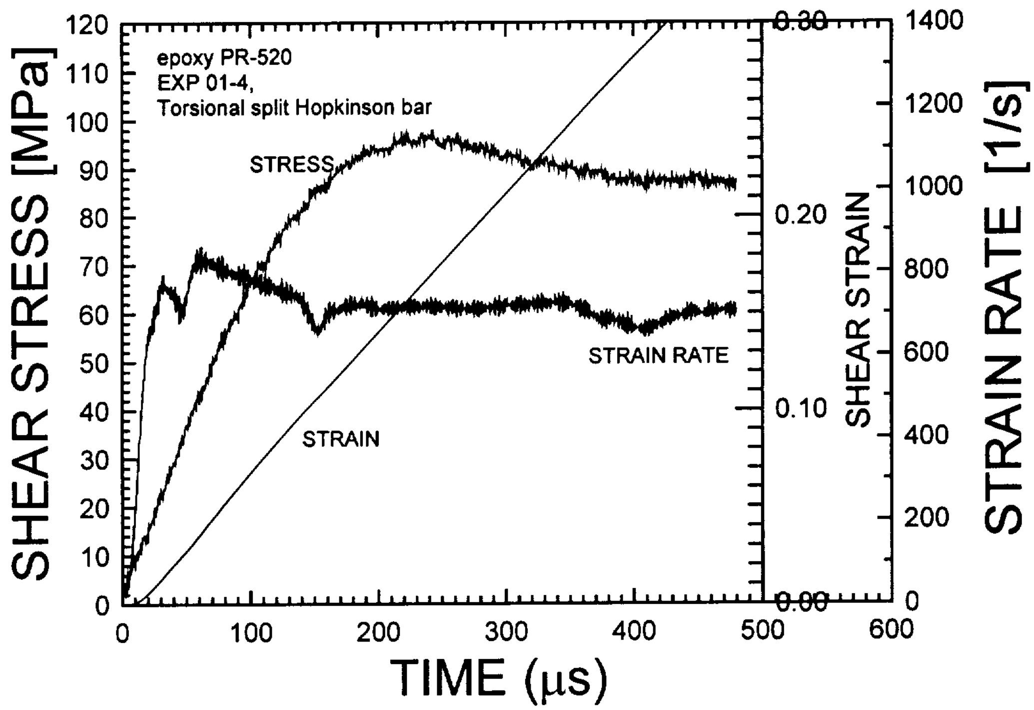
epoxy E-862
EXP 01-2,
Torsional split Hopkinson bar
STRESS
STRAIN RATE
STRAIN
SHEAR STRESS [MPa]
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

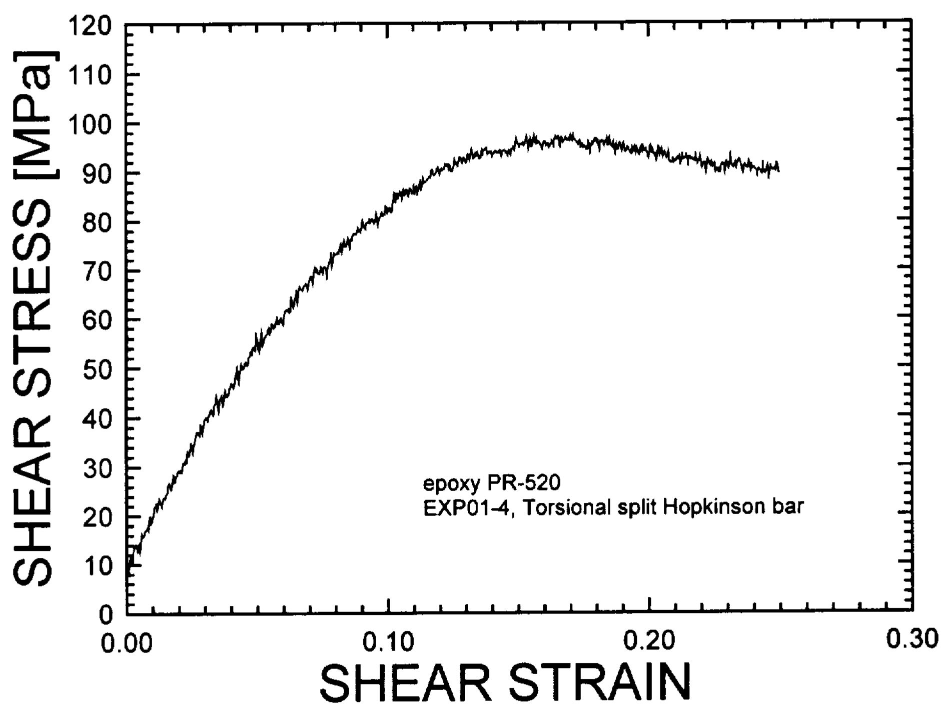


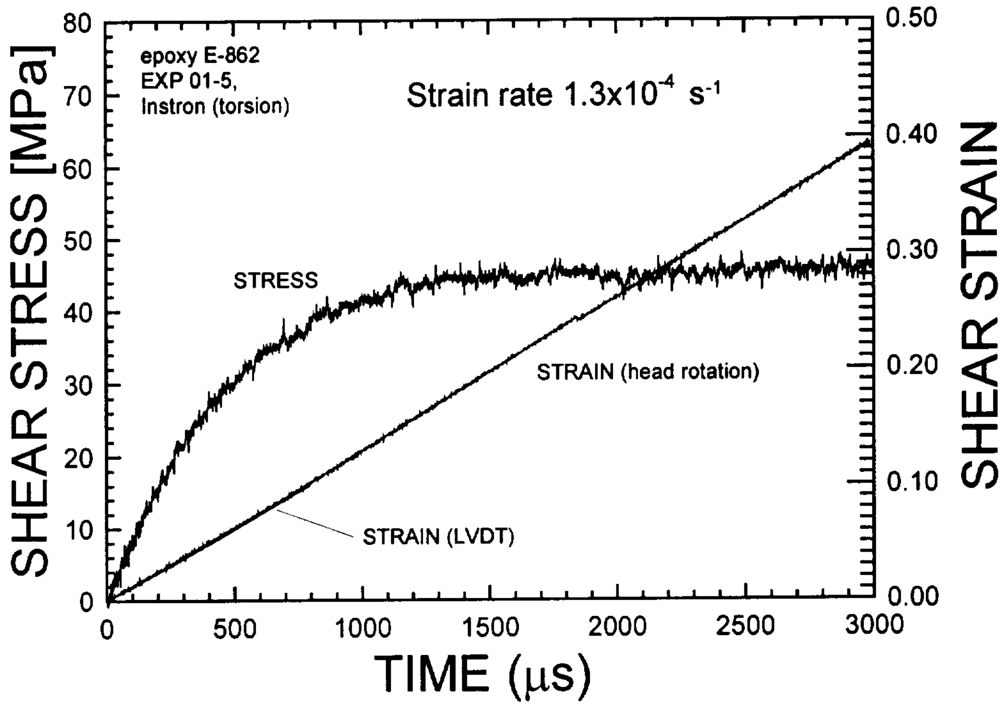
epoxy E-862
EXP01-2, Torsional split Hopkinson bar
SHEAR STRESS [MPa]
SHEAR STRAIN


epoxy PR-520
EXP 01-3,
Torsional split Hopkinson bar
STRESS
STRAIN RATE
STRAIN
SHEAR STRESS [MPa]
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

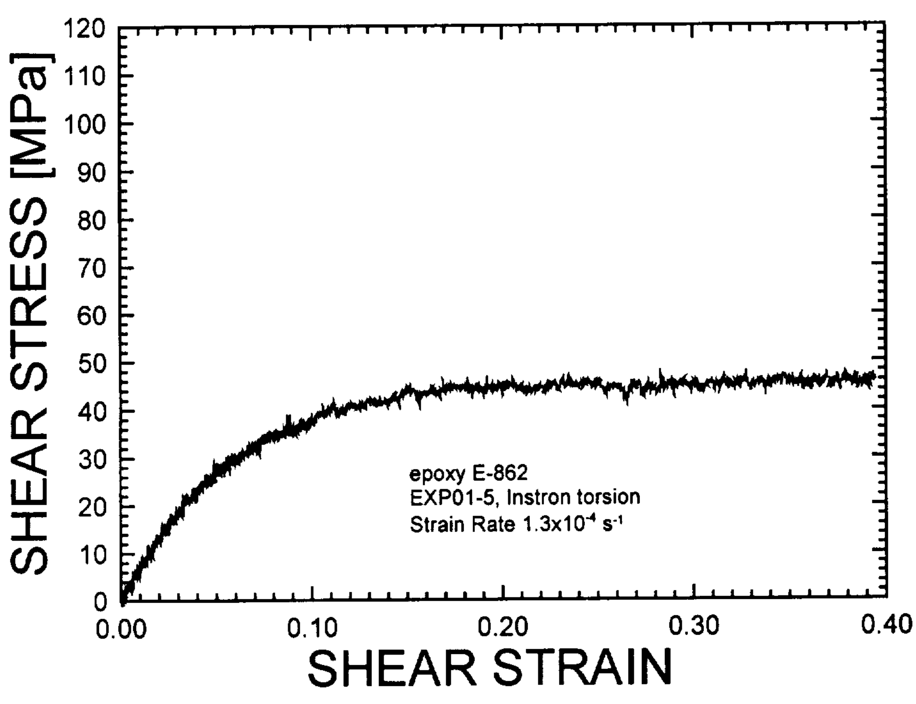

epoxy PR-520
EXP01-3, Torsional split Hopkinson bar
SHEAR STRESS [MPa]
SHEAR STRAIN


epoxy PR-520
EXP 01-4,
Torsional split Hopkinson bar
STRESS
STRAIN RATE
STRAIN
SHEAR STRESS [MPa]
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

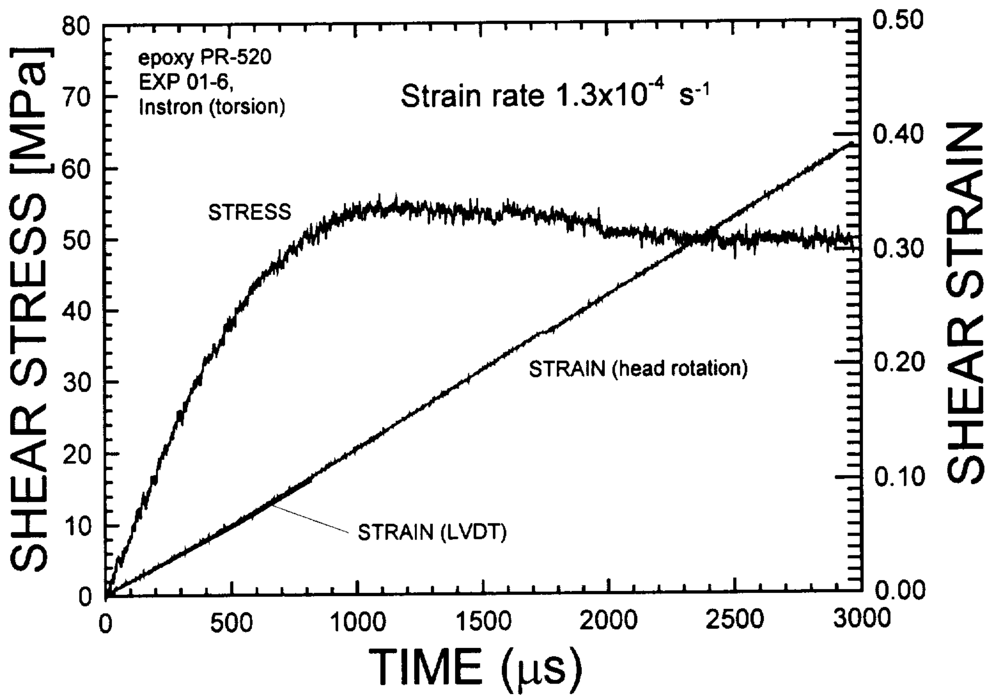

epoxy PR-520
EXP01-4, Torsional split Hopkinson bar
SHEAR STRESS [MPa]
SHEAR STRAIN

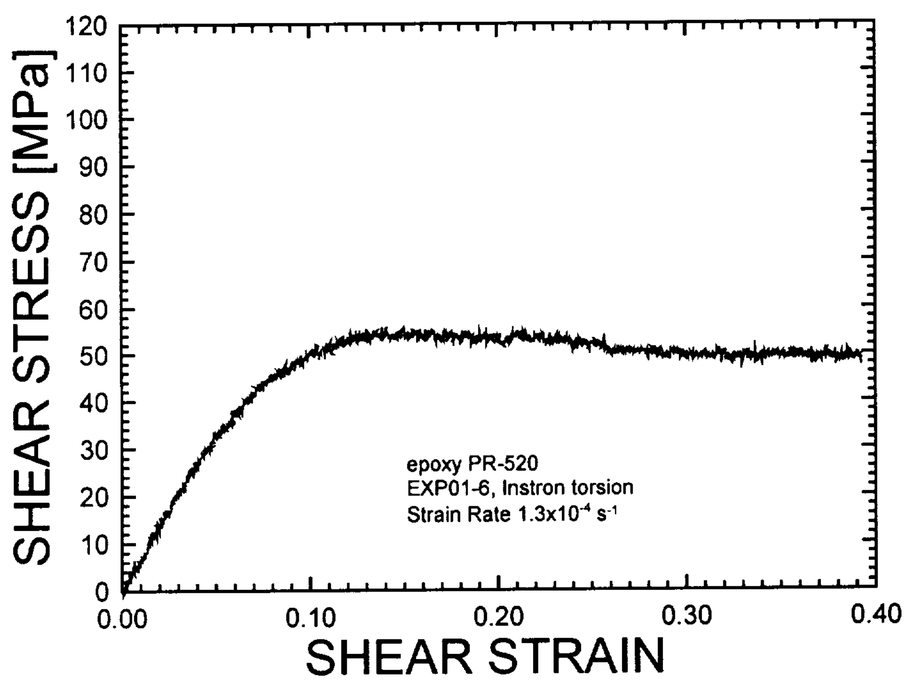


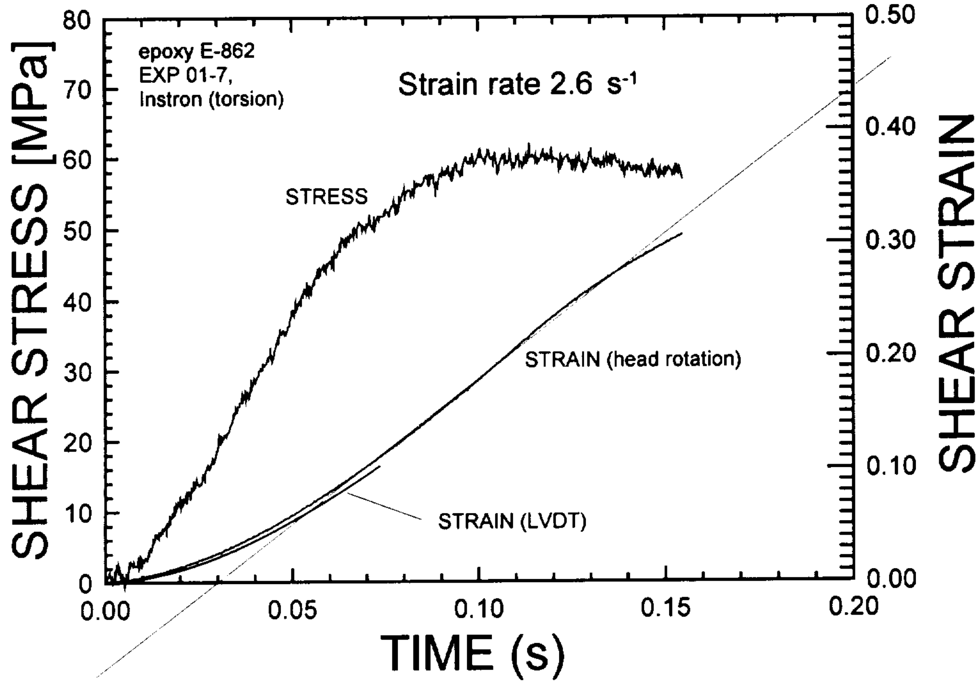
epoxy E-862
EXP 01-5,
Instron (torsion)
Strain rate 1.3x10^{-4} s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)



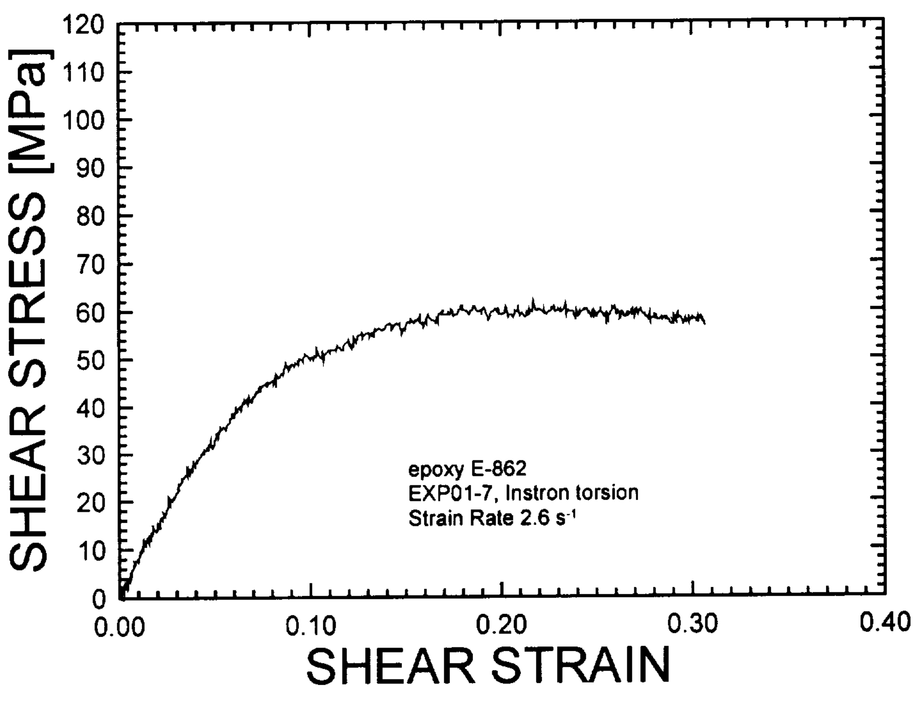
epoxy E-862
EXP01-5, Instron torsion
Strain Rate 1.3x10^{-4} s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN


epoxy PR-520
EXP 01-6,
Instron (torsion)
Strain rate 1.3x10^{-4} s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)
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

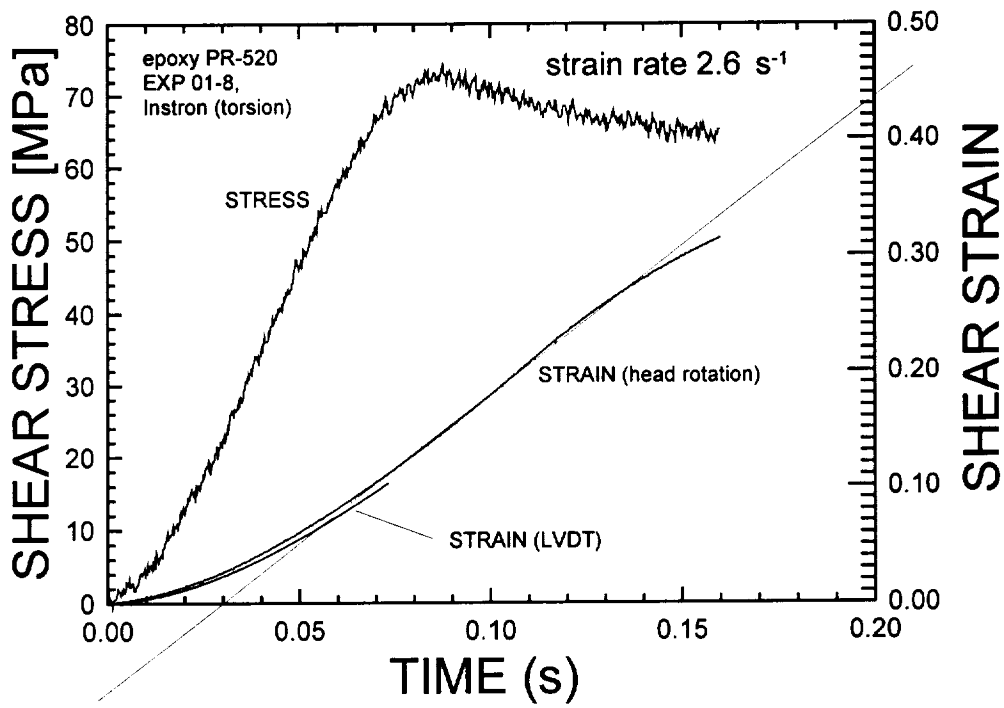

epoxy PR-520
EXP01-6, Instron torsion
Strain Rate 1.3x10^{-4} s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN
120
110
100
90
80
70
60
50
40
30
20
10
0
0.00
0.10
0.20
0.30
0.40



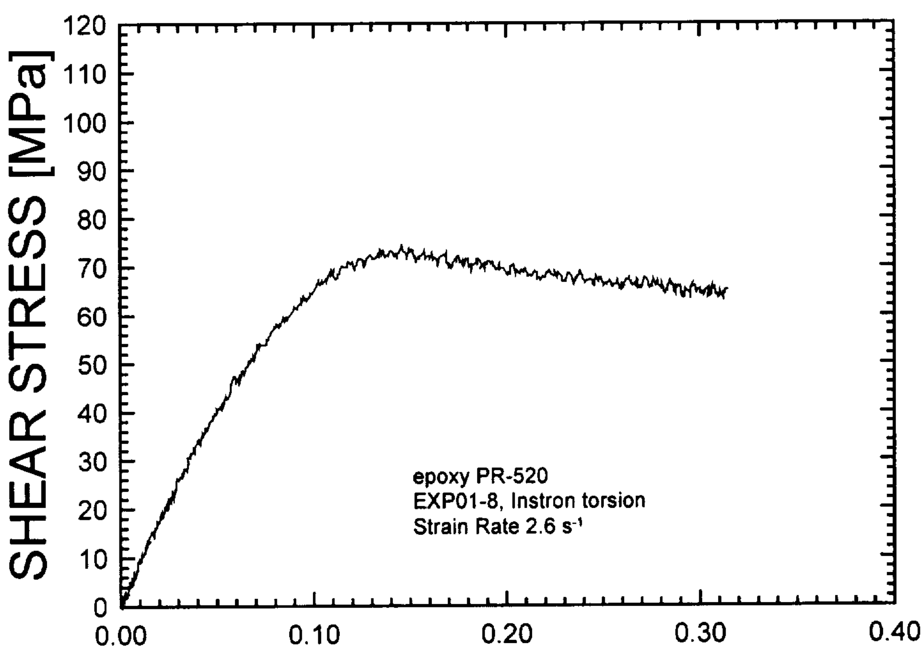
epoxy E-862
EXP 01-7,
Instron (torsion)
Strain rate 2.6 s-1
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0
10
20
30
40
50
60
70
80
0.00
0.05
0.10
0.15
0.20
0.10
0.20
0.30
0.40
0.50



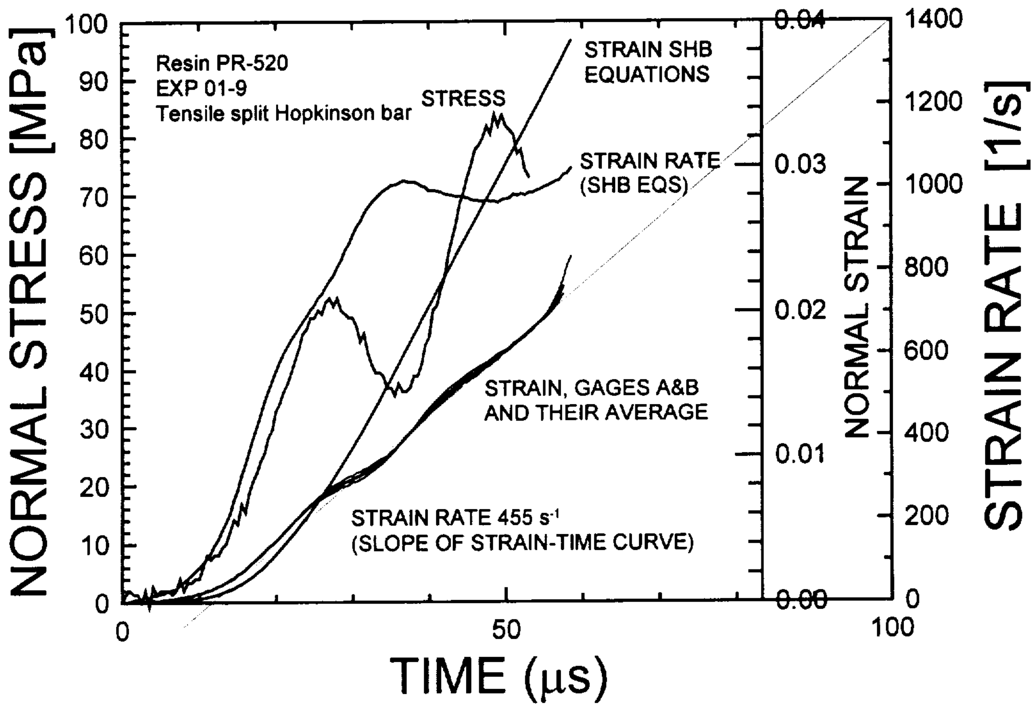
epoxy E-862
EXP01-7, Instron torsion
Strain Rate 2.6 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40

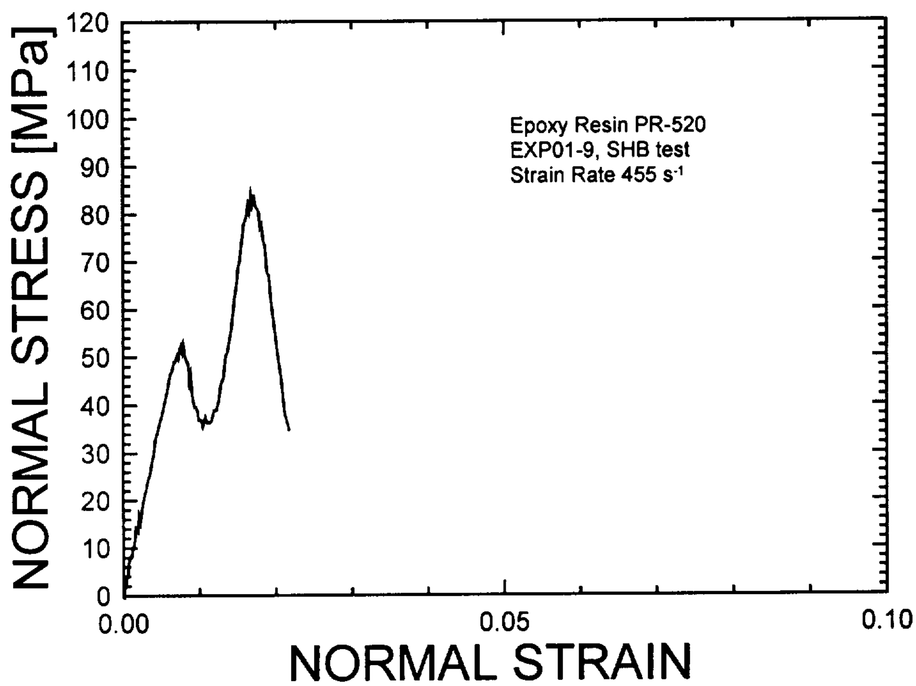


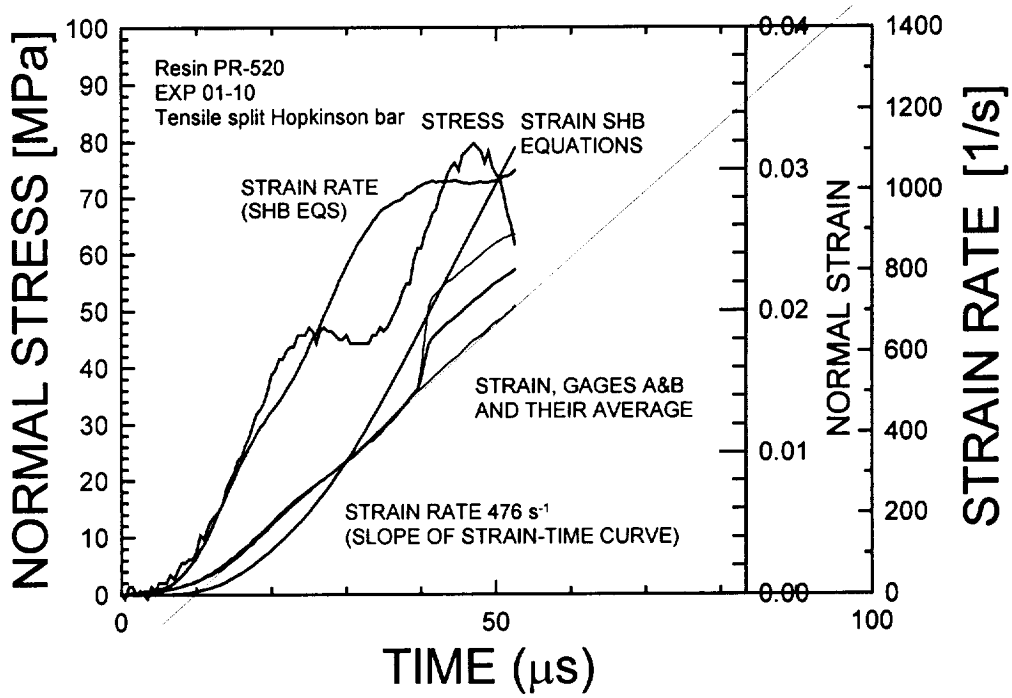
epoxy PR-520
EXP 01-8,
Instron (torsion)
strain rate 2.6 s-1
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)



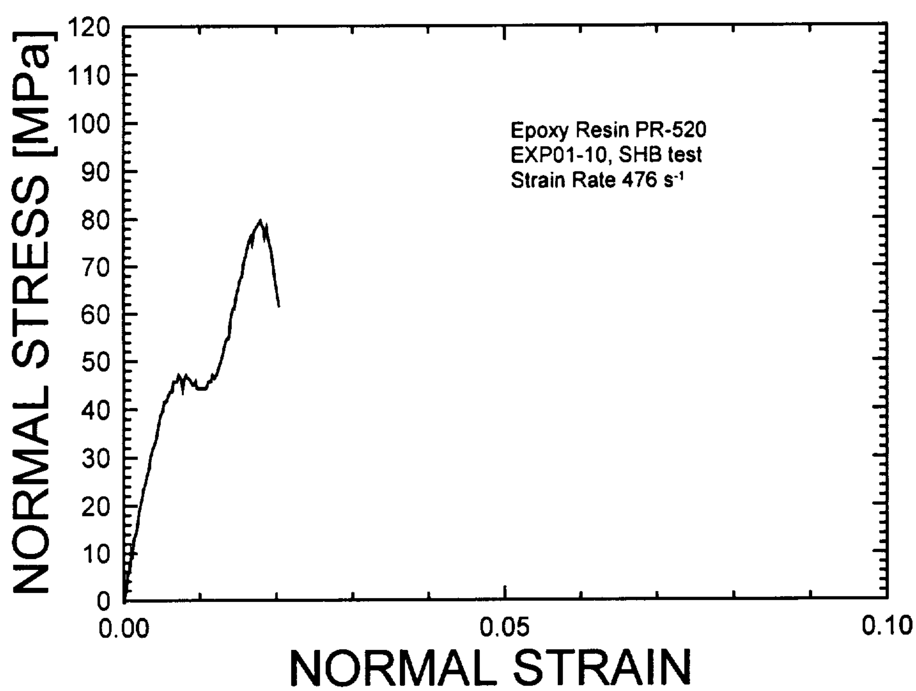
epoxy PR-520
EXP01-8, Instron torsion
Strain Rate 2.6 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN


NORMAL STRESS [MPa]
Resin PR-520
EXP 01-9
Tensile split Hopkinson bar
STRESS
STRAIN SHB EQUATIONS
STRAIN RATE (SHB EQS)
STRAIN, GAGES A&B AND THEIR AVERAGE
STRAIN RATE 455 s-1 (SLOPE OF STRAIN-TIME CURVE)
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

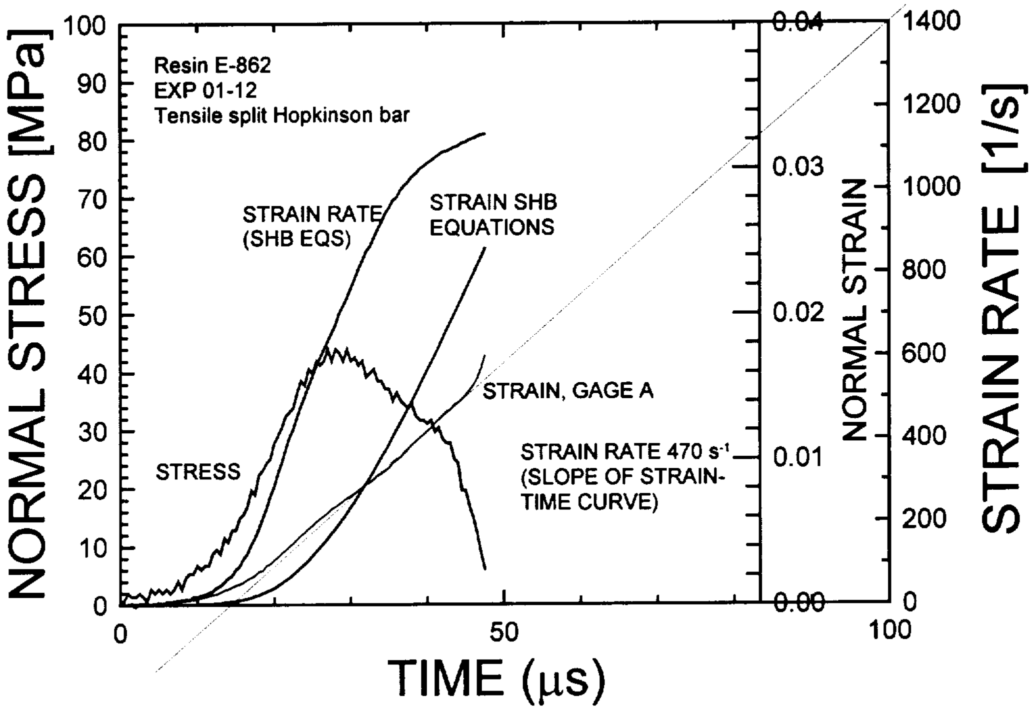

NORMAL STRESS [MPa]
Epoxy Resin PR-520
EXP01-9, SHB test
Strain Rate 455 s-1
NORMAL STRAIN

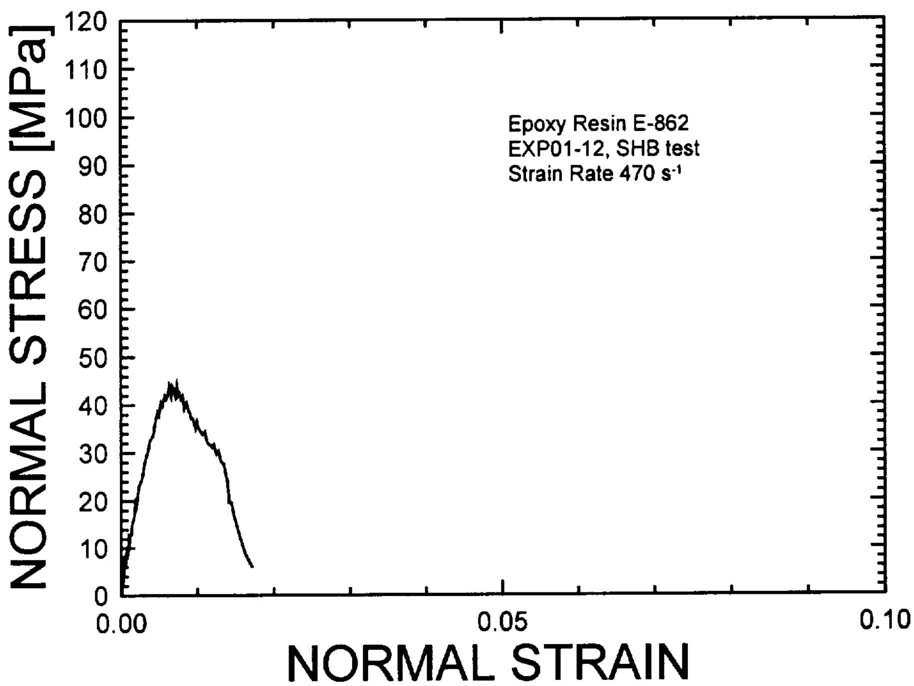


Resin PR-520
EXP 01-10
Tensile split Hopkinson bar
STRESS
STRAIN SHB EQUATIONS
STRAIN RATE (SHB EQS)
STRAIN, GAGES A&B AND THEIR AVERAGE
STRAIN RATE 476 s-1 (SLOPE OF STRAIN-TIME CURVE)
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)



Epoxy Resin PR-520
EXP01-10, SHB test
Strain Rate 476 s-1
NORMAL STRESS [MPa]
NORMAL STRAIN


Resin E-862
EXP 01-12
Tensile split Hopkinson bar
STRAIN RATE (SHB EQS)
STRAIN SHB EQUATIONS
STRESS
STRAIN, GAGE A
STRAIN RATE 470 s-1 (SLOPE OF STRAIN-TIME CURVE)
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)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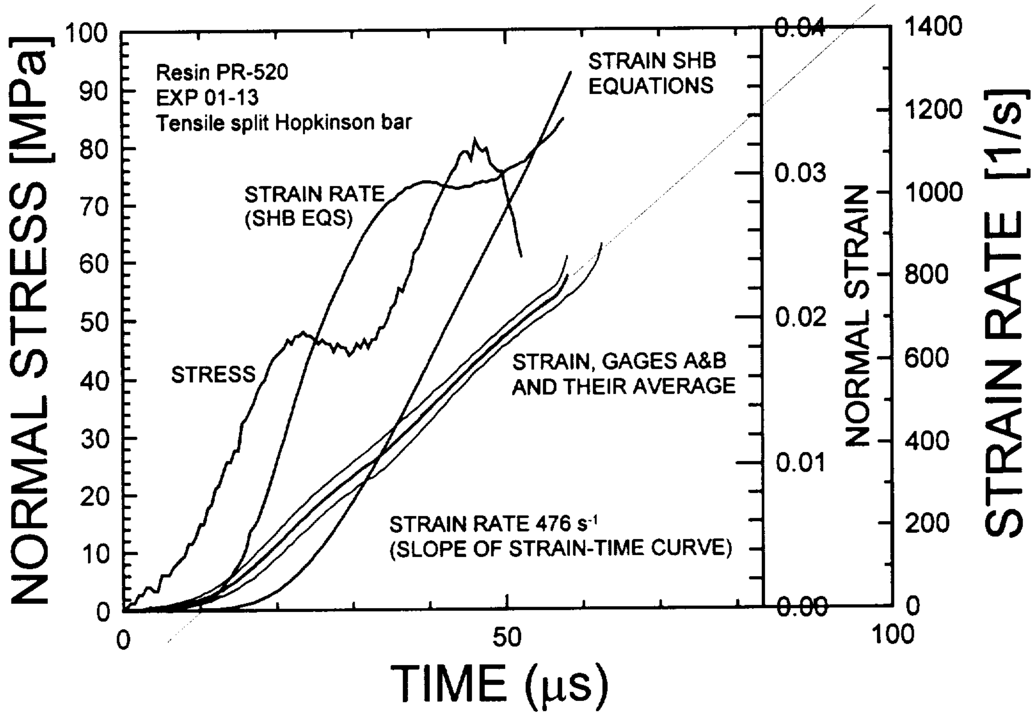
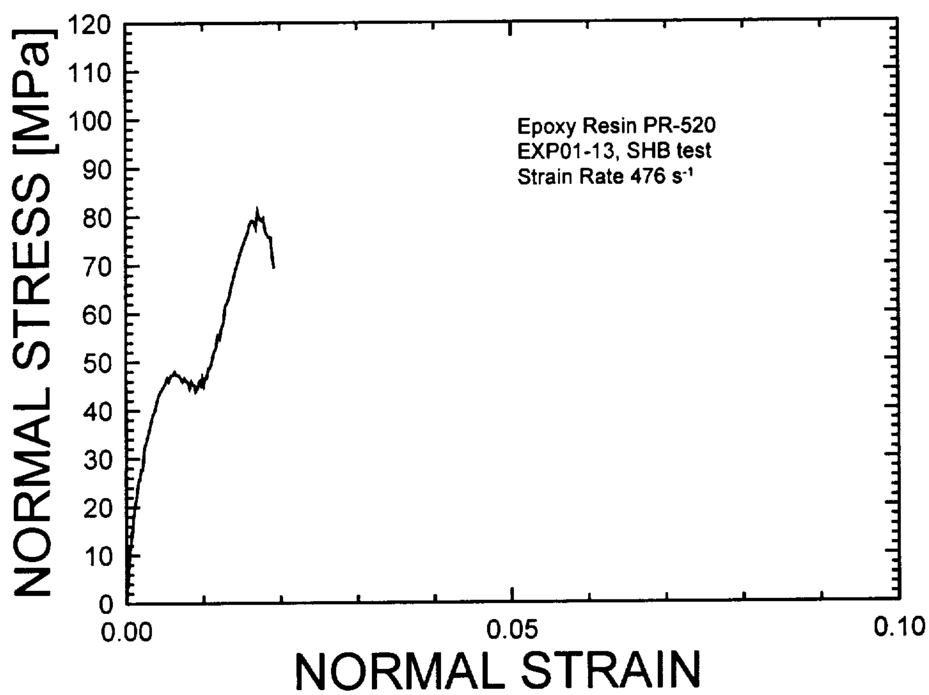
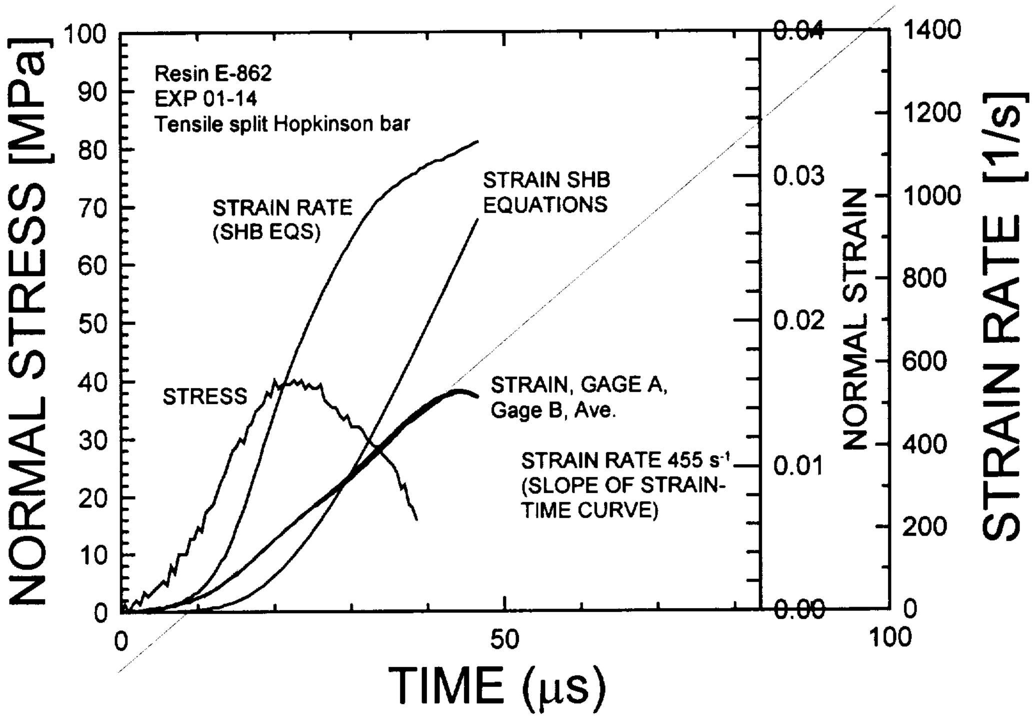
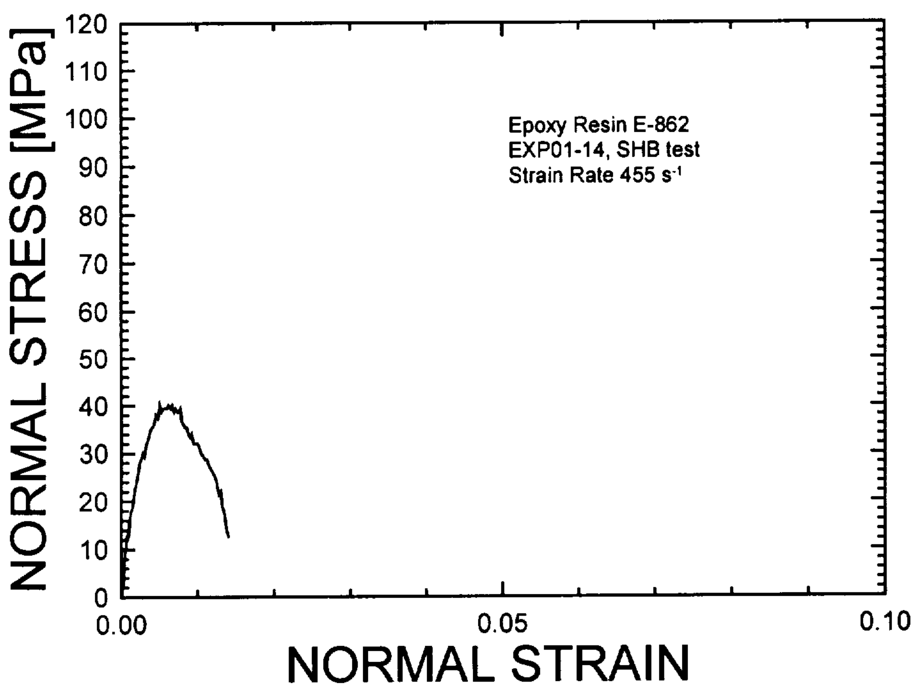
EXP01-12, SHB test
Strain Rate 470 s-1
NORMAL STRESS [MPa]
NORMAL STRAIN


Resin PR-520
EXP 01-13
Tensile split Hopkinson bar
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
STRESS
STRAIN, GAGES A&B
AND THEIR AVERAGE
STRAIN RATE 476 s^{-1}
(SLOPE OF STRAIN-TIME CURVE)
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)


Epoxy Resin PR-520
EXP01-13, SHB test
Strain Rate 476 s^{-1}
NORMAL STRESS [MPa]
NORMAL STRAIN


NORMAL STRESS [MPa]
Resin E-862
EXP 01-14
Tensile split Hopkinson bar
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
STRESS
STRAIN, GAGE A,
Gage B, Ave.
STRAIN RATE 455 s-1
(SLOPE OF STRAIN-
TIME CURVE)
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)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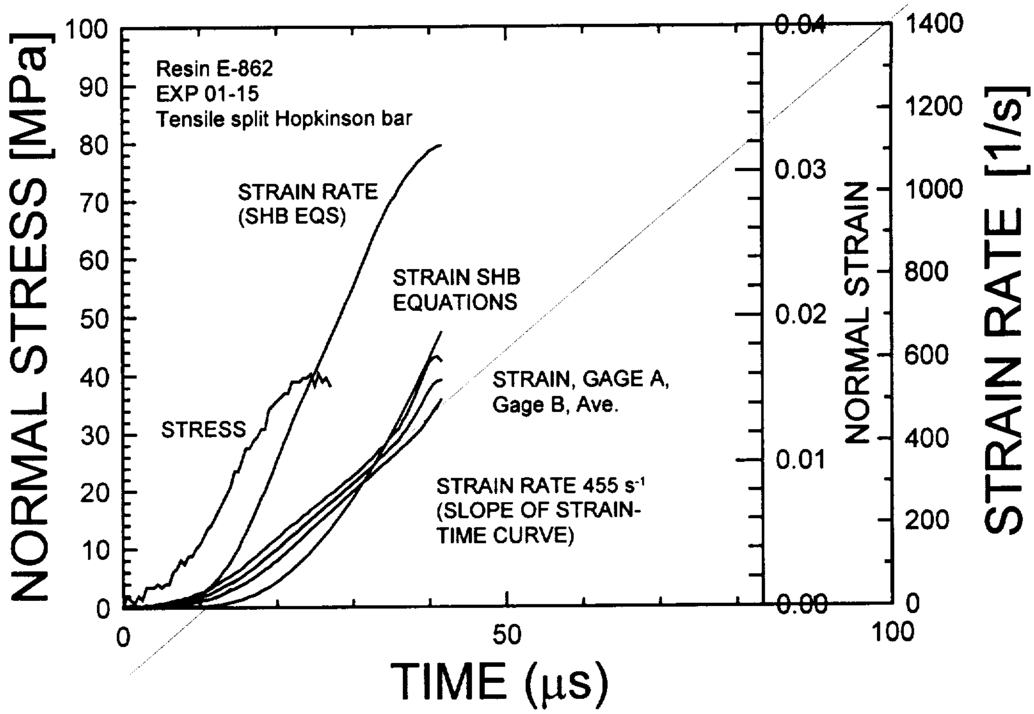
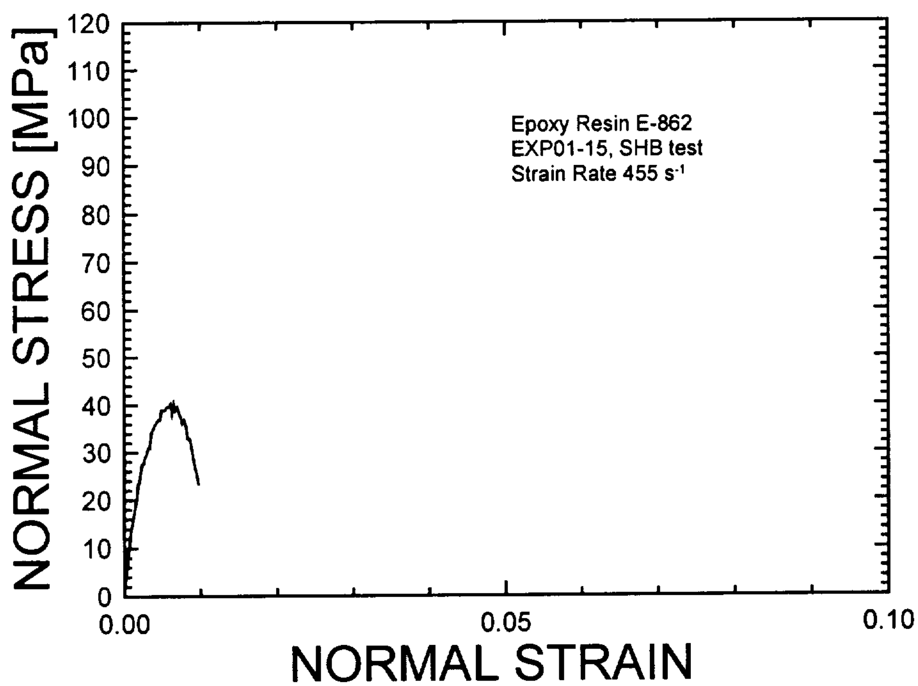
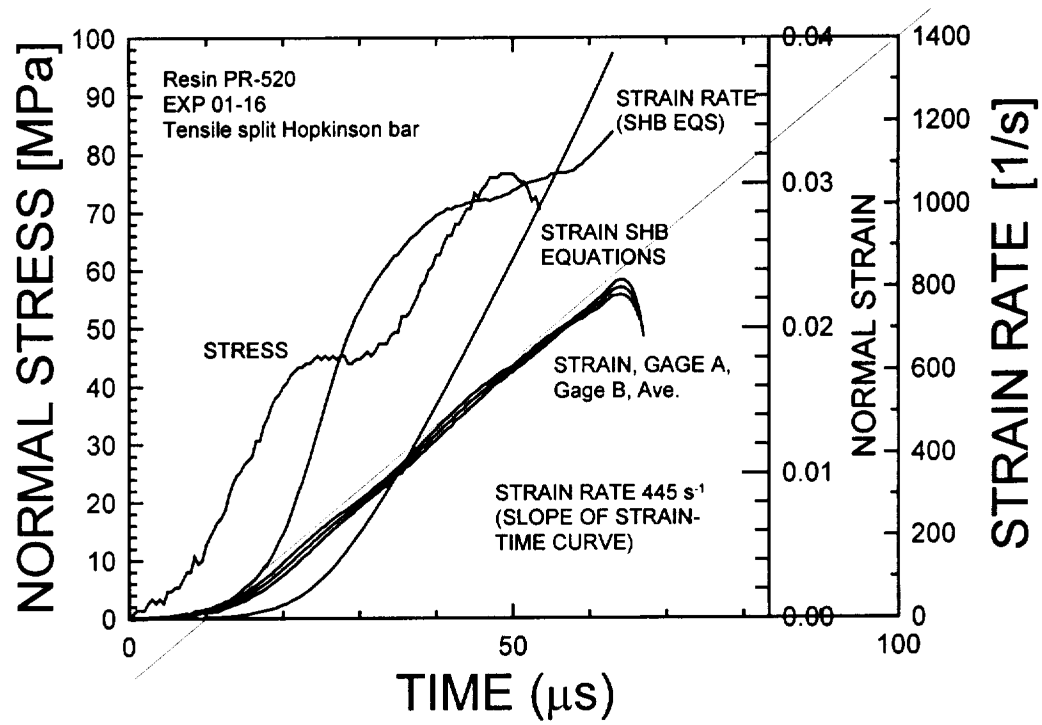
Epoxy Resin E-862
EXP01-14, SHB test
Strain Rate 455 s-1
NORMAL STRAIN

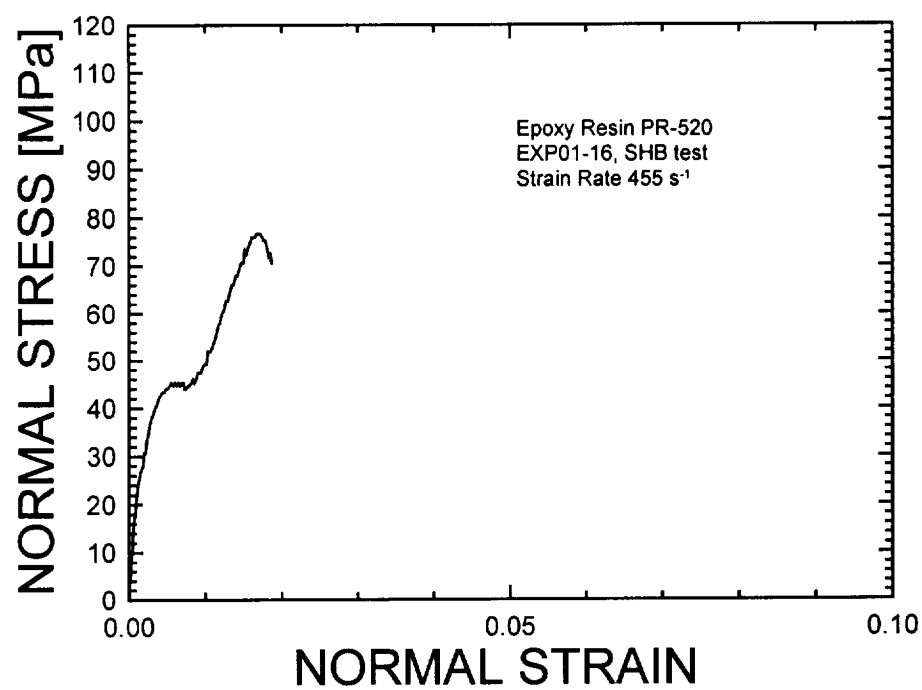


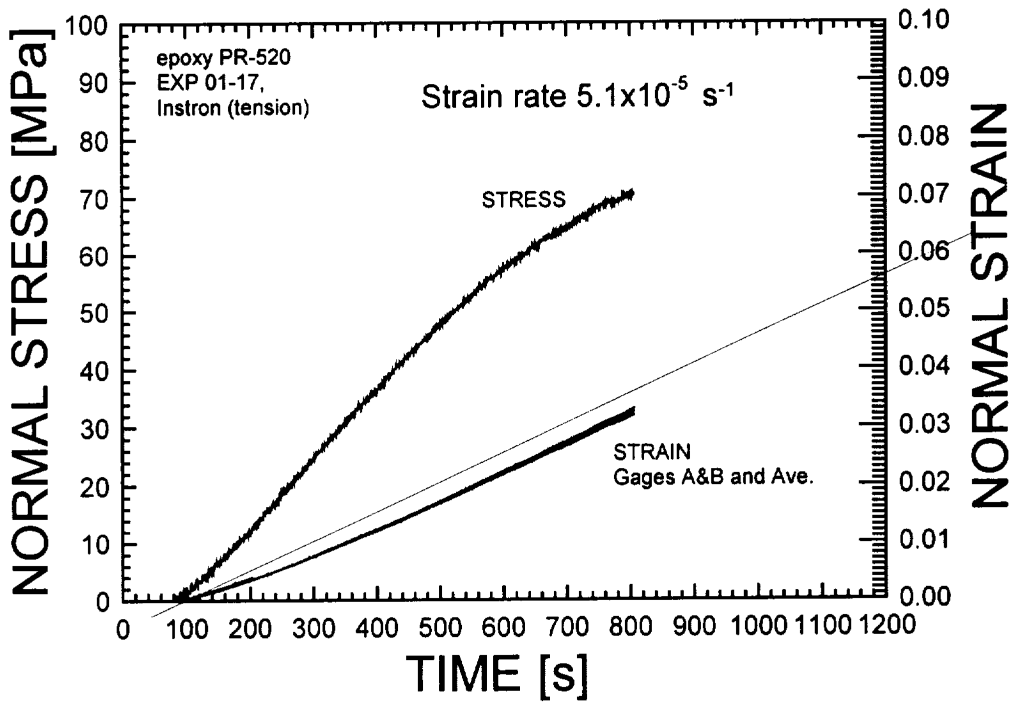
Resin E-862
EXP 01-15
Tensile split Hopkinson bar
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
STRESS
STRAIN, GAGE A,
Gage B, Ave.
STRAIN RATE 455 s-1
(SLOPE OF STRAIN-
TIME CURVE)
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

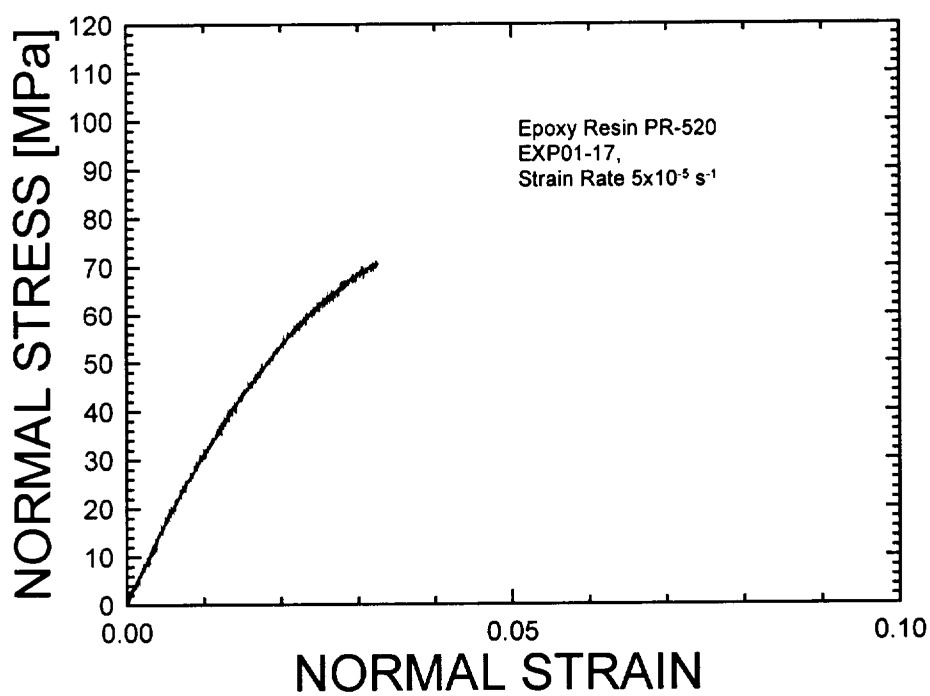


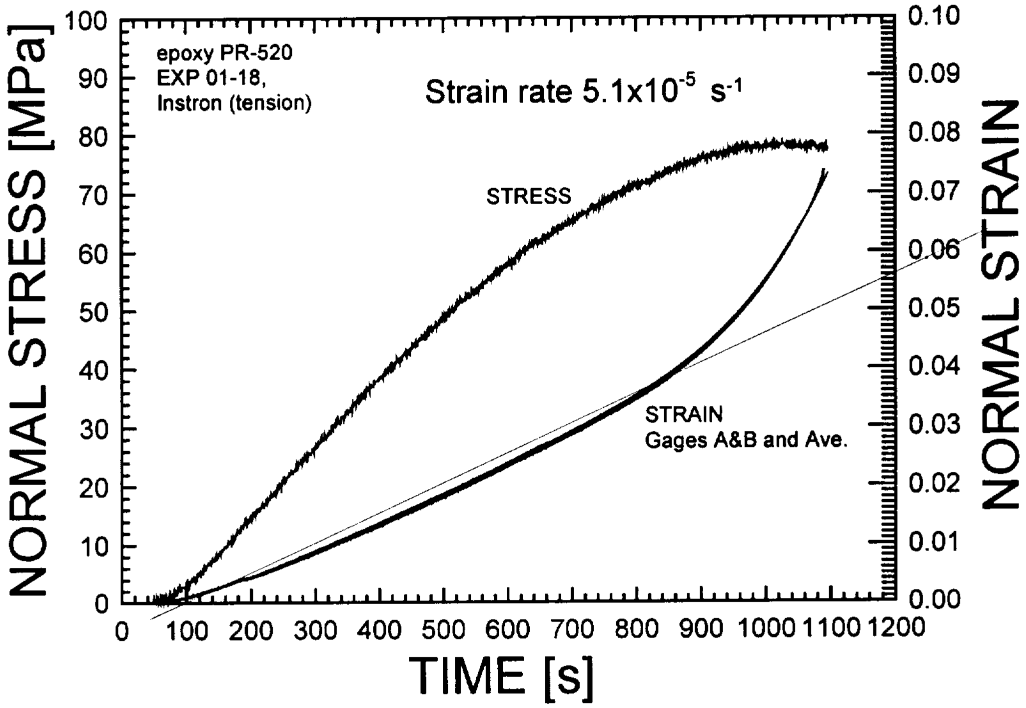
Epoxy Resin E-862
EXP01-15, SHB test
Strain Rate 455 s-1
NORMAL STRESS [MPa]
NORMAL STRAIN

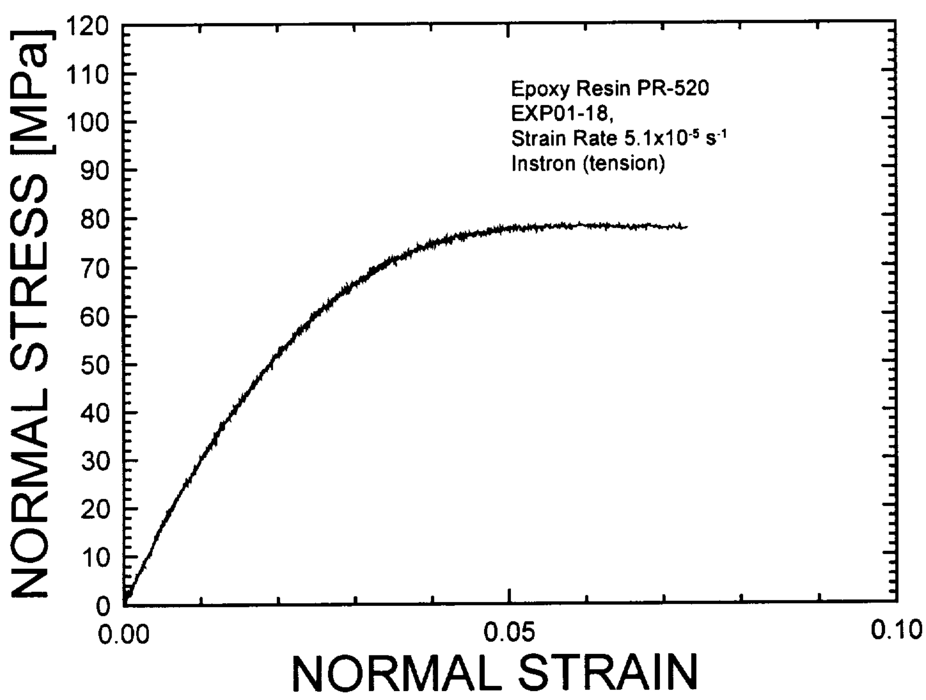

NORMAL STRESS [MPa]
Resin PR-520
EXP 01-16
Tensile split Hopkinson bar
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
STRESS
STRAIN, GAGE A,
Gage B, Ave.
STRAIN RATE 445 s-1
(SLOPE OF STRAIN-
TIME CURVE)
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

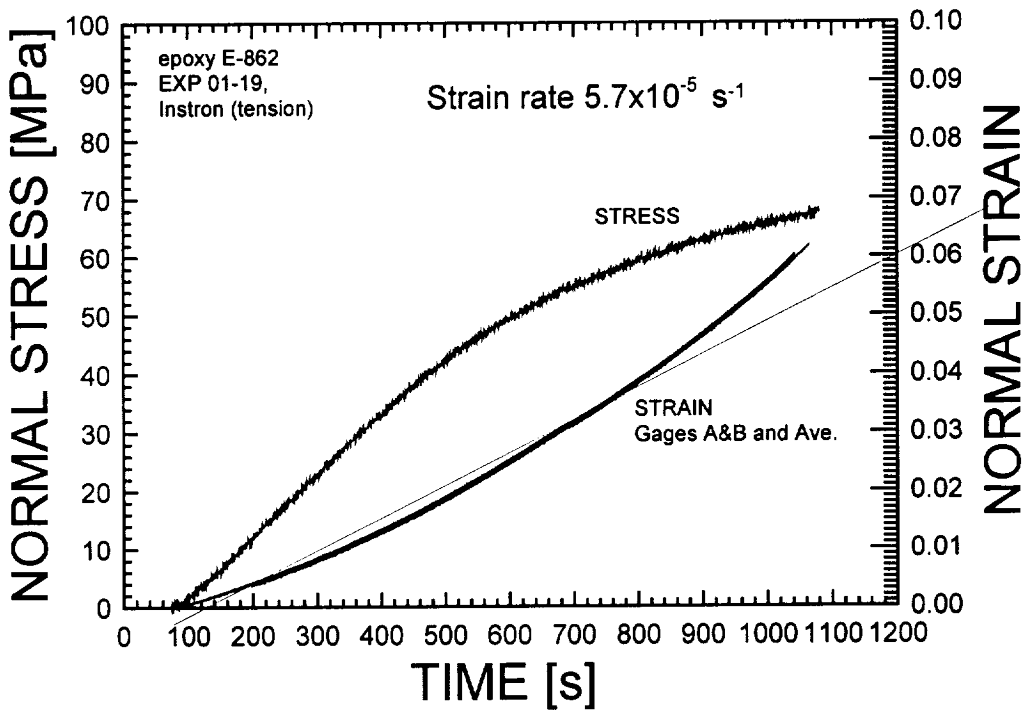

NORMAL STRESS [MPa]
Epoxy Resin PR-520
EXP01-16, SHB test
Strain Rate 455 s-1
NORMAL STRAIN

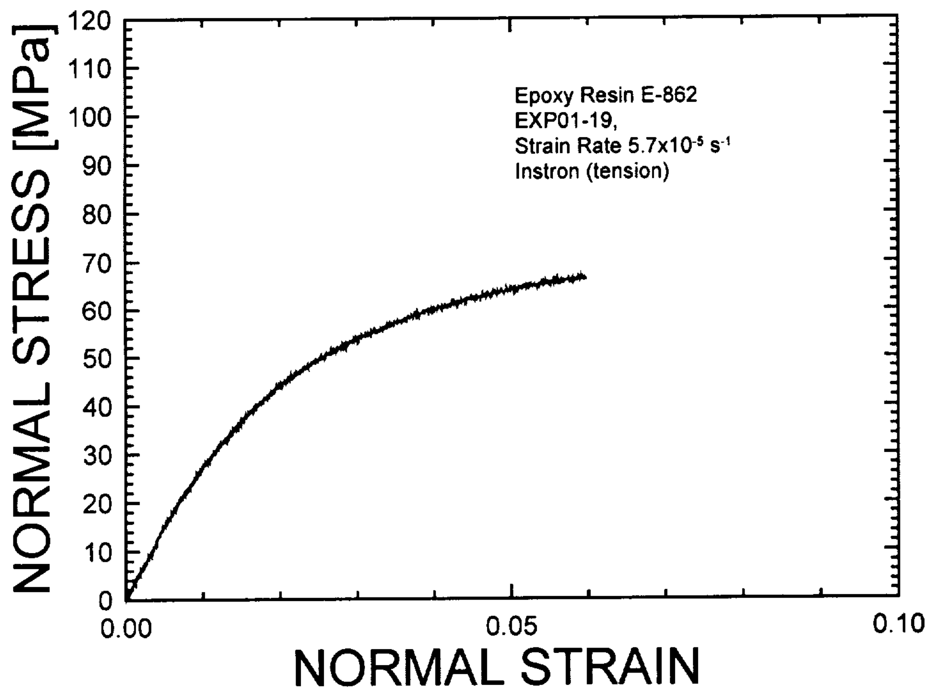

epoxy PR-520
EXP 01-17,
Instron (tension)
Strain rate 5.1x10^{-5} s^{-1}
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]

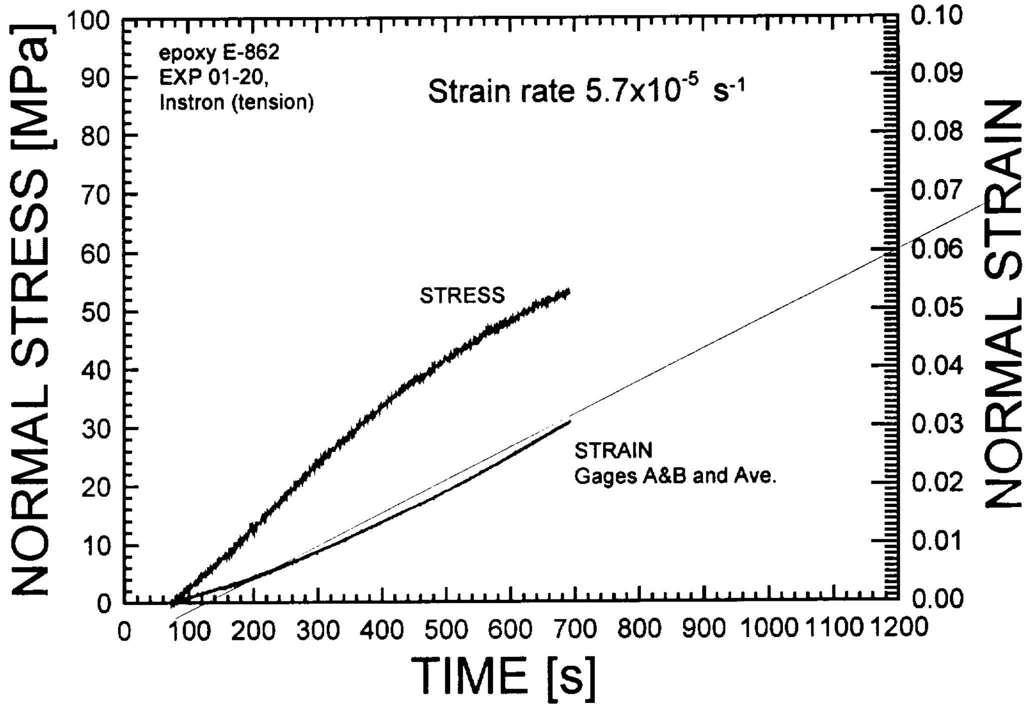

Epoxy Resin PR-520
EXP01-17,
Strain Rate 5x10^{-5} s^{-1}
NORMAL STRESS [MPa]
NORMAL STRAIN

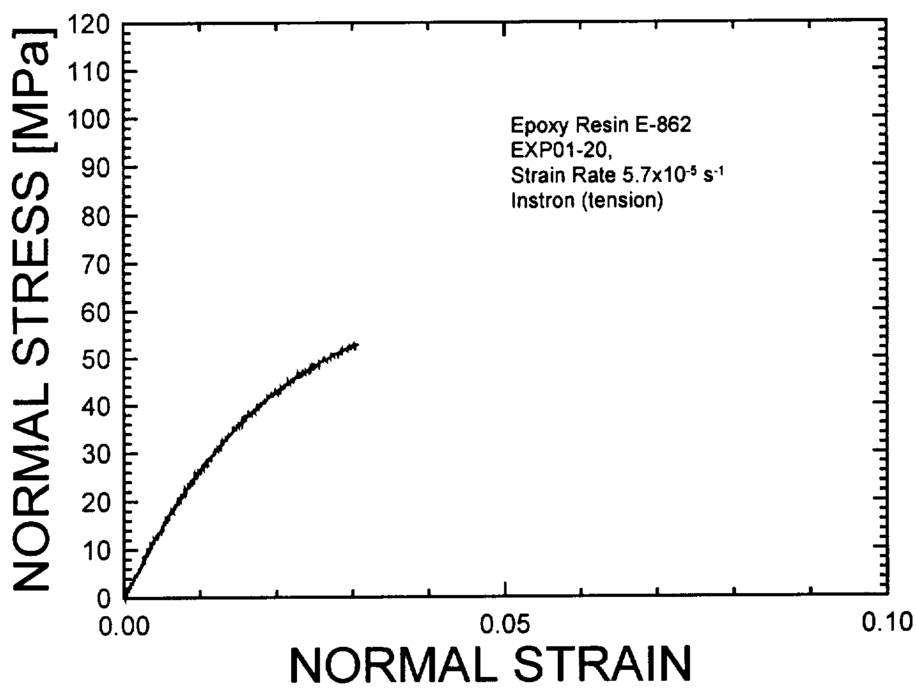

epoxy PR-520
EXP 01-18,
Instron (tension)
Strain rate 5.1x10^{-5} s^{-1}
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]

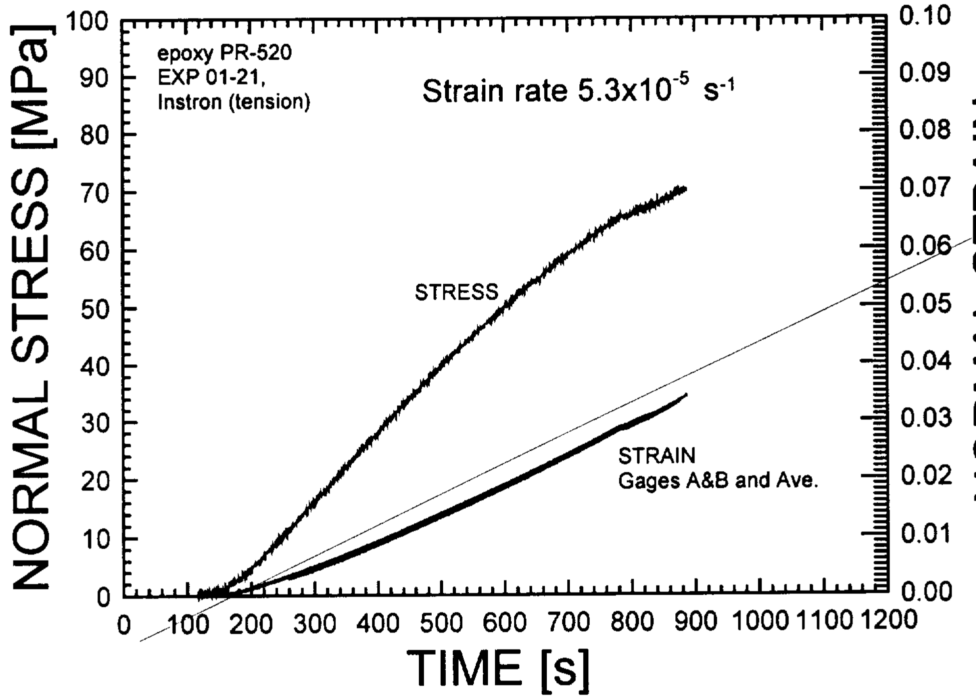

Epoxy Resin PR-520
EXP01-18,
Strain Rate 5.1x10^{-5} s^{-1}
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN

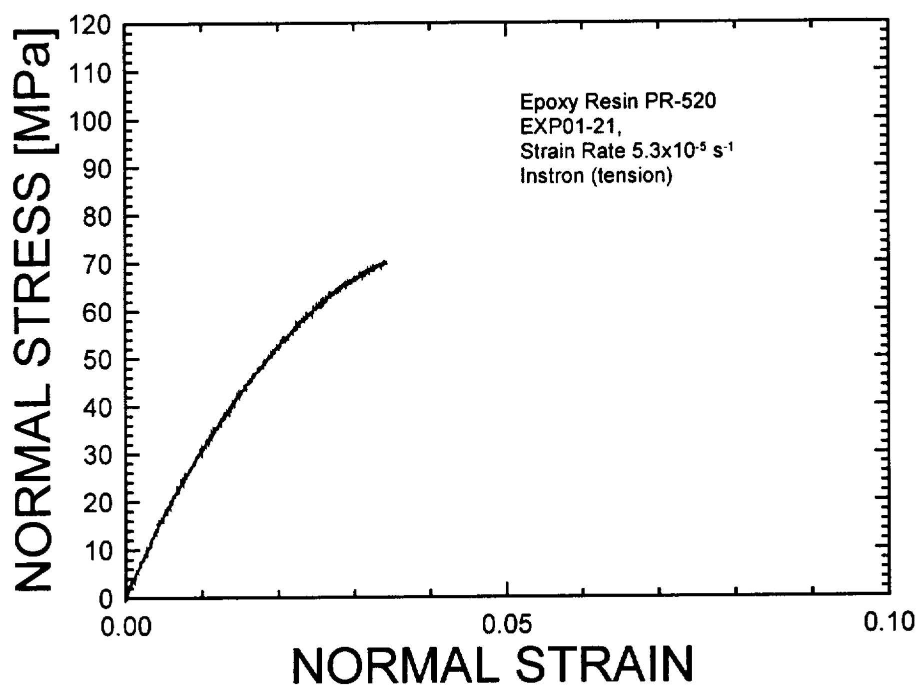

epoxy E-862
EXP 01-19,
Instron (tension)
Strain rate 5.7x10-5 s-1
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]

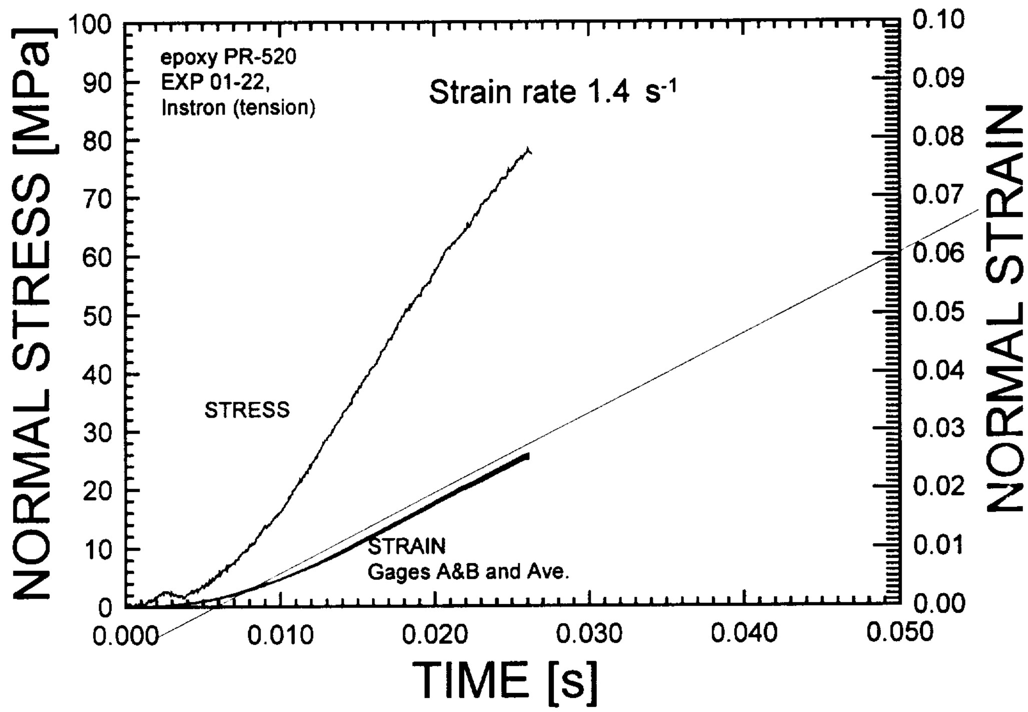

Epoxy Resin E-862
EXP01-19,
Strain Rate 5.7x10-5 s-1
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN


epoxy E-862
EXP 01-20,
Instron (tension)
Strain rate 5.7x10^-5 s^-1
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]
0 100 200 300 400 500 600 700 800 900 1000 1100 1200
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

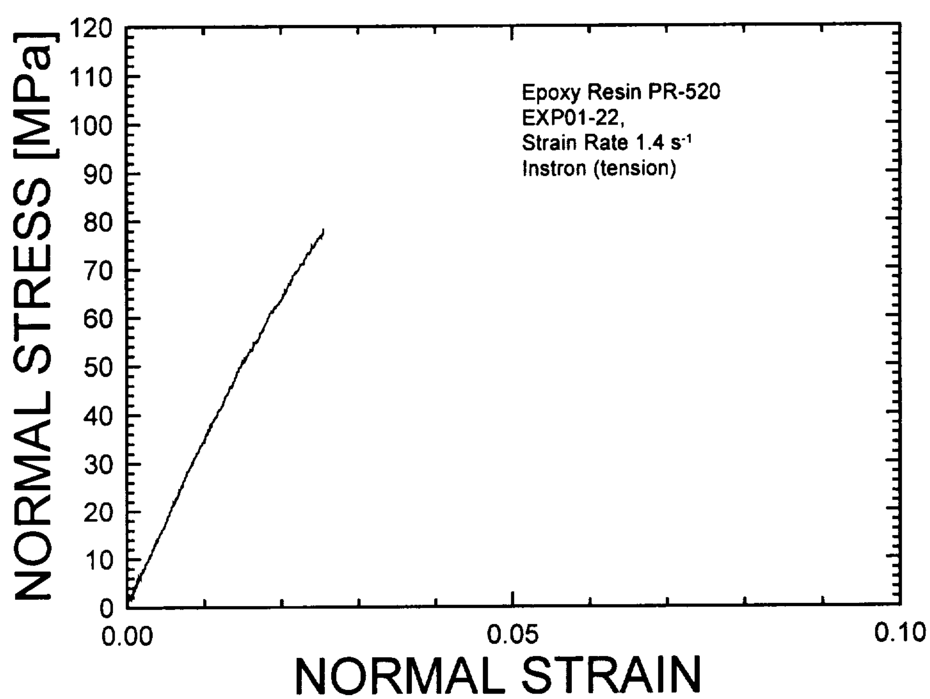

Epoxy Resin E-862
EXP01-20,
Strain Rate 5.7x10^-5 s^-1
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN
0 10 20 30 40 50 60 70 80 90 100 110 120
0.00 0.05 0.10


epoxy PR-520
EXP 01-21,
Instron (tension)
Strain rate 5.3x10^{-5} s^{-1}
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]

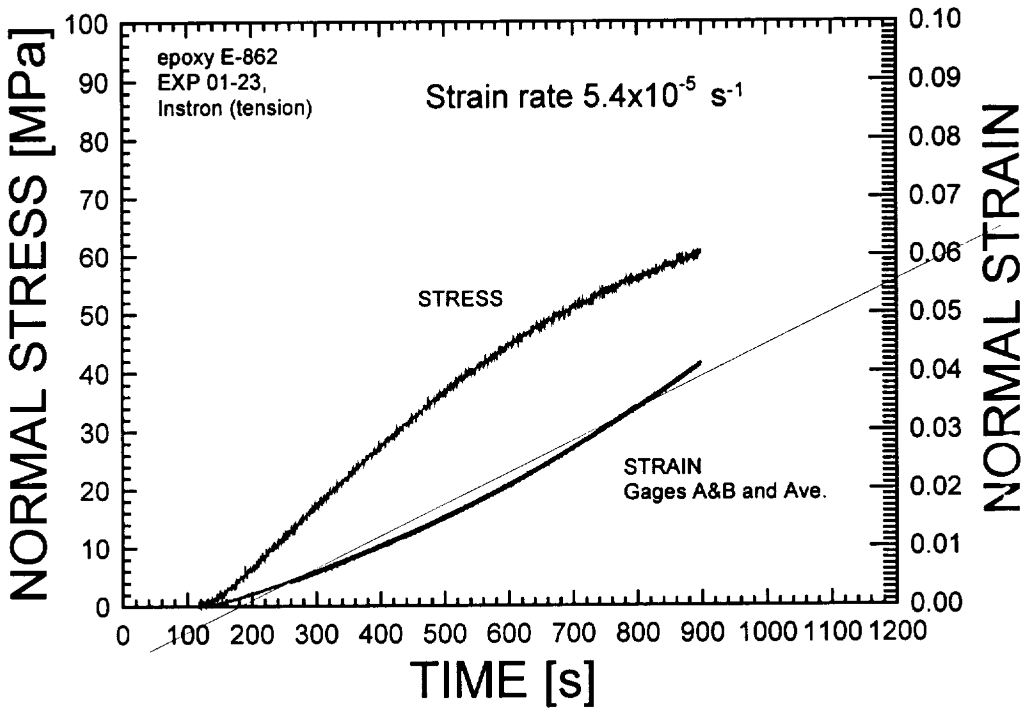

Epoxy Resin PR-520
EXP01-21,
Strain Rate 5.3x10^{-5} s^{-1}
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN

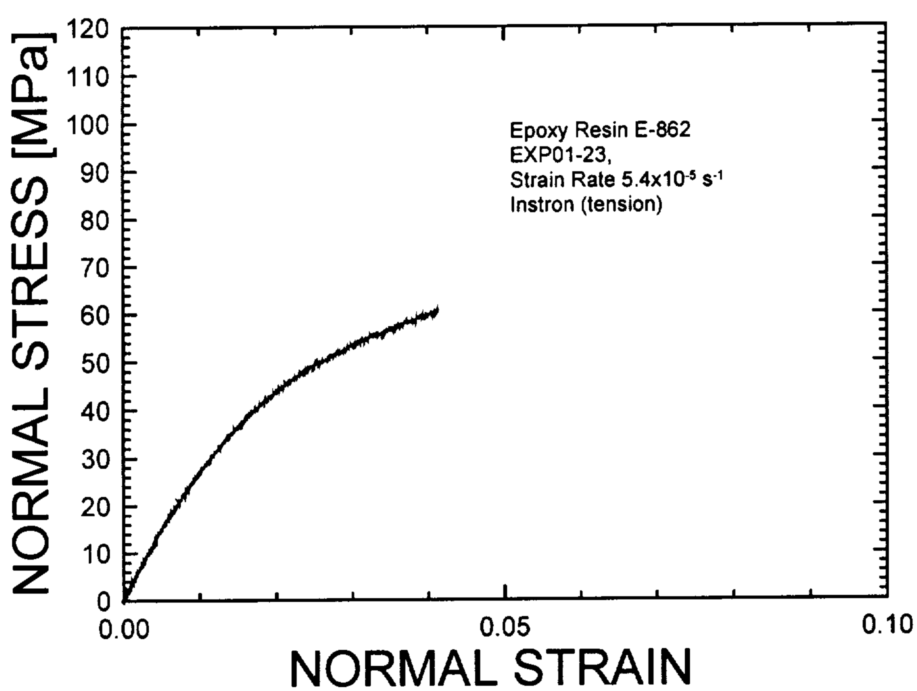


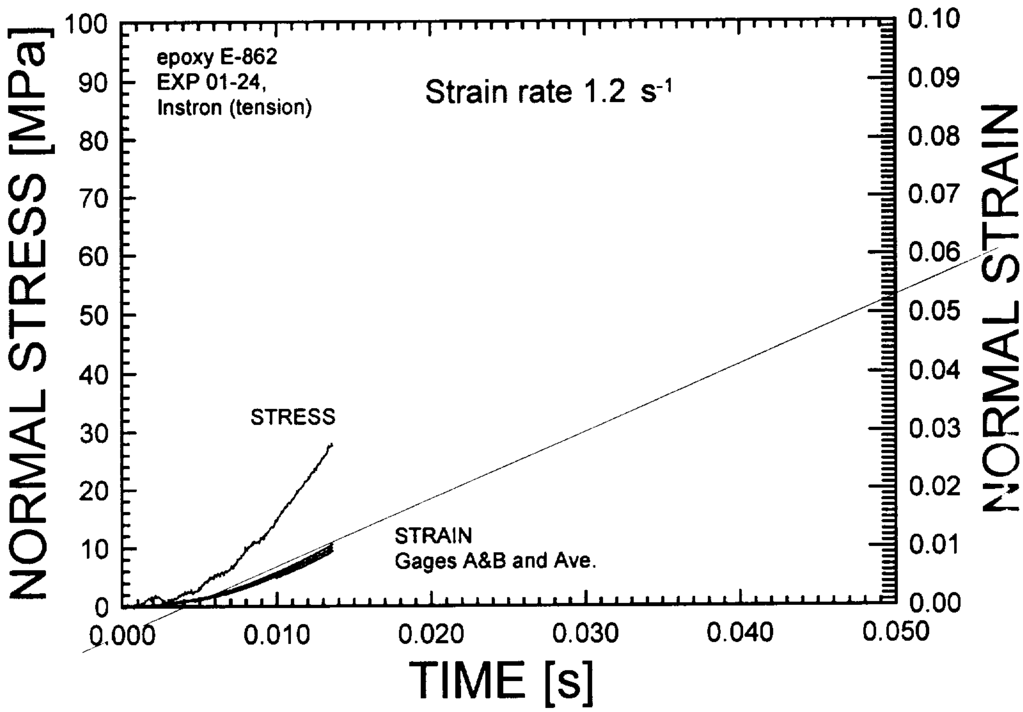
epoxy PR-520
EXP 01-22,
Instron (tension)
Strain rate 1.4 s^{-1}
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]
0
10
20
30
40
50
60
70
80
90
100
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.000
0.010
0.020
0.030
0.040
0.050

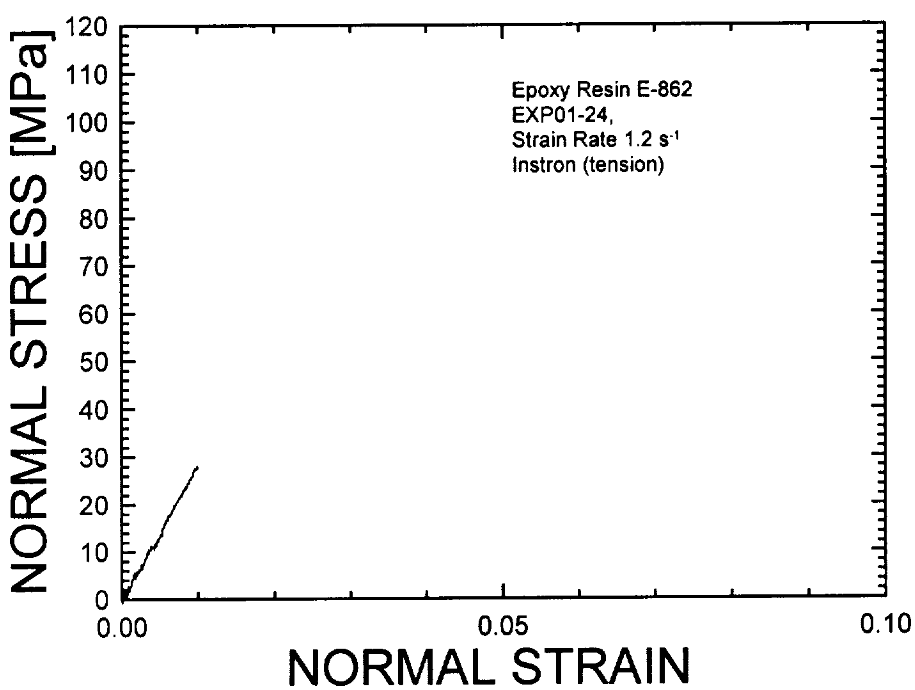


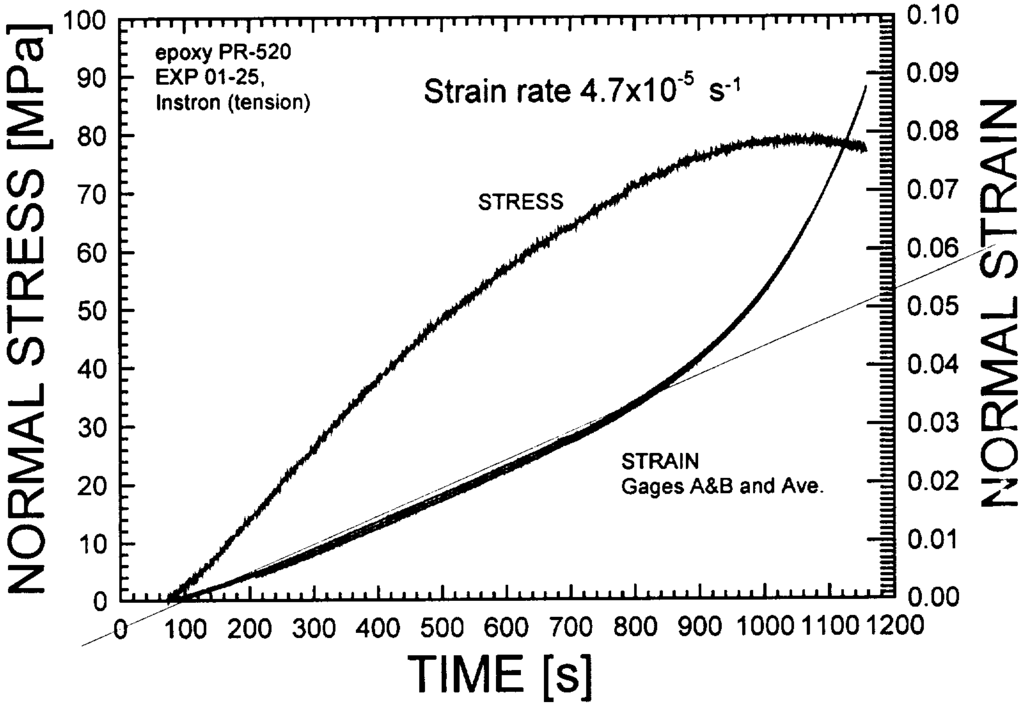
Epoxy Resin PR-520
EXP01-22,
Strain Rate 1.4 s^{-1}
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.05
0.10


epoxy E-862
EXP 01-23,
Instron (tension)
Strain rate 5.4x10^{-5} s^{-1}
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]

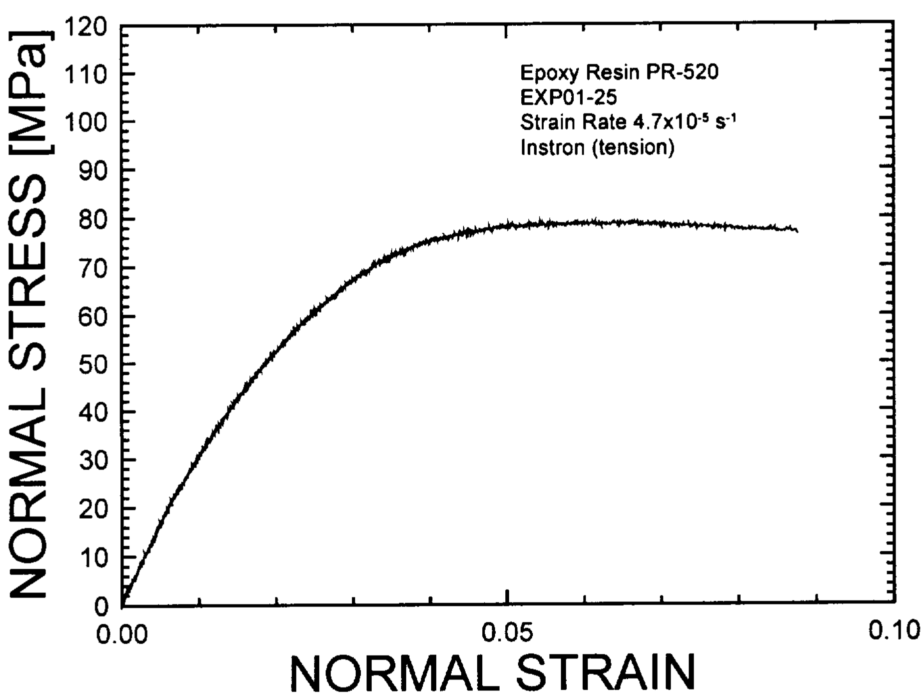

Epoxy Resin E-862
EXP01-23,
Strain Rate 5.4x10^{-5} s^{-1}
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN


epoxy E-862
EXP 01-24,
Instron (tension)
Strain rate 1.2 s-1
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]
0.000
0.010
0.020
0.030
0.040
0.050
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0
10
20
30
40
50
60
70
80
90
100

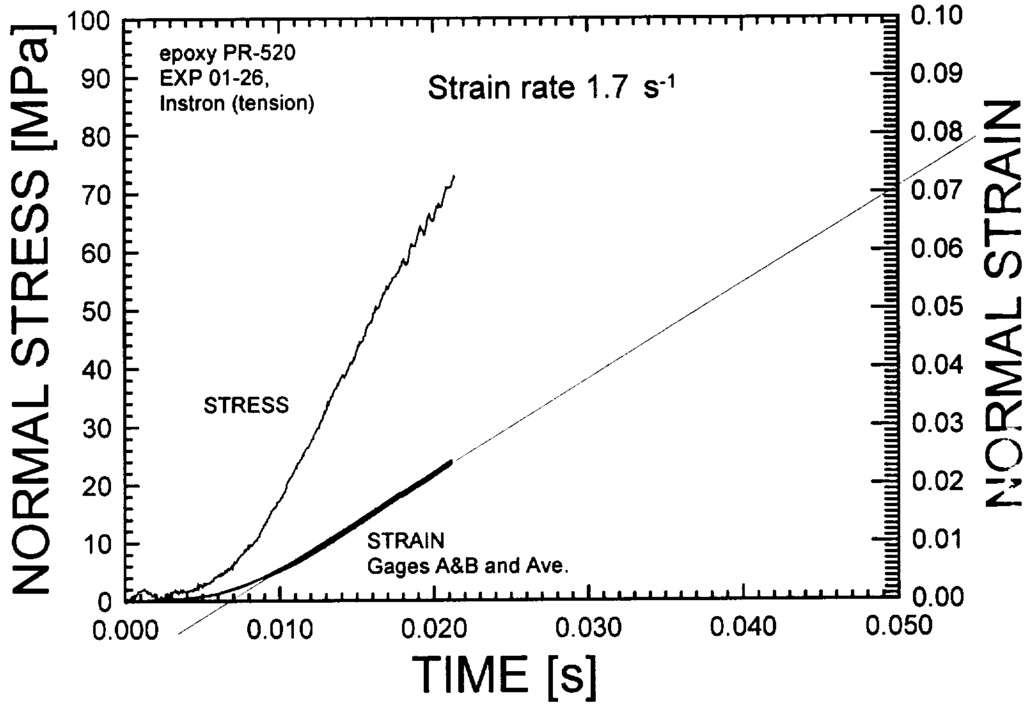

Epoxy Resin E-862
EXP01-24,
Strain Rate 1.2 s-1
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN
0.00
0.05
0.10
0
10
20
30
40
50
60
70
80
90
100
110
120

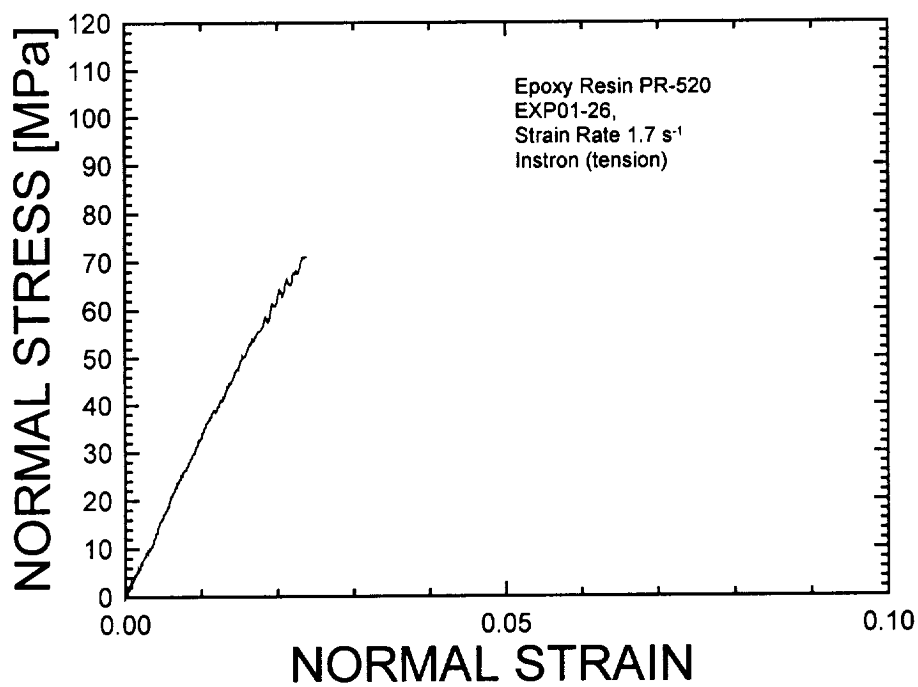


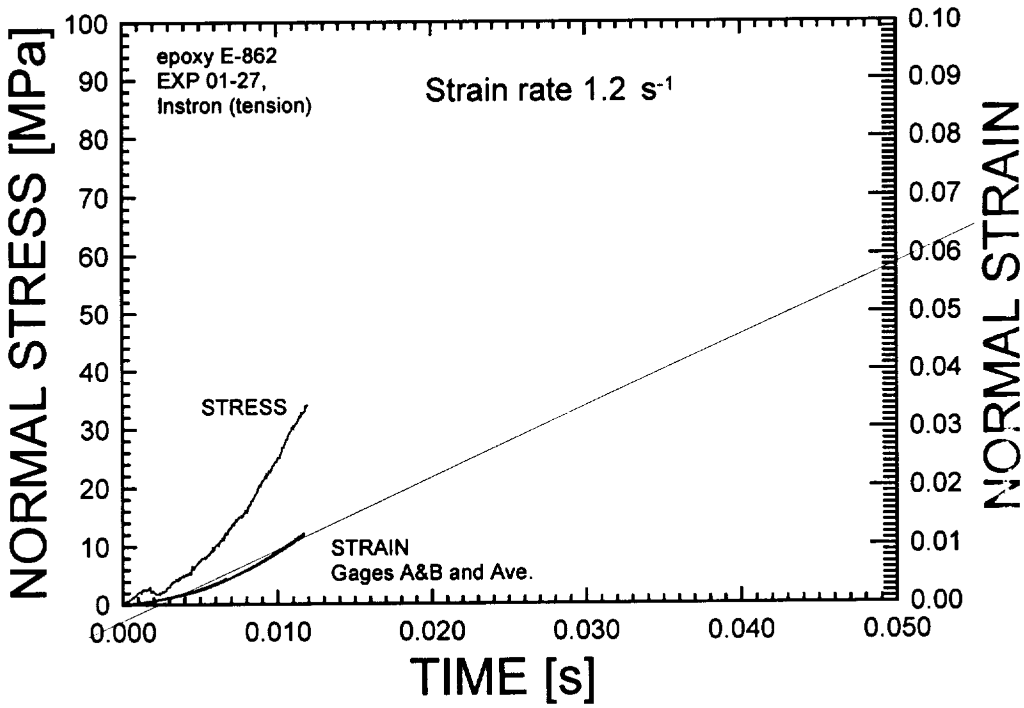
epoxy PR-520
EXP 01-25,
Instron (tension)
Strain rate 4.7x10-5 s-1
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]

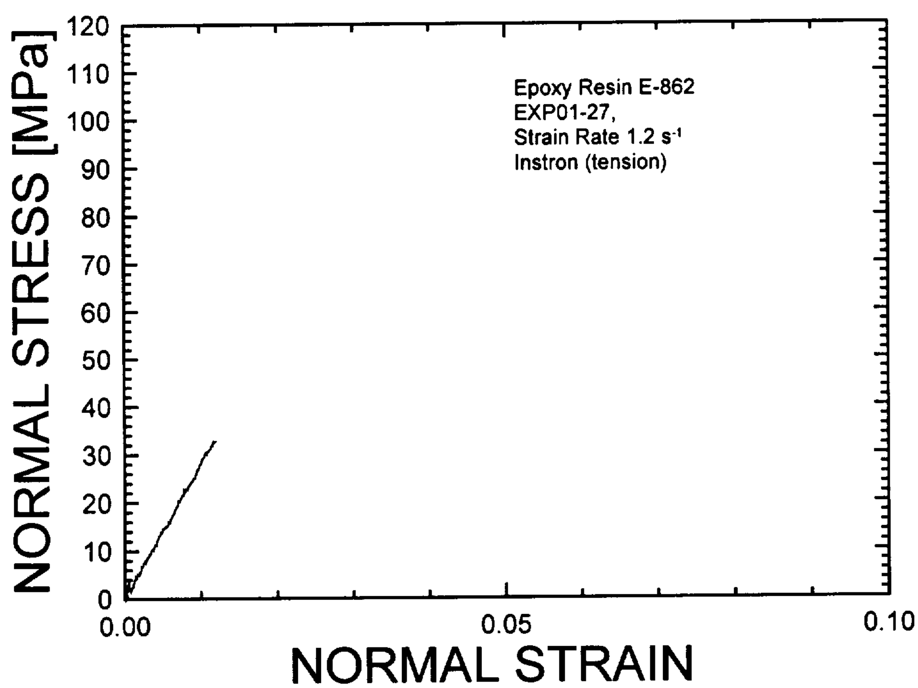


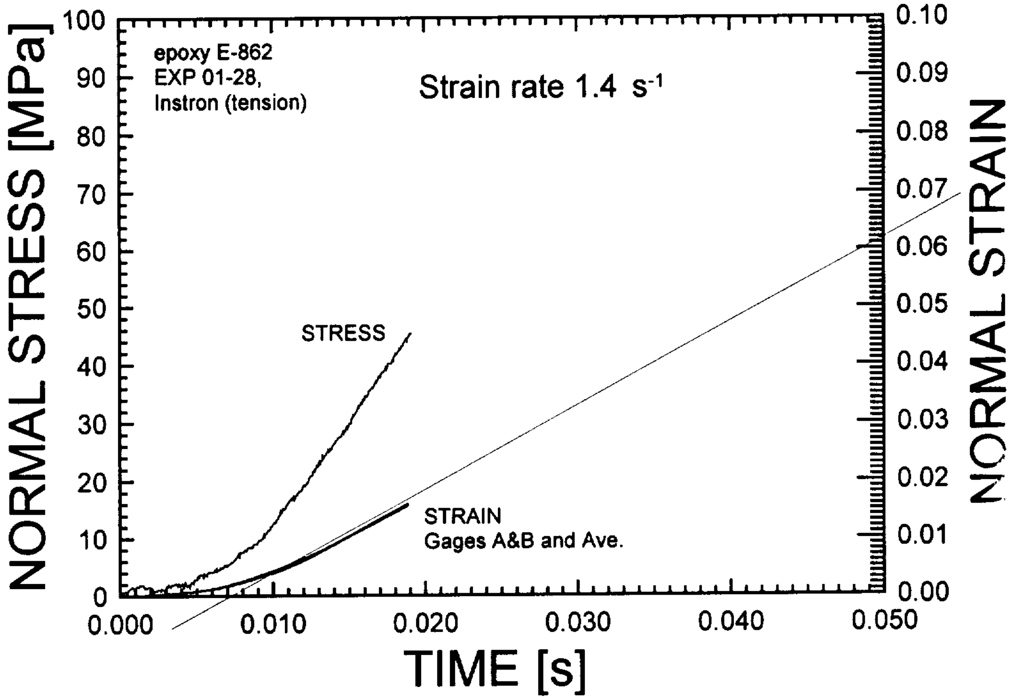
Epoxy Resin PR-520
EXP01-25
Strain Rate 4.7x10-5 s-1
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN

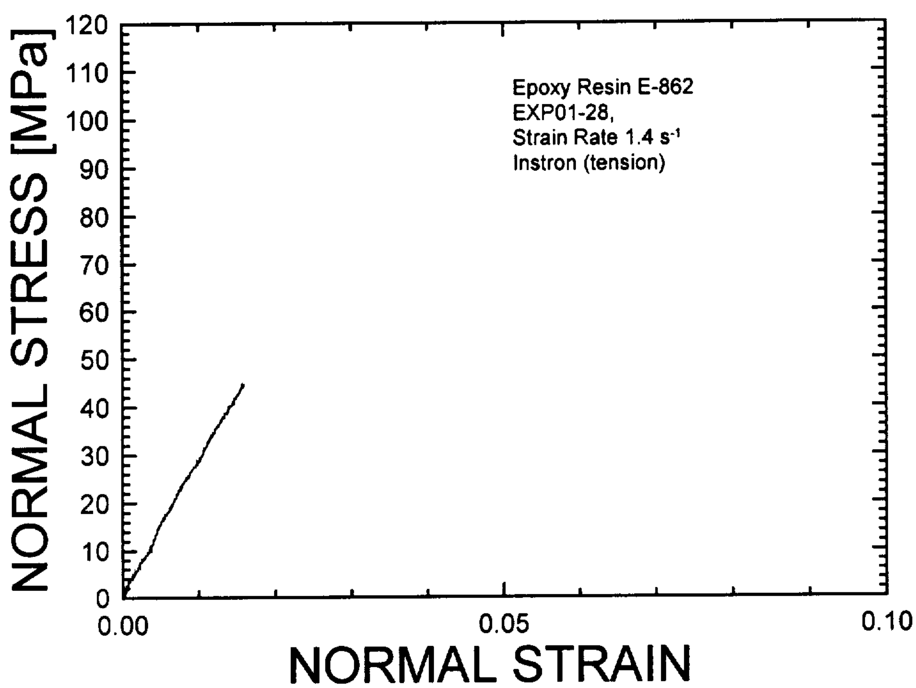

NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]
epoxy PR-520
EXP 01-26,
Instron (tension)
Strain rate 1.7 s-1
STRESS
STRAIN
Gages A&B and Ave.
0
10
20
30
40
50
60
70
80
90
100
0.00
0.01
0.02
0.03
0.04
0.05
0.06
0.07
0.08
0.09
0.10
0.000
0.010
0.020
0.030
0.040
0.050


NORMAL STRESS [MPa]
NORMAL STRAIN
Epoxy Resin PR-520
EXP01-26,
Strain Rate 1.7 s-1
Instron (tension)
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.05
0.10


epoxy E-862
EXP 01-27,
Instron (tension)
Strain rate 1.2 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
0.000
0.010
0.020
0.030
0.040
0.050


Epoxy Resin E-862
EXP01-27,
Strain Rate 1.2 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 E-862
EXP 01-28,
Instron (tension)
Strain rate 1.4 s^{-1}
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]
100
90
80
70
60
50
40
30
20
10
0
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
0.000
0.010
0.020
0.030
0.040
0.050


Epoxy Resin E-862
EXP01-28,
Strain Rate 1.4 s^{-1}
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN
120
110
100
90
80
70
60
50
40
30
20
10
0
0.00
0.05
0.10