Study of High Strain Rate Response of Composites

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1. BACKGROUND

The objective of the research was to continue the experimental study of the effect of strain rate on mechanical response (deformation and failure) of epoxy resins and carbon fibers/epoxy matrix composites, and to initiate a study of the effects of temperature by developing an elevated temperature test. The experimental data provide the information needed for NASA scientists for the development of a nonlinear, rate dependent deformation and strength models for composites that can subsequently be used in design. This year effort was directed into testing the epoxy resin. Three types of epoxy resins were tested in tension and shear at various strain rates that ranges from 5×10^{-5}, to 1000 s^{-1}. Pilot shear experiments were done at high strain rate and an elevated temperature of 80^{o}C. The results show that all, the strain rate, the mode of loading, and temperature significantly affect the response of epoxy.

2. EXPERIMENTAL SETUP

Tension and torsion tests were conducted at strain rates of approximately 5×10^{-5}, 2, and 400-1000 s^{-1}. The low and medium strain rate tests (5×10^{-5} and 2 s^{-1}) were done using a hydraulic Instron machine, and the high strain rate tests were done using a tensile or a torsional Split Hopkinson Bar apparatus (SHB). The Instron machine is bi-axial (tension/torsion) and the loading can be tensile, torsion, or a combination of the two. In tests with the Instron machine, the load cell of the machine measures the force or the torque. In the tensile tests strain is determined from displacement of the machine's head and in some of the tests the strain is also measured with strain gages that are cemented to the specimen. In such tests two strain gages (Measurements Group EA-06-125BZ-350 or EA-06-031DE-350) are 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 the rotation of the machine's head and 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 SHB configuration (and a torque in the torsional SHB configuration) in the end section of the incident bar, and then releasing the clamp. Upon loading, part of the loading wave reflects back to the incident bar, and part propagates on through the specimen to the transmitter bar. The incident and transmitter bars remain elastic throughout the test. In the standard SHB 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 test (and pure shear in the torsion test). In the present research the tensile split Hopkinson bar technique was also modified such that strain was also 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

Tensile tests

Several types of specimens were used in the tensile tests. Most tests were done with specimens having one of two types of dog-bone geometry, shown in Figs. 2(*a*) and 2(*b*). The specimen in Fig. 2(*a*) has a uniform thickness of 0.28 in., while in Fig. 2(*b*) the thickness of the specimen in the gage section is reduced to 0.11 in. In some of the tests with the split Hopkinson bar apparatus, a very short cylindrical specimen was used, Fig. 4(*a*). The specimen coupons were glued into two cylindrical adapters, shown in Figs 3(*a*), and 3(*b*) for the dog-bone specimens and in Fig. 4(*b*) for the cylindrical specimens. 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.

Torsion tests

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. 5. 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. To examine the effect of thickness of the specimen on the results, specimens with wall thickness of 0.025 and 0.050 in. were used.

4. RESULTS

Tests were conducted with specimens made of E-862, PR-520 and 977-2 resin materials. The E-862 and PR-520 resins were tested in tension and in shear at strain rates of approximately 5×10^{-5}, 2, and 400-1000 s^{-1}. The 977-2 resin was tested only in shear, since tensile tests of this material have been done before.

The tests are summarized in tables 1 and 2. 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).

Stress-strain curves are presented in Figs. 6-19. For completeness, the figures include also results from experiments that were conducted in 2001 and were reported in the final report of Grant No. NAG3-2522, submitted to NASA in January 2002. Table 3 shows a summary of the tests done in 2001.

Details of the results are presented next in Sections 4.1-4.3 for the three materials tested. The preliminary results from the elevated temperature tests are presented in Section 4.4.

4.1 Results for E-862 Resin

The results for E-862 are shown in Figs. 6-11. Figure 6 shows the shear stress-strain curves from all the tests. The following observations can be made from Fig. 6:

- The material is very sensitive to the strain rate. Both, the stiffness (the slope of the curves in the initial part of the curves) and the maximum stress increase with strain rate. At the high strain rate tests the maximum stress is about twice the maximum stress in the low strain rate tests.

- The E-862 epoxy is relatively ductile in shear. The maximum strain, however, decreases with strain rate. At the low strain rate tests the maximum strain reaches 0.4. At high rate the maximum strain is about half of that.
- The results are independent of the wall-thickness of the specimen. Results from tests with wall thickness of about 0.025 and 0.049 in. are indistinguishable.

Figure 7 shows tensile stress-strain curves from all the tensile tests. The following observations can be made from Fig. 7:

- The E-862 epoxy is very sensitive to the strain rate. A stiffer material behavior is observed with increasing strain rate. The maximum stress is only a little bit higher at the medium and high strain rates than in the low strain rate tests. This is discussed further later.
- The material response in tension is much more brittle than in shear. In the low strain rate the maximum strain is 0.05, while in the medium and high strain rate tests it is 0.02-0.03.

The initial tests were conducted in 2001 with the dog-bone shaped specimens that are shown in Fig. 2(*a*). These specimens had a thickness of about 0.28 in. It was observed in these tests that in the low strain rate tests the specimens failed within the gage section. In the medium and high strain rate tests, however, it was noticed that the specimens fractured in the rounded end region, as shown in Fig. 20, or at the edge of the strain gage that was cemented to the specimen. To investigate the effect of the specimen geometry and the presence of the strain gages on the experimental results, additional tests were conducted. These tests were done with two new specimen geometries. One, identified in Table 1 as "reduced area" is shown in Fig. 2(*b*). This specimen is the same as the original one except that the thickness (perpendicular to the plane of the page) in the gage section is reduced to about 0.110 in. (The specimen has a dog-bone shape in two directions.) The objective was to increase the stress in the gage section and reduce the stress in the rounded ends such that the specimen will fail in the gage section and not in the rounded ends. In addition, smaller strain gages (Measurements Group EA06-031 DE-350) were used for measuring the strain. Several experiments were also done without using strain gages on the specimens at all. Figures 22 and 23 show photographs of "reduced area" specimens with large and small strain gages. In experiments without strain gages on the specimens, the strain in the medium strain rate tests was first determined from the displacement of the machine's head. Then a correction was introduced from comparing the strain determined from the head displacement and the strain measured by strain gages in experiments where strain gages were used. In high strain rate tests without strain gages on the specimen, the strain was determined first by the SHB analysis, and then corrected from comparing the strain from the SHB analysis with the strain measured by the strain gages in experiments where they were used. A "reduced area" specimen without a strain gage is shown in Fig. 24.

The second specimen that was introduced has a very short round gage section, as shown in Fig. 4. This specimen was used only in split Hopkinson bar tests in order to eliminate stress wave effects. These specimens are too small and short for cementing strain gages on them, and the stress-strain curves were determined with the standard SHB analysis. Photographs of the short round specimens are shown in Figs. 25 and 26. Ideally in the Split Hopkinson bar experiment, the specimen has to be short such that the time for the stress waves to traverse the gage section is short and the specimen is in a homogeneous state of stress. The dog-bone shaped specimen in Fig. 2 has a relative long gage length, and the stress measured contains large oscillations.

Figure 8 shows the results from all the medium strain rate tests. The slope of the stress-strain curves from all the tests are in excellent agreement. The differences between the tests are shown in Fig. 9 where results from tests with each type of specimens are presented separately. This figure shows that while the slope of the stress-strain diagram is about the same in all tests, the maximum stress was the lowest in the specimens with the standard area and large strain gages (plot (*a*)), and largest in the specimens with the reduced area and no strain gages (plot (*d*)). The max stress in tests with reduced area and strain gages is in between with higher stress in the experiment with the smaller strain gage.

Figures 10 and 11 show the results from the SHB tests. Figure 10 shows the stress-strain curves from all the tests together. Overall the results from all the tests are consistent. The differences in the results between tests with different specimens are shown in Fig. 11. In the first three tests with the standard cross-sectional area and the larger strain gages the maximum stress is about 40 MPa (plot (*a*)). When the cross sectional area is reduced, the max stress is about the same (40 MPa) when the large strain gages are used. The stress reaches about 75 MPa when small strain gages are used (plot (*b*)). Results from tests with specimens with reduced area and without strain gages shows much higher stresses (plot (*c*)). The stress-strain curve, however, has large oscillations due to the long length of the gage section. In the tests with the short cylindrical specimens (plot (*d*)) two of the specimens fracture at low stress at the rounded end of the specimens, see Fig. 26. In one test the stress reached about 85 MPa, which is the highest stress level from all the tests. As expected in the tests with the short cylindrical specimens there are no oscillations due to stress waves within the gage section.

4.2 Results for PR-520 Resin

The results for E-862 are shown in Figs. 12-19. Figure 12 shows the shear stress-strain curves from all the tests. The following observations can be made from Fig. 12:

- The material is very sensitive to the strain rate. Both, the slope of the curves in the initial part of the curves and the maximum stress increases with strain rate. At the high rate the maximum stress is nearly twice the maximum stress at the low rate.
- The PR-520 epoxy is relatively ductile. Unlike the E-862, the ductility is independent of the strain rates. At all of the strain rates the strain reached at least 0.4.
- At all strain rates the stress reaches a maximum at strain of about 0.15. Then there is a reduction of stress with increasing strain. The reduction is larger in the medium and high strain rate tests than in the low strain rate tests.
- The results are independent of the wall-thickness of the specimen. Results from tests with wall thickness of about 0.025 and 0.049 in. are indistinguishable.

Figure 13 shows tensile stress-strain curves from all the tests. The following observations can be made from Fig. 13:

- The material is very sensitive to the strain rate. A stiffer material behavior is observed with increasing strain rate. The slope of the curves in the initial part of the curves increases with strain rate. The maximum stress in the medium and high strain rates is about the same and is higher than in the low strain rate. This is discussed further later.

- The material response in tension in brittle compared with the response in shear. In the low strain rate, however, the response is much more ductile, than in the medium and high strain rate tests

Unlike the E-862 resin, the failure of the PR-520 resin appears not to be sensitive to hydrostatic component of the stress. The presence of strain gages on the specimen have a minor or no effect on the failure. The PR-520 was tested at medium and high strain rate by using dog-bone shaped specimens with standard and reduced cross sectional area with and without strain gages. In addition, high strain rate tests with the SHB technique were done with short cylindrical specimens.

Figure 14 shows the results from all the medium strain rate tests. The stress-strain curves from all the tests are in excellent agreement. The differences between the tests are shown in Fig. 15 where each type of test is presented separately. This figure shows that the maximum stress in tests with specimens with reduced area and small strain gages, and in specimens with reduced area and no strain gages is about the same (plots (*b*) and (*c*)). In specimens with the standard area and large strain gages (plot (*a*)) the stress is slightly lower.

Figures 16 and 17 show the results from the SHB tests. Figure 16 shows the stress-strain curves from all the tests together. Overall the results from all the tests are consistent. For clarity, the results from the different types of experiments are shown separately in Fig. 17. This figure shows that the results from all the tests with the dog-bone shaped specimens are very similar. All have the oscillations in the stress due to the long gage length. The maximum stress in the test in which strain gages were not placed on the specimen is slightly higher than the maximum stress when strain gages were used. In tests with the short cylindrical specimens there are no oscillations in the curves.

4.3 Results for 977-2 Resin

The 977-2 resin was only tested in shear. Results from tensile tests with this material were reported in previous reports. Stress strain curves from all the tests are shown in Fig. 18. As with the other resins, this material shows great strain rate sensitivity. Both, the initial stiffness and the maximum stress significantly increase with strain rate. Compared with the other two resins, the 977-2 appears to be much more brittle. The maximum shear strain at the low strain rate test is less than 0.3, and in the high strain rate test is about 0.1.

4.4 Results From Tests at an Elevated Temperature

Two shear high strain rate pilot experiments at elevated temperature of $80^{o}C$ were conducted. The specimens were heated by means of air guns. The results are shown in Fig. 19 where the stress-strain curves from the elevated temperature tests are presented together with the room temperature tests. The stress-strain curves in Fig. 19 show that at $80^{o}C$ the stiffness and maximum stress are significantly reduced compared to their values at room temperature.

Table 1: Summary of 2002 Tests.

TEST NO.	SPECIMEN'S MATERIAL	STRAIN RATE (1/s)	COMMENTS
EXP02-1	Epoxy resin PR-520	1200	Torsion, wall 0.049 in.
EXP02-2	Epoxy resin PR-520	850	Torsion, wall 0.049 in.
EXP02-3	Epoxy resin E-862	----	Torsion, glue failed
EXP02-4	Epoxy resin E-862	900	Torsion, wall 0.0495 in.
EXP02-5	Epoxy resin PR-520	850	Torsion, wall 0.0495 in.
EXP02-6	Epoxy resin E-862	900	Torsion, wall 0.0495 in.
EXP02-7	Epoxy resin PR-520	650	Torsion, wall 0.025 in.
EXP02-8	Epoxy resin E-862	700	Torsion, wall 0.04925 in.
EXP02-9	Epoxy resin E-862	700	Torsion, wall 0.025 in.
EXP02-10	Epoxy resin E-862	450	Tension, reduced area
EXP02-11	Epoxy resin E-862	480	Tension, reduced area
EXP02-12	Epoxy resin E-862	510	Tension, reduced area
EXP02-13	Epoxy resin E-862	1.7	Tension, reduced area
EXP02-14	Epoxy resin E-862	1.7	Tension, reduced area
EXP02-15	Epoxy resin E-862	1.7	Tension, reduced area, no strain gages on specimen
EXP02-16	Epoxy resin E-862	1175 (SHB Eqs)	Tension, reduced area, no strain gages on specimen
EXP02-17	Epoxy resin PR-520	1.6	Tension, no strain gages on specimen
EXP02-18	Epoxy resin PR-520	1050 (SHB Eqs)	Tension, no strain gages on specimen
EXP02-19	Epoxy resin E-862	$1.3\text{x}10^{-4}$	Torsion, wall 0.025 in.
EXP02-20	Epoxy resin PR-520	$1.0\text{x}10^{-4}$	Torsion, wall 0.025 in.
EXP02-21	Epoxy resin E-862	$1.3\text{x}10^{-4}$	Torsion, wall 0.04925 in.
EXP02-22	Epoxy resin PR-520	$4.1\text{x}10^{-4}$	Torsion, wall 0.0495 in.
EXP02-23	Epoxy resin PR-520	$1.3\text{x}10^{-4}$	Torsion, wall 0.04925 in.
EXP02-24	Epoxy resin E-862	$1.3\text{x}10^{-4}$	Torsion, wall 0.025 in.
EXP02-25	Epoxy resin E-862	2.8	Torsion, wall 0.025 in.
EXP02-26	Epoxy resin PR-520	2.1	Torsion, Glue in gage section
EXP02-27	Epoxy resin E-862	2.0	Torsion, wall 0.025 in.
EXP02-28	Epoxy resin PR-520	2.1	Torsion, Glue in gage section
EXP02-29	Epoxy resin PR-520	2.6	Torsion, Glue in gage section
EXP02-30	Epoxy resin E-862	2.5	Torsion, wall 0.04975 in.
EXP02-31	Epoxy resin PR-520	2.6	Torsion, wall 0.0495 in.
EXP02-32	Epoxy resin PR-520	2.6	Torsion, wall 0.025 in.
EXP02-33	Epoxy resin PR-520	2.6	Torsion, wall 0.0495 in.
EXP02-34	Epoxy resin PR-520	1150 (SHB)	Tension, Reduced area, no strain gages
EXP02-35	Epoxy resin PR-520	525, 1000(SHB)	Tension, Reduced area, with strain gages
EXP02-36	Epoxy resin PR-520	470 (SHB)	Tension, short round specimen
EXP02-37	Epoxy resin E-862	390 (SHB)	Tension, short round specimen
EXP02-38	Epoxy resin E-862	1100 (SHB)	Tension, Reduced area, no strain gages

EXP02-39	Epoxy resin E-862	550, 1000(SHB)	Tension, Reduced area, with strain gages
EXP02-40	Epoxy resin 977-2	700	Torsion, wall 0.02325 in.
EXP02-41	Epoxy resin 977-2		Torsion, Glue in the gage section
EXP02-42	Epoxy resin PR-520	1.65	Tension, Reduced area, with strain gages
EXP02-43	Epoxy resin PR-520	1.65	Tension, Reduced area, with strain gages
EXP02-44	Epoxy resin E-862	1.65	Tension, Reduced area, with strain gages
EXP02-45	Epoxy resin E-862	1.65	Tension, Reduced area, no strain gages
EXP02-46	Epoxy resin PR-520	1.65	Tension, Reduced area, no strain gages
EXP02-47	Epoxy resin PR-520	870	Torsion, 80^{o}C, Connection broke before the specimen failed.
EXP02-48	Epoxy resin PR-520	700	Torsion, 80^{o}C.
EXP02-49	Epoxy resin E-862	570	Tension, short cylindrical specimen.
EXP02-50	Epoxy resin PR-520	510	Tension, short cylindrical specimen.

Table 2: Summary of 2003 (January – February) Tests.

TEST NO.	SPECIMEN'S MATERIAL	STRAIN RATE (1/s)	COMMENTS
EXP03-1	Epoxy resin PR-520	510	Tension, short round specimen
EXP03-2	Epoxy resin E-862	510	Tension, short round specimen
EXP03-3	Epoxy resin E-862	500	Tension, short round specimen
EXP03-4	Epoxy resin 977-2	1.3×10^{-4}	Torsion, wall 0.0275 in.
EXP03-5	Epoxy resin 977-2	2.8	Torsion, wall 0.02725 in.
EXP03-6	Epoxy resin 977-2	2.6	Torsion, wall 0.027 in.
EXP03-7	Epoxy resin 977-2	1.4×10^{-4}	Torsion, wall 0.028 in.
EXP03-8	Epoxy resin 977-2	750	Torsion, wall 0.027 in.
EXP03-9	Epoxy resin 977-2	700	Torsion, wall 0.02775 in.
EXP03-10	Epoxy resin 977-2	1.4×10^{-4}	Torsion, wall 0.027 in
EXP03-11	Epoxy resin 977-2	1.4×10^{-4}	Torsion, wall 0.0275 in
EXP03-12	Epoxy resin 977-2	2.6	Torsion, wall 0.02725 in

Table 3: Summary of 2001 Tests.

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	$1.3x10^{-4}$	Torsion
EXP01-6	Epoxy resin PR-520	$1.3x10^{-4}$	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	$5x10^{-5}$	Tension
EXP01-18	Epoxy resin PR-520	$5.1x10^{-5}$	Tension
EXP01-19	Epoxy resin E-862	$5.7x10^{-5}$	Tension
EXP01-20	Epoxy resin E-862	$5.7x10^{-5}$	Tension
EXP01-21	Epoxy resin PR-520	$5.3x10^{-5}$	Tension
EXP01-22	Epoxy resin PR-520	1.4	Tension
EXP01-23	Epoxy resin PR-862	$5.4x10^{-5}$	Tension
EXP01-24	Epoxy resin E-862	1.2	Tension
EXP01-25	Epoxy resin PR-520	$4.7x10^{-5}$	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

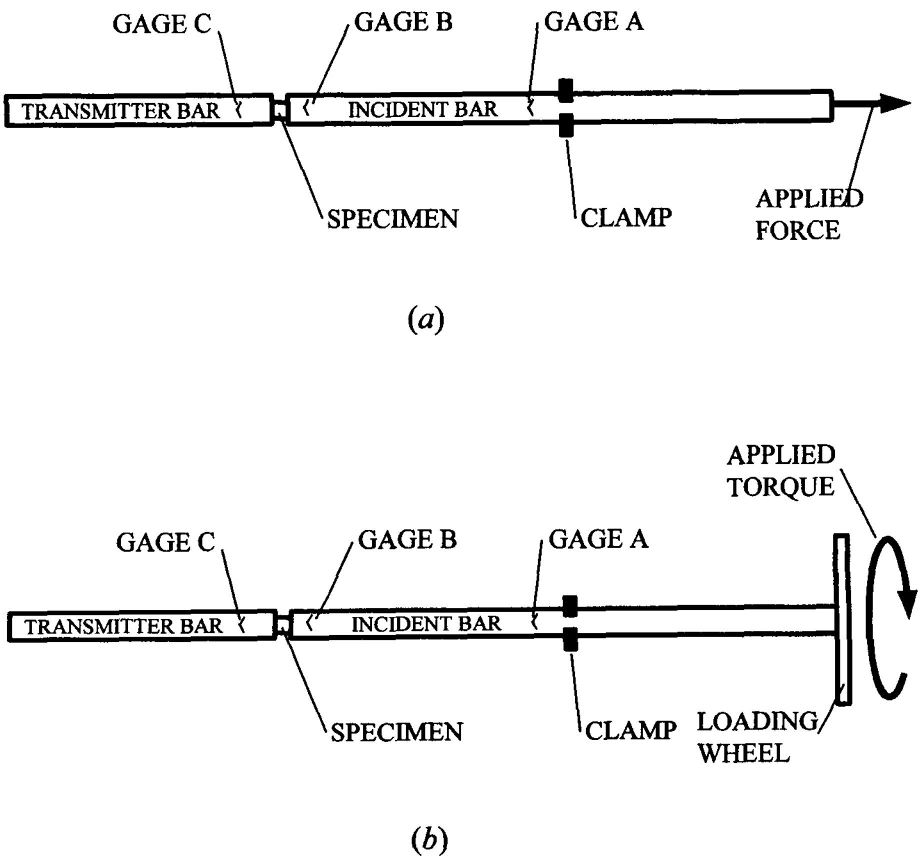


Fig. 1: Schematic of the tensile split Hopkinson bar apparatus, (*a*) tensile, (*b*) torsion.

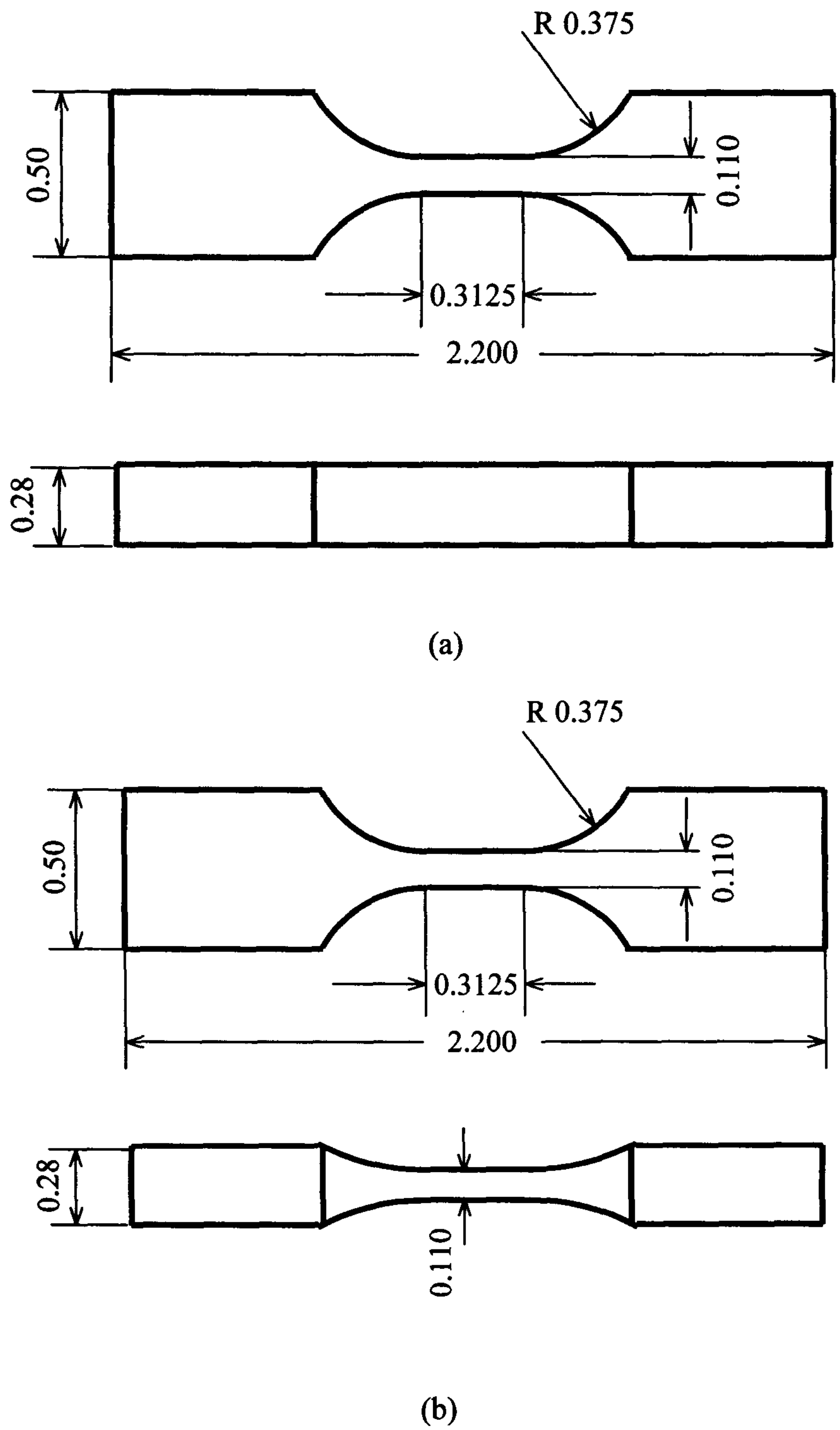
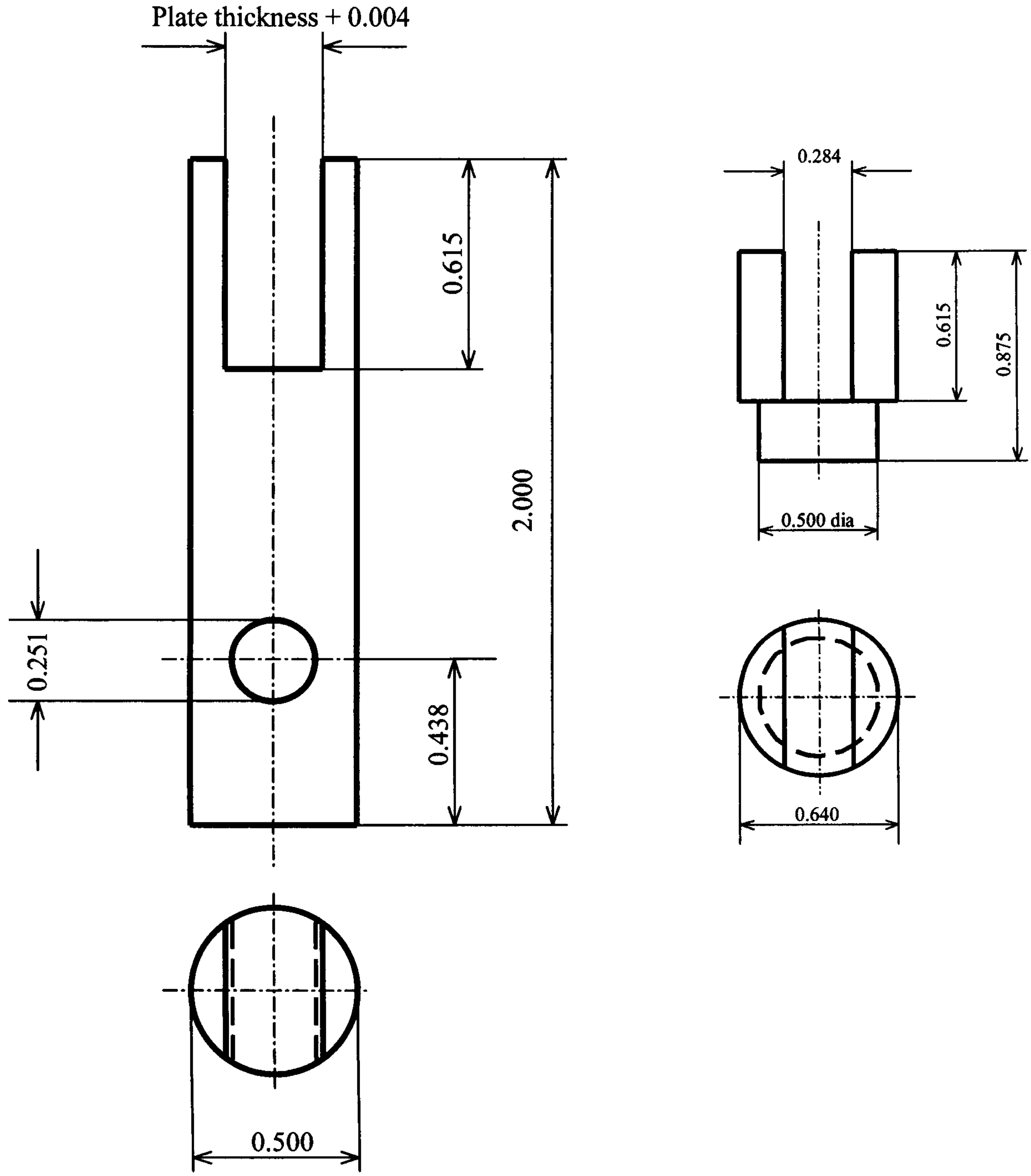


Fig. 2: Dog-bone shaped tensile test specimen and adapters, (*a*) specimen with uniform thickness, (*b*) specimen with reduced cross sectional area.



(*a*) (*b*)

Fig. 3: Adapters for the dog-bone shaped tensile test specimems, (*a*) adapter for the Instron machine, (*b*) adapter for the SHB apparatus.

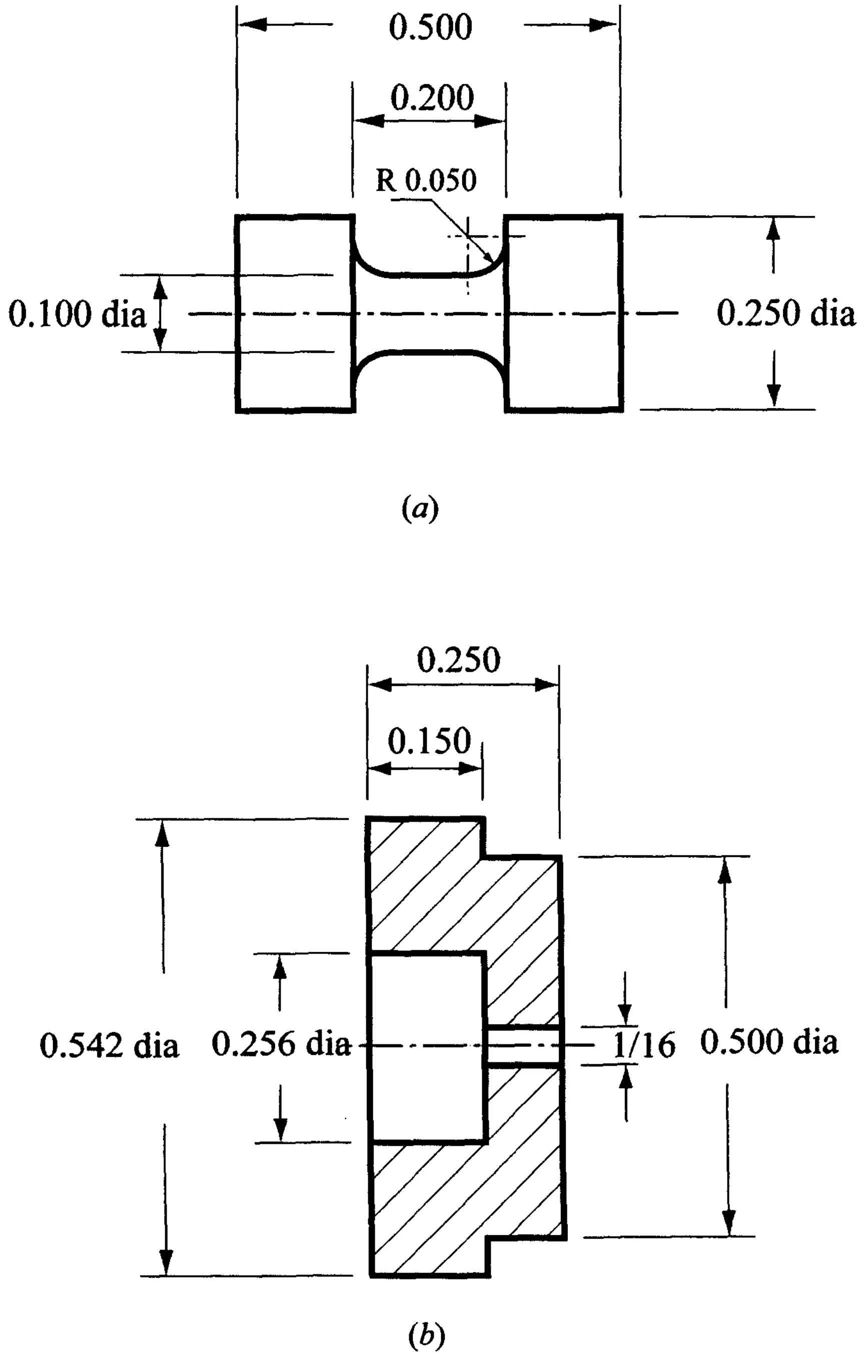
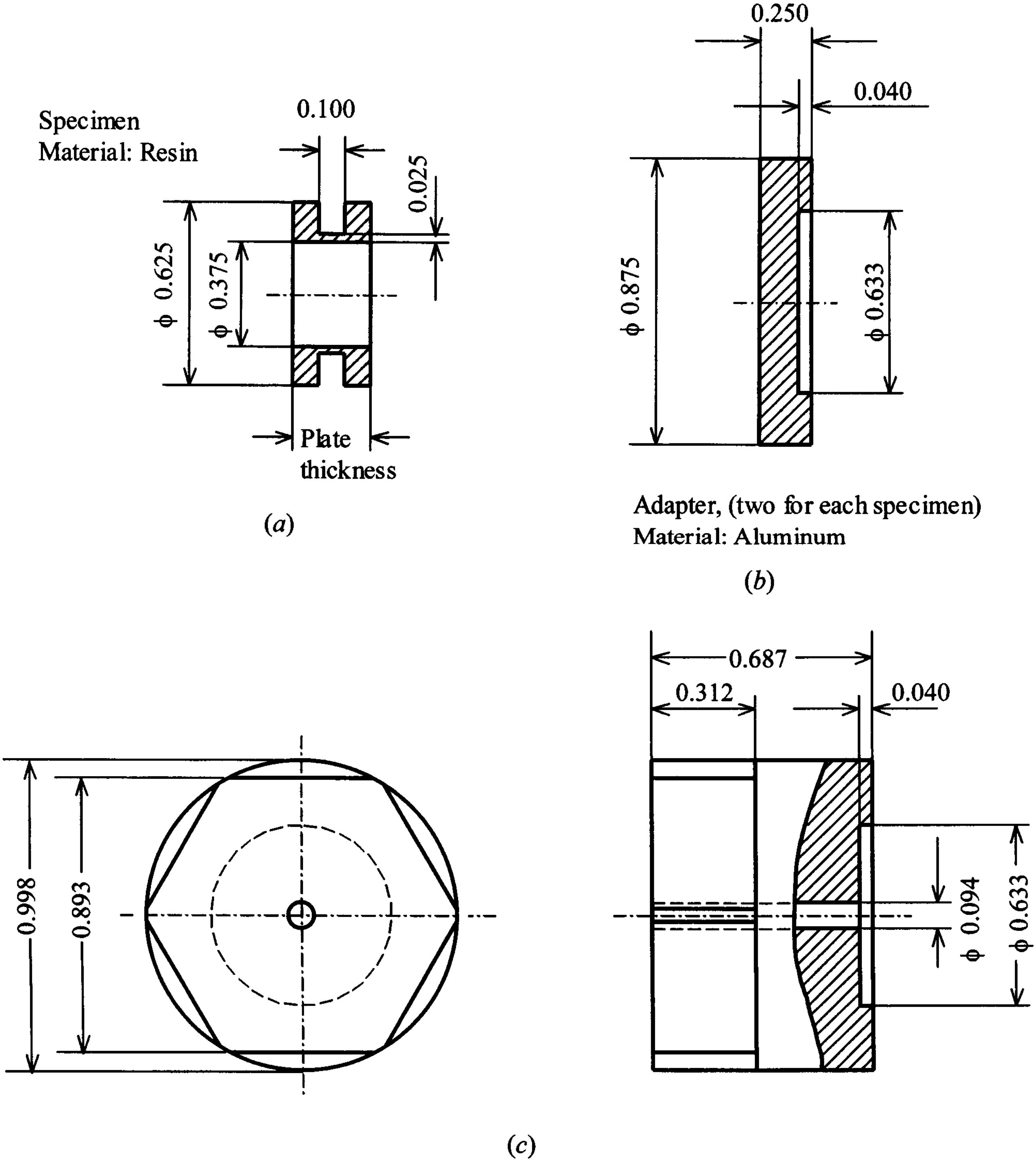


Fig. 4: Very short cylindrical specimen and adapter for the tensile SHB tests. (*a*) specimen, (*b*) adapter.



All dimensions are in inches.

Fig. 5: Torsion test specimen and adapters.
(*a*) specimen, (*b*) adapter for SHB test,
(*c*) adapter for test in the Instron machine.

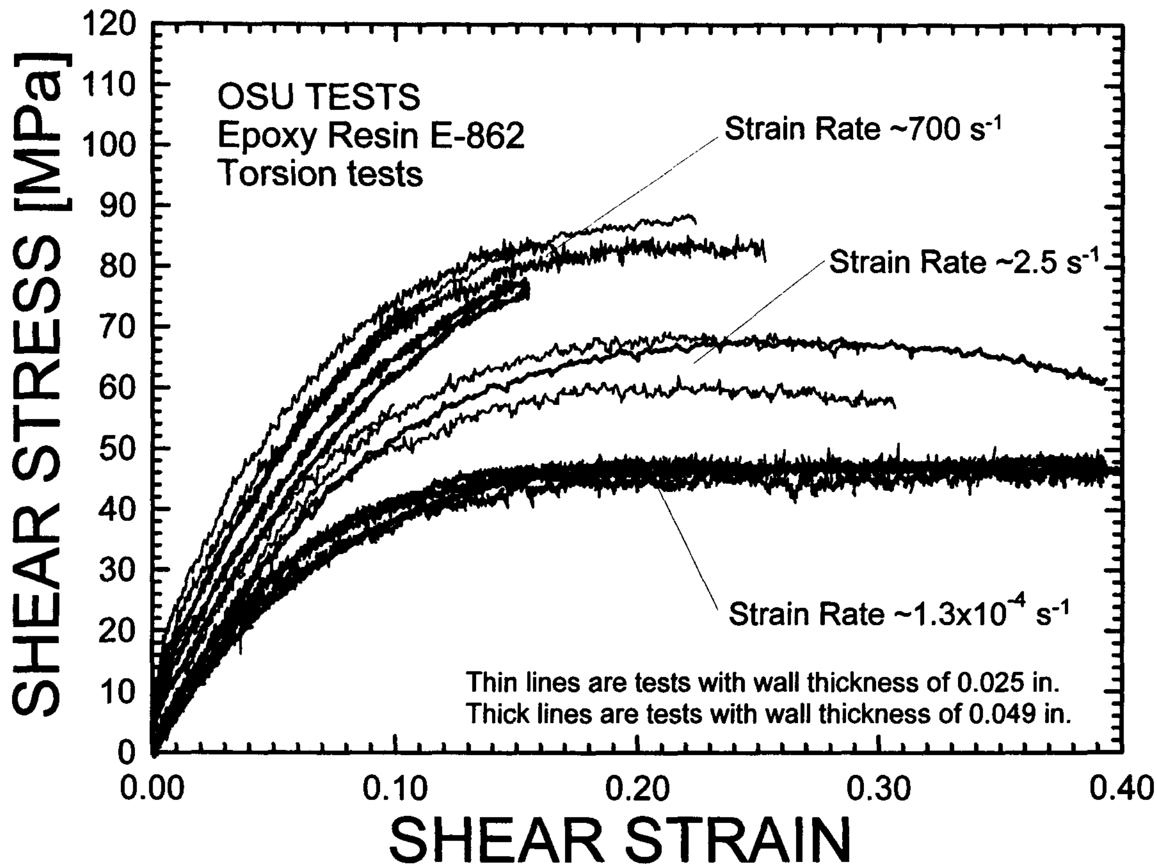


Fig. 6: Shear stress strain curves for E-862 epoxy at different strain rates.

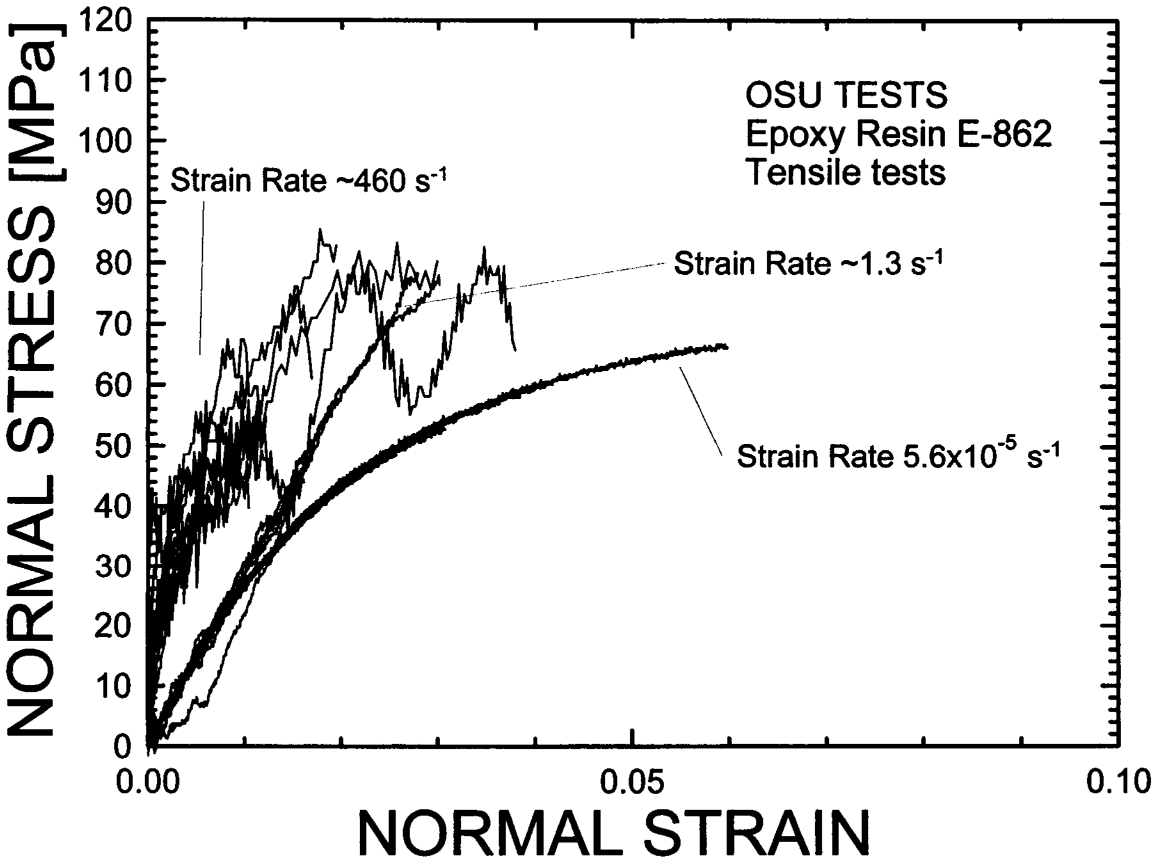


Fig. 7: Tensile stress strain curves for E-862 epoxy at different strain rates.

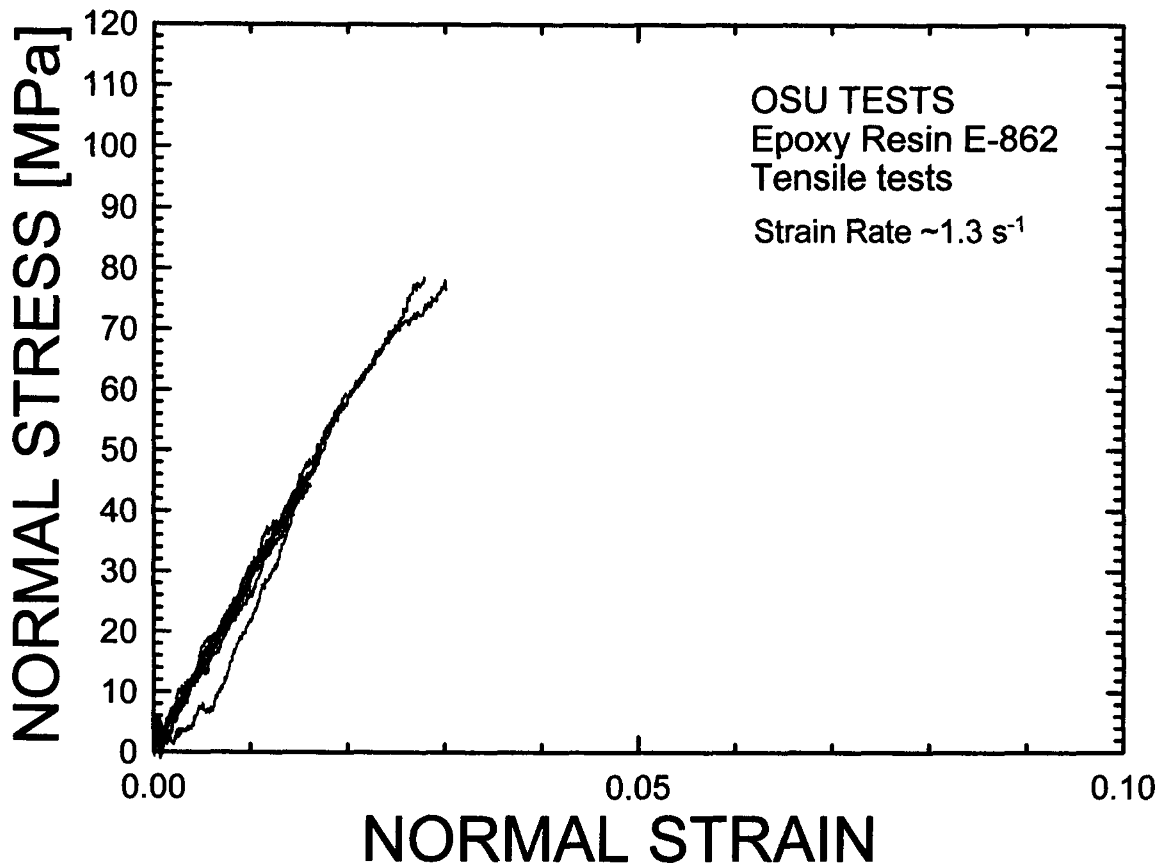


Fig. 8: Tensile stress strain curves for E-862 epoxy from medium strain rate experiments.

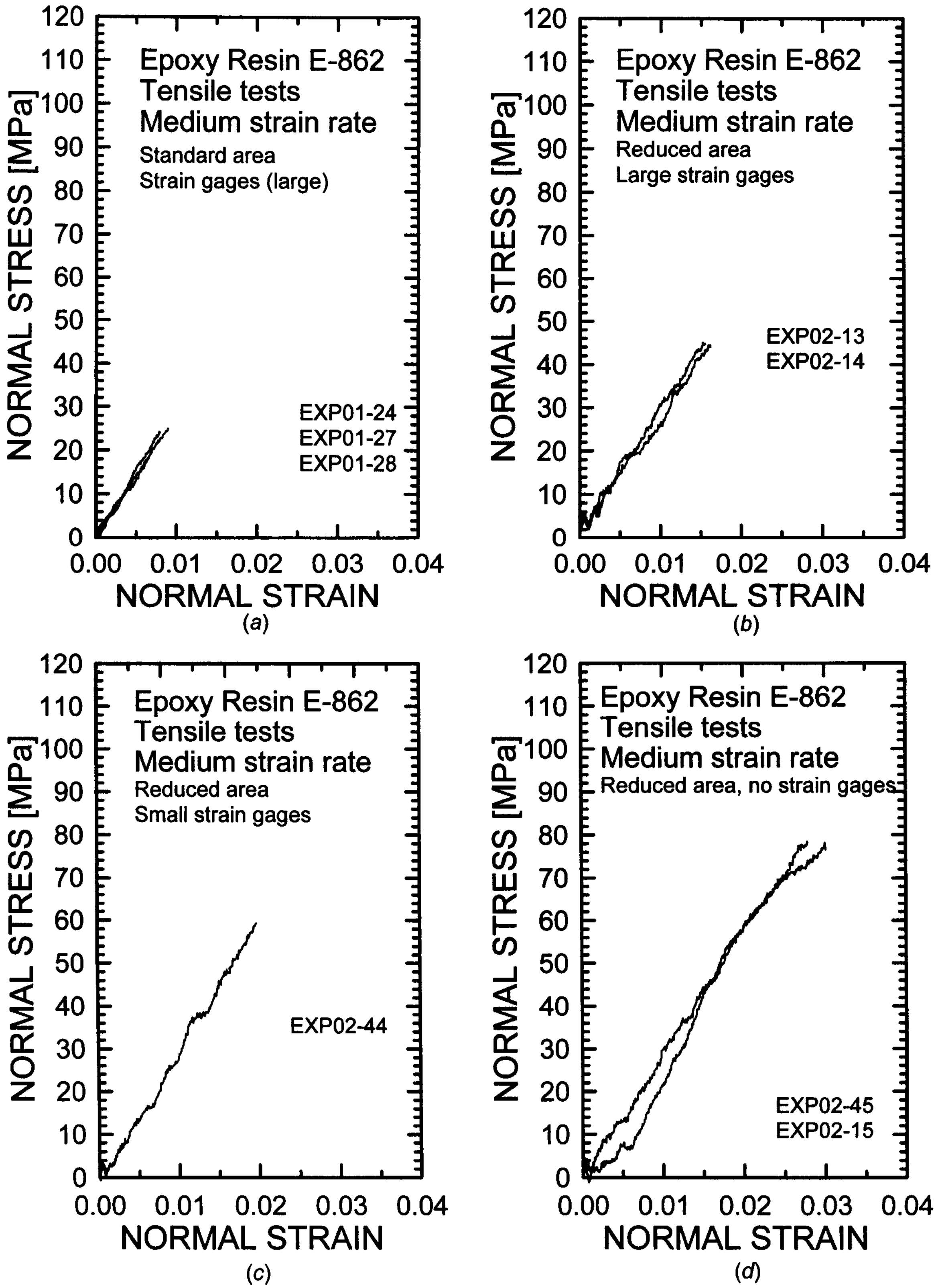


Fig. 9: Tensile stress strain curves for E-862 epoxy from medium strain rate experiments.

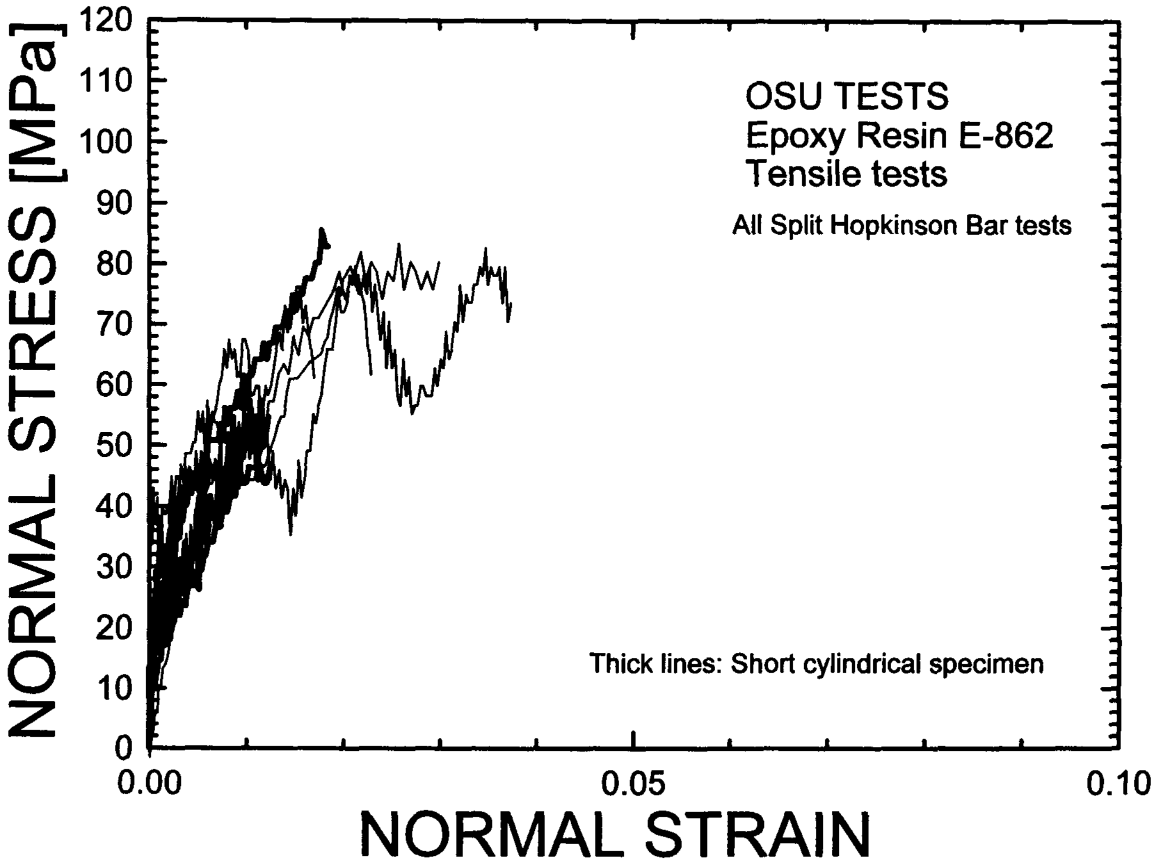


Fig. 10: Tensile stress strain curves for E-862 epoxy from split Hopkinson bar experiments.

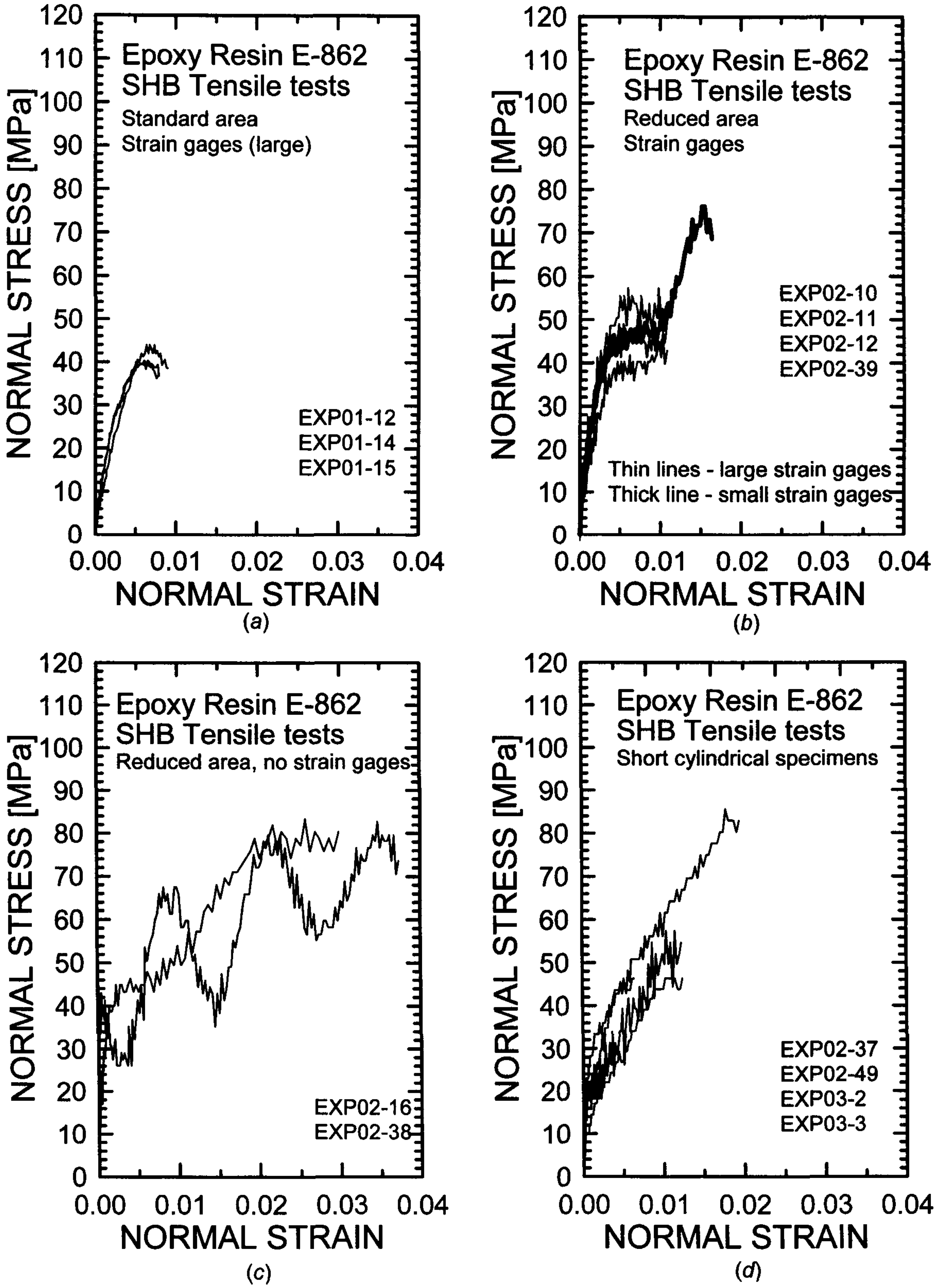


Fig. 11: Tensile stress strain curves for E-862 epoxy from split Hopkinson bar experiments.

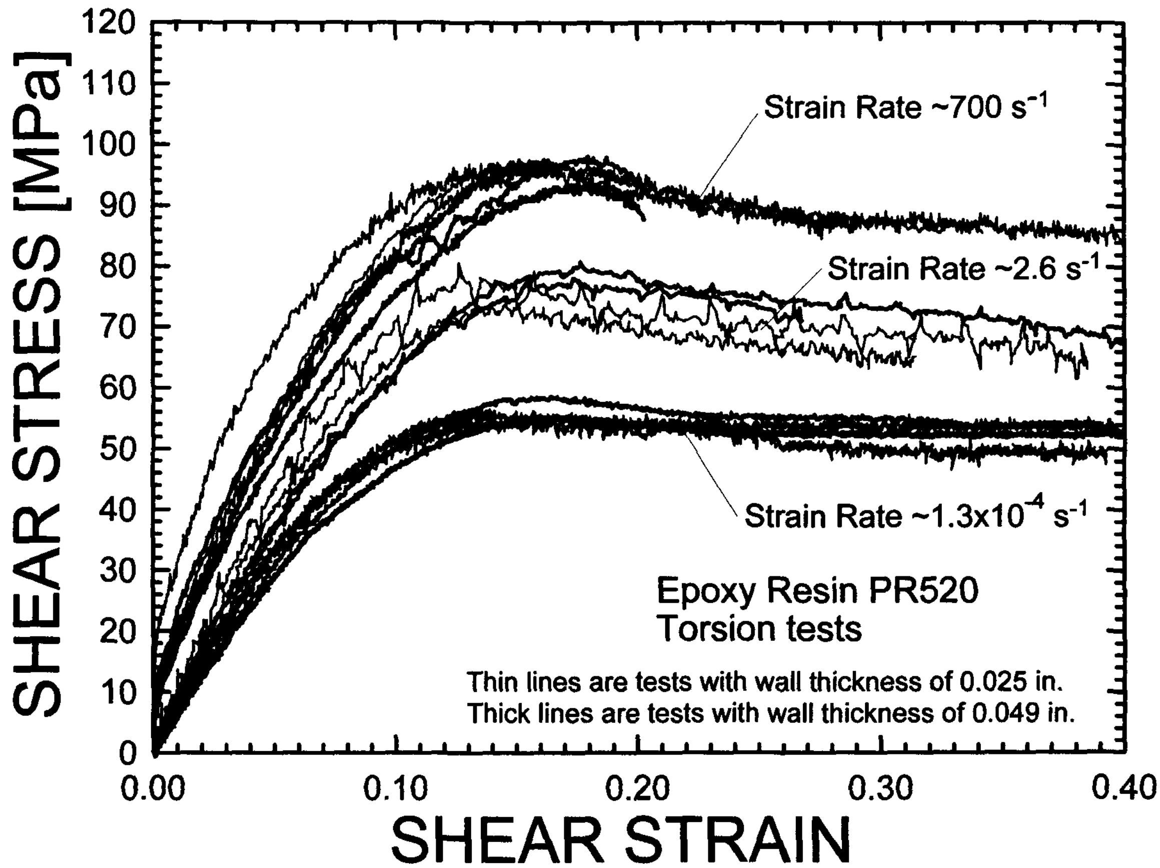


Fig. 12: Shear stress strain curves for PR-520 epoxy at different strain rates.

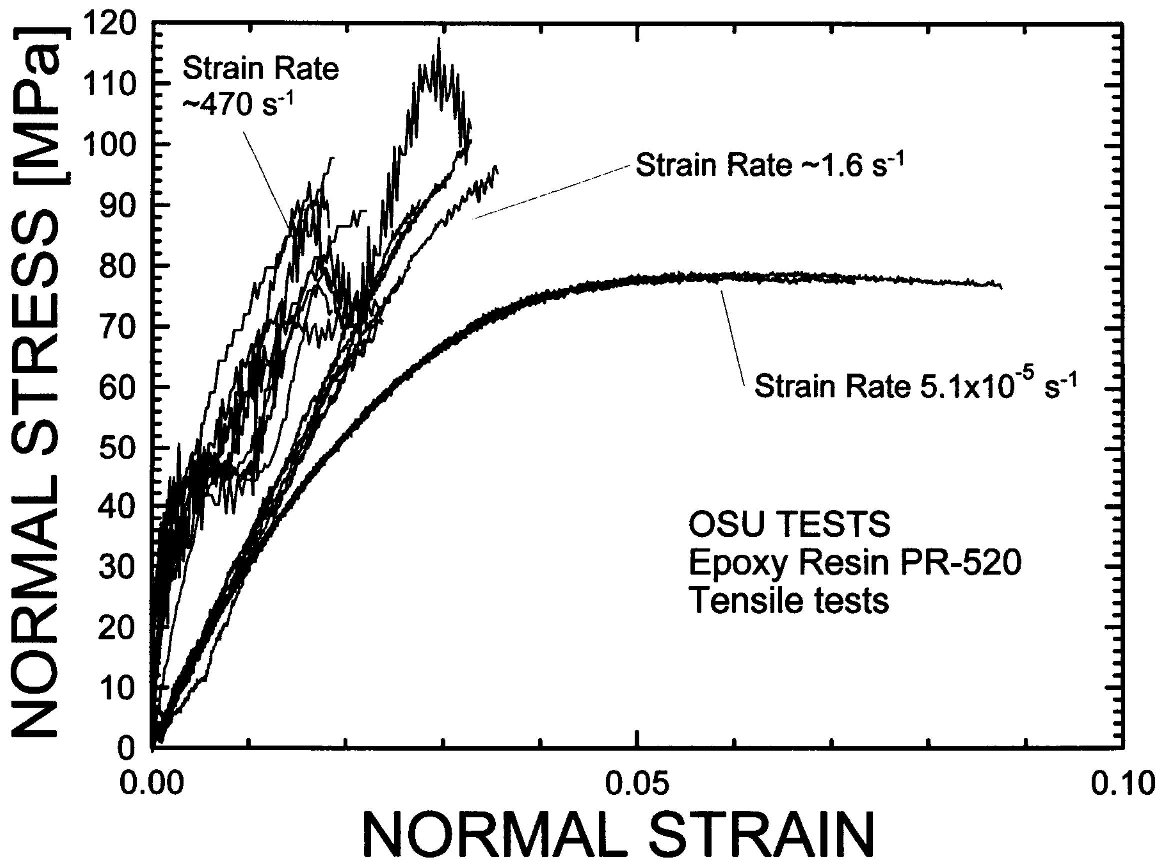


Fig. 13: Tensile stress strain curves for PR-520 epoxy at different strain rates.

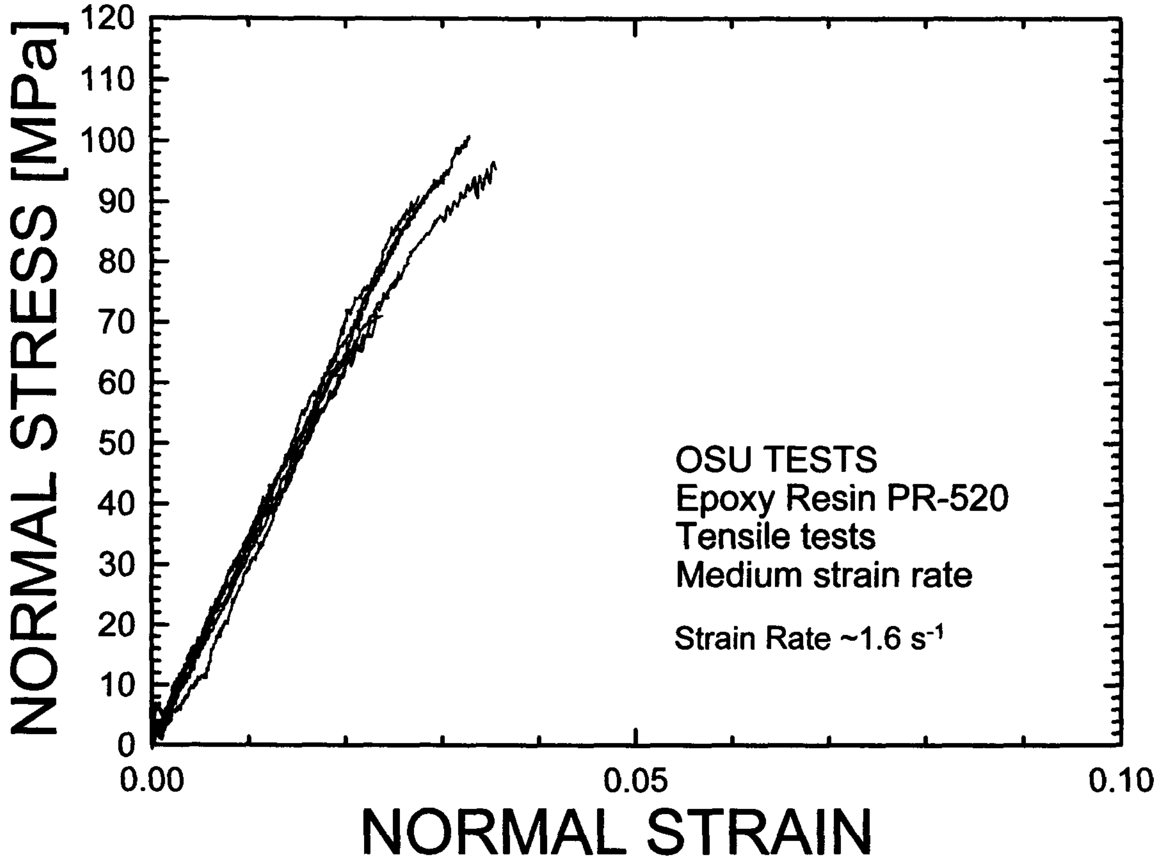


Fig. 14: Tensile stress strain curves for E-862 epoxy from medium strain rate experiments.

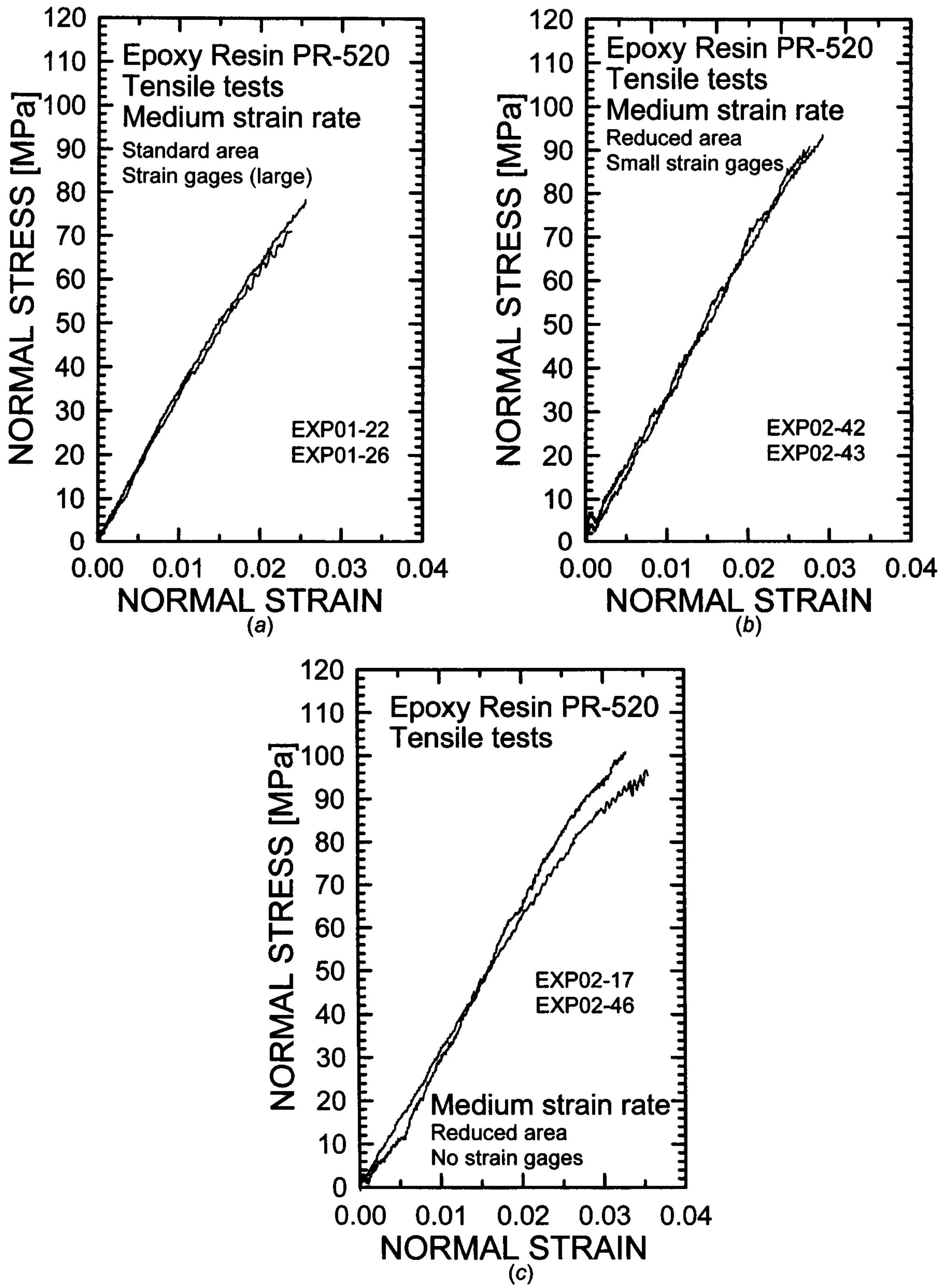


Fig. 15: Tensile stress strain curves for E-862 epoxy from medium strain rate experiments.

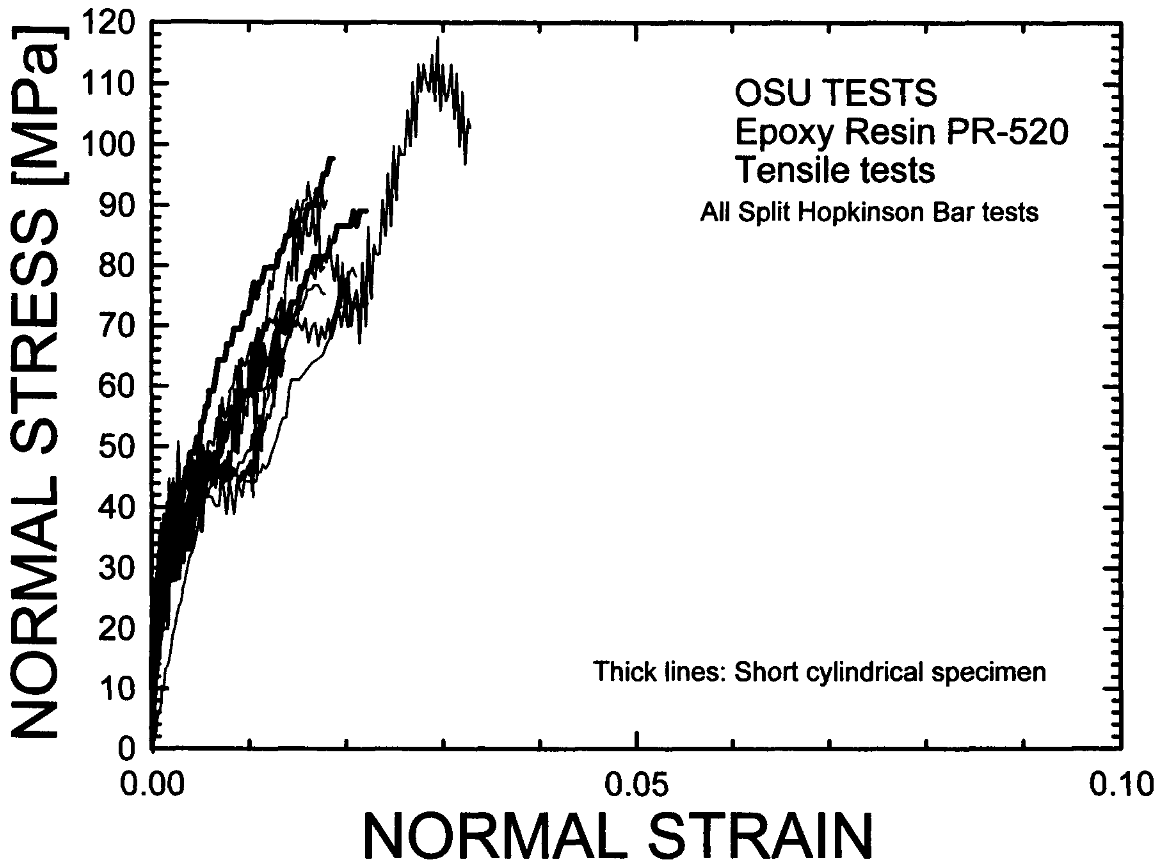


Fig. 16: Tensile stress strain curves for PR-520 epoxy from split Hopkinson bar experiments.

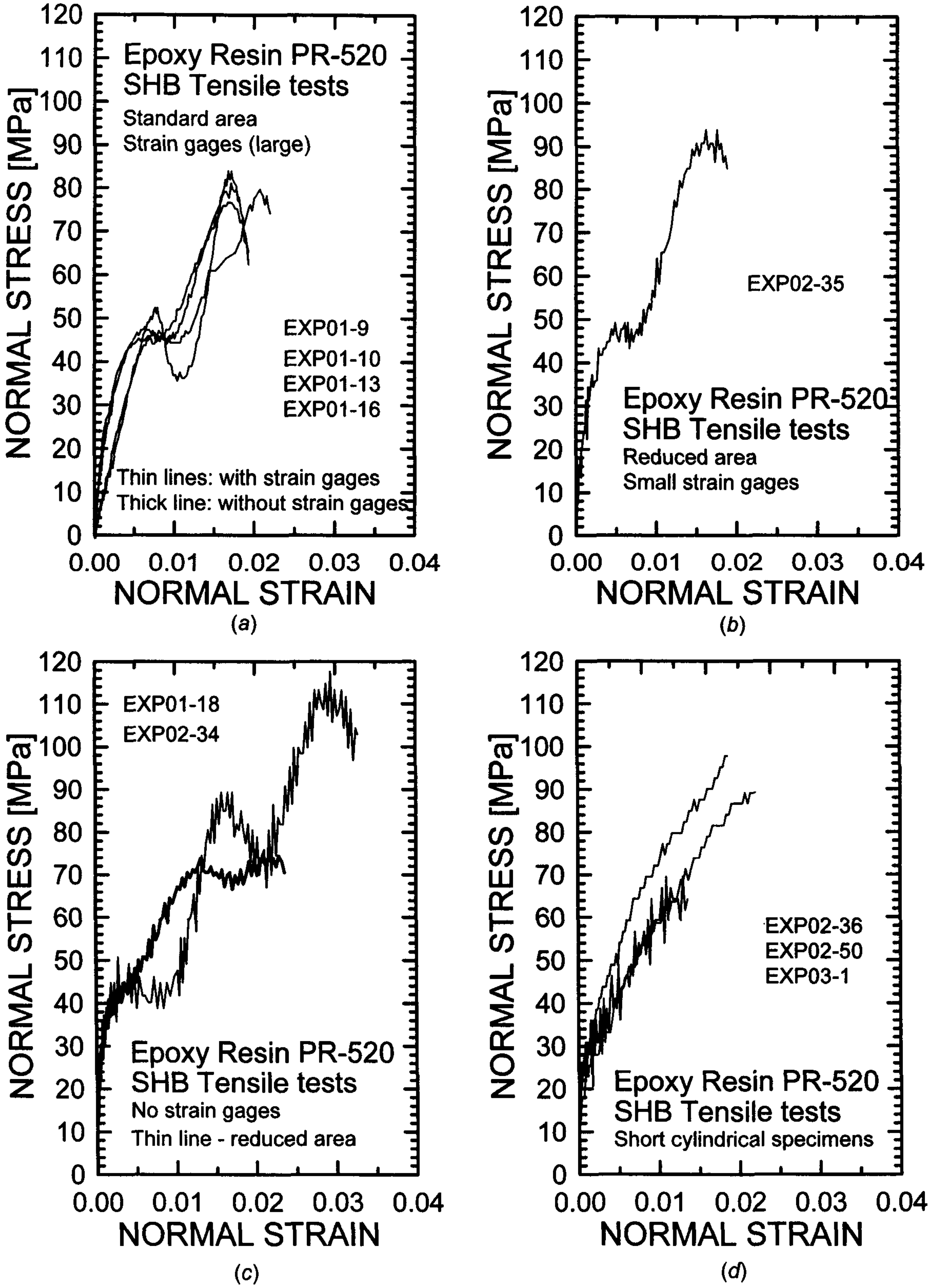


Fig. 17: Tensile stress strain curves for PR-520 epoxy from split Hopkinson bar experiments.

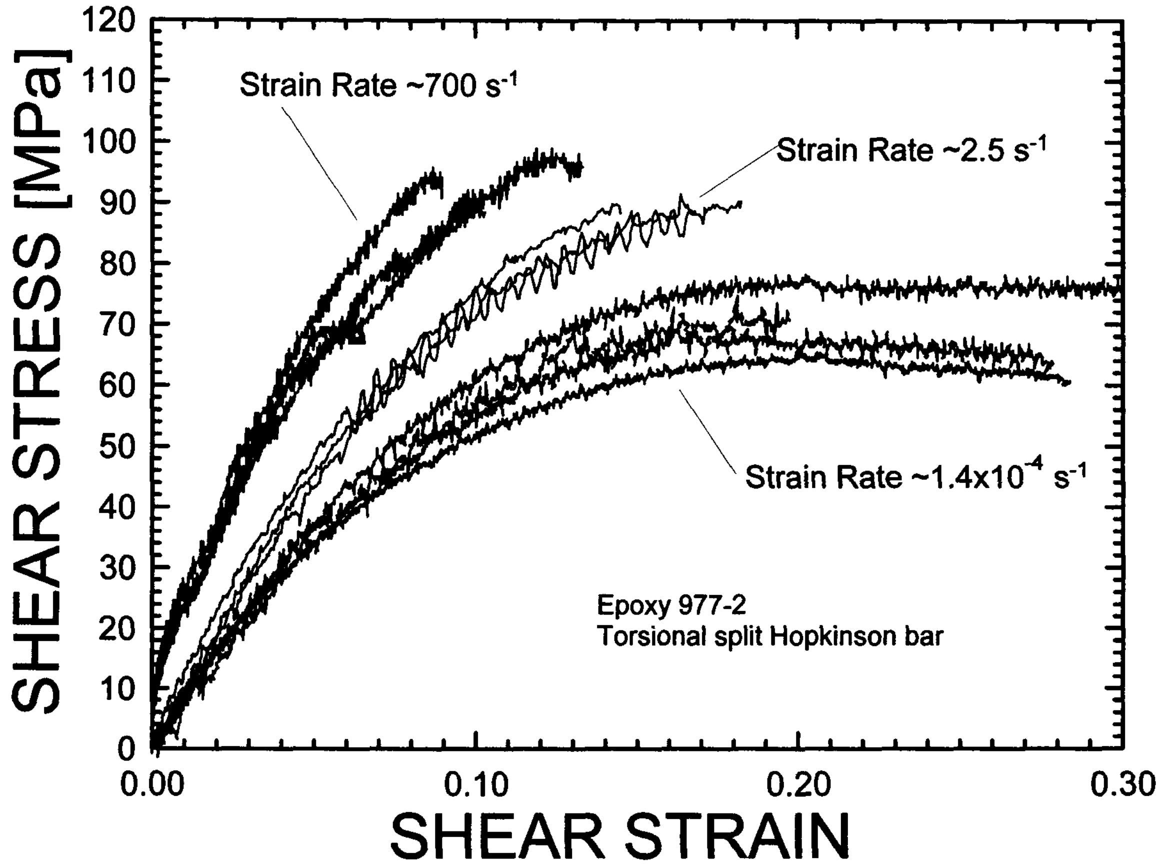


Fig. 18: Shear stress strain curves for 977-2 epoxy at different strain rates.

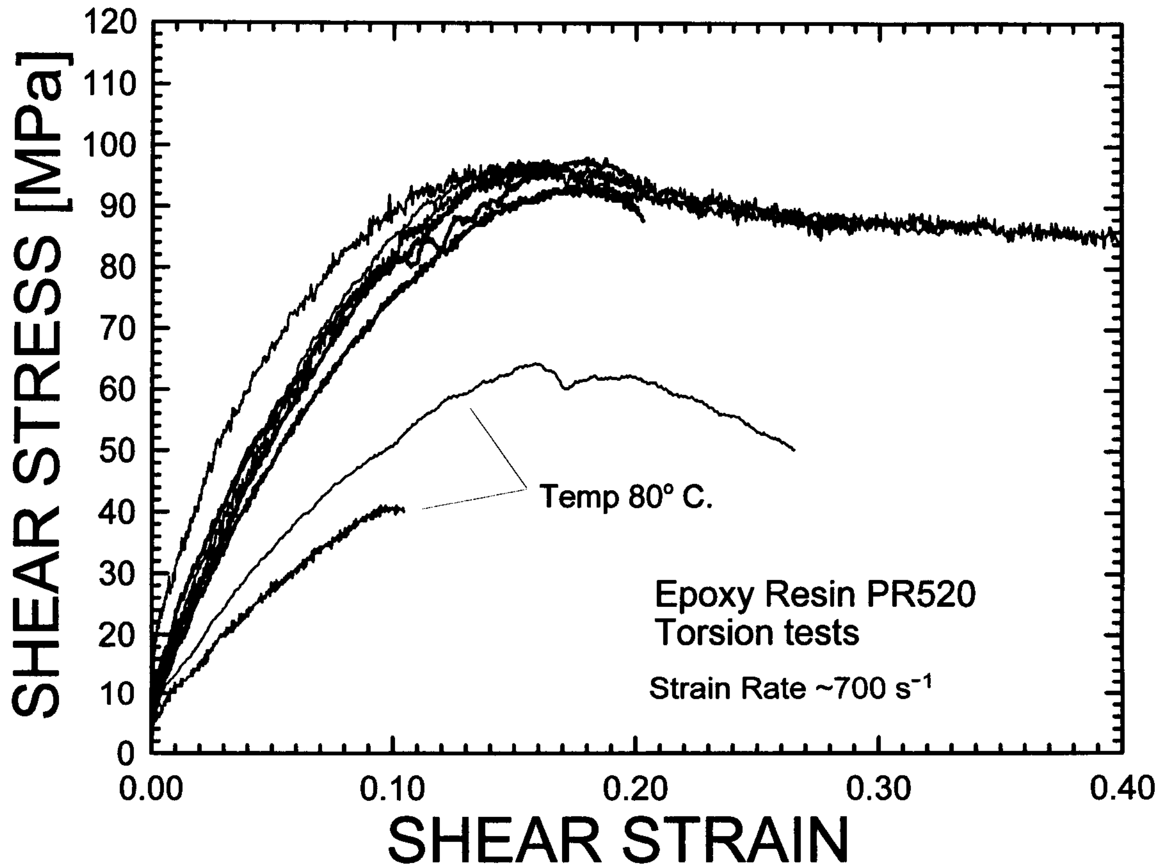


Fig. 19: Room temp and 80°C shear stress strain curves for PR-520 epoxy at high strain rates.

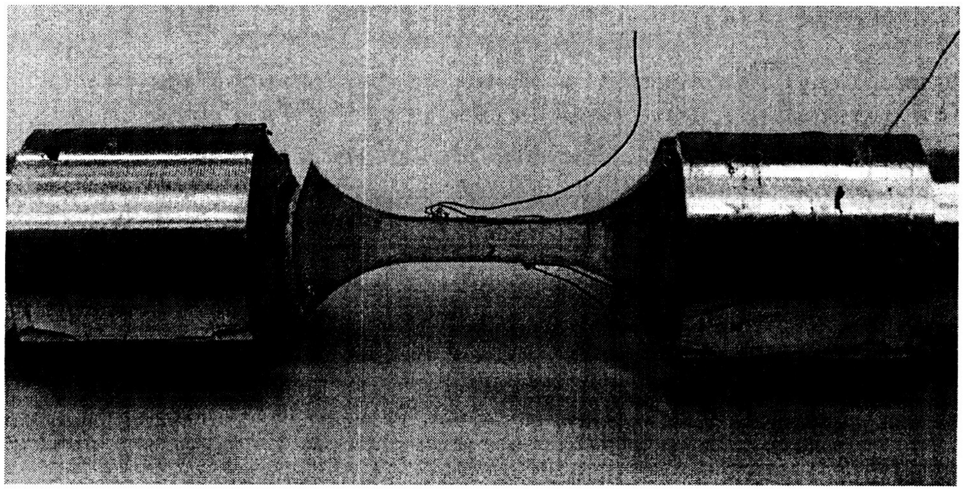


Fig. 20: A E-862 resin dog-bone shaped specimen that fractured at the rounded end.

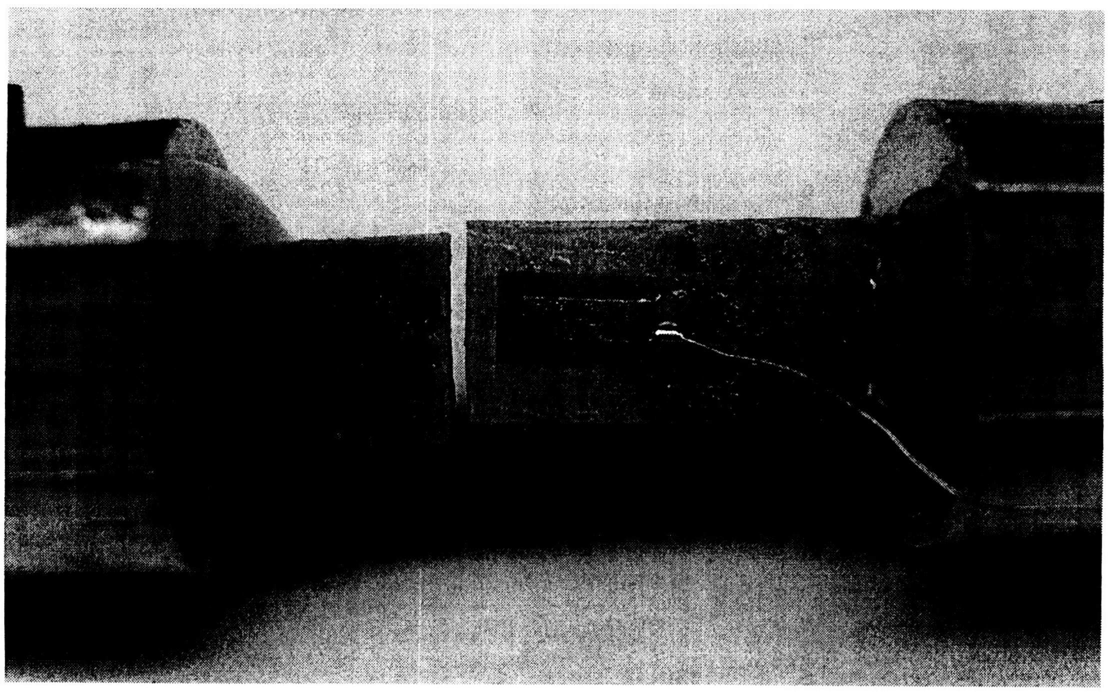


Fig. 21: A PR-520 resin dog-bone shaped specimen that fractured at the gage section.

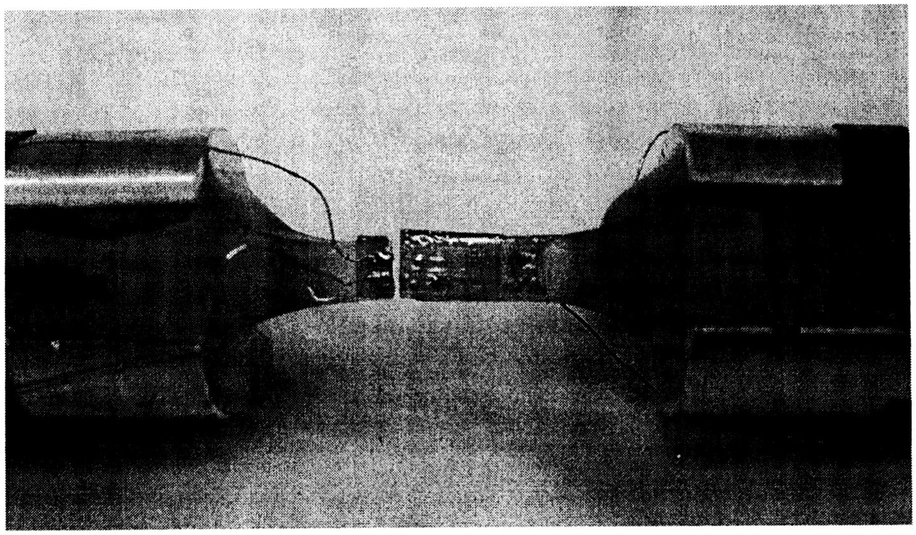


Fig. 22: A "reduced area" E-862 resin dog-bone shaped specimen with large strain gages.

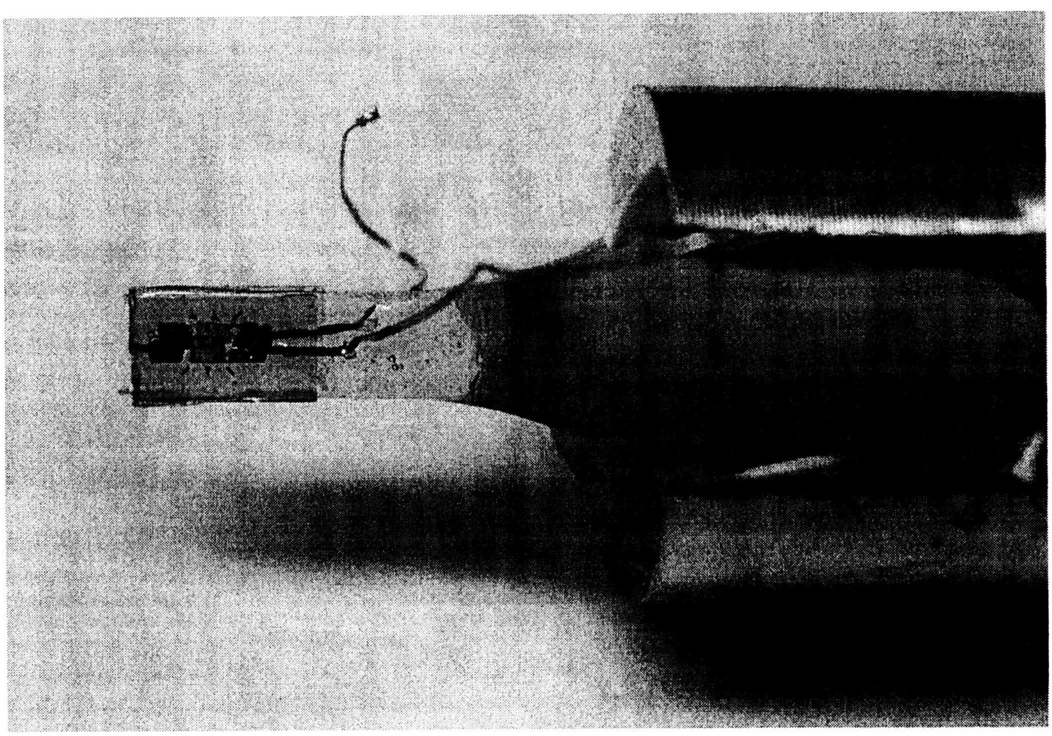


Fig. 23: A "reduced area" E-862 resin dog-bone shaped specimen with small strain gages.

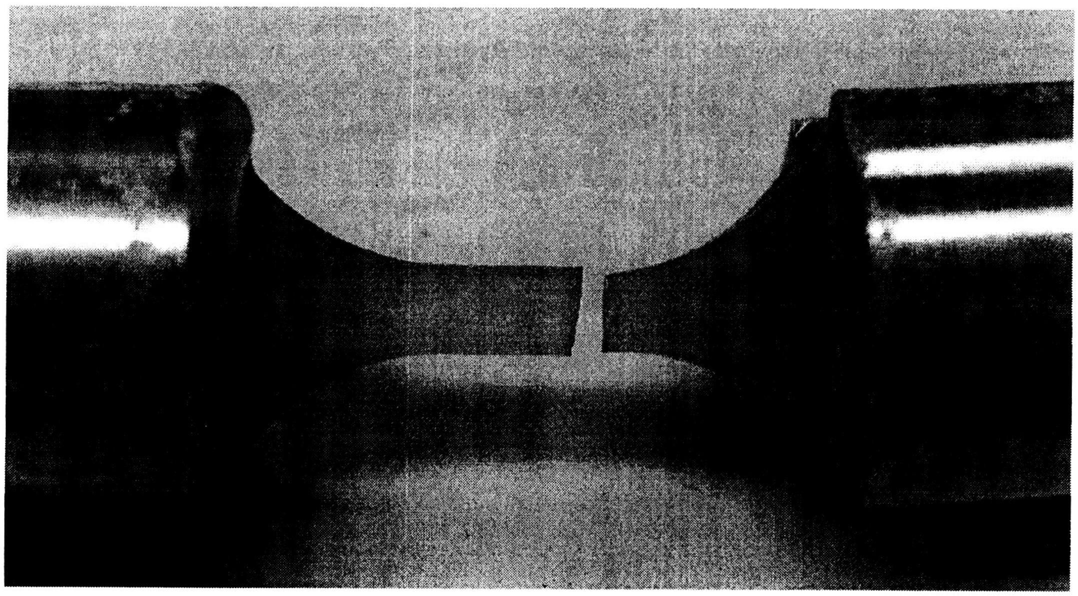


Fig. 24: A “reduced area” E-862 resin dog-bone shaped specimen with no strain gages that fractured at the gage section.

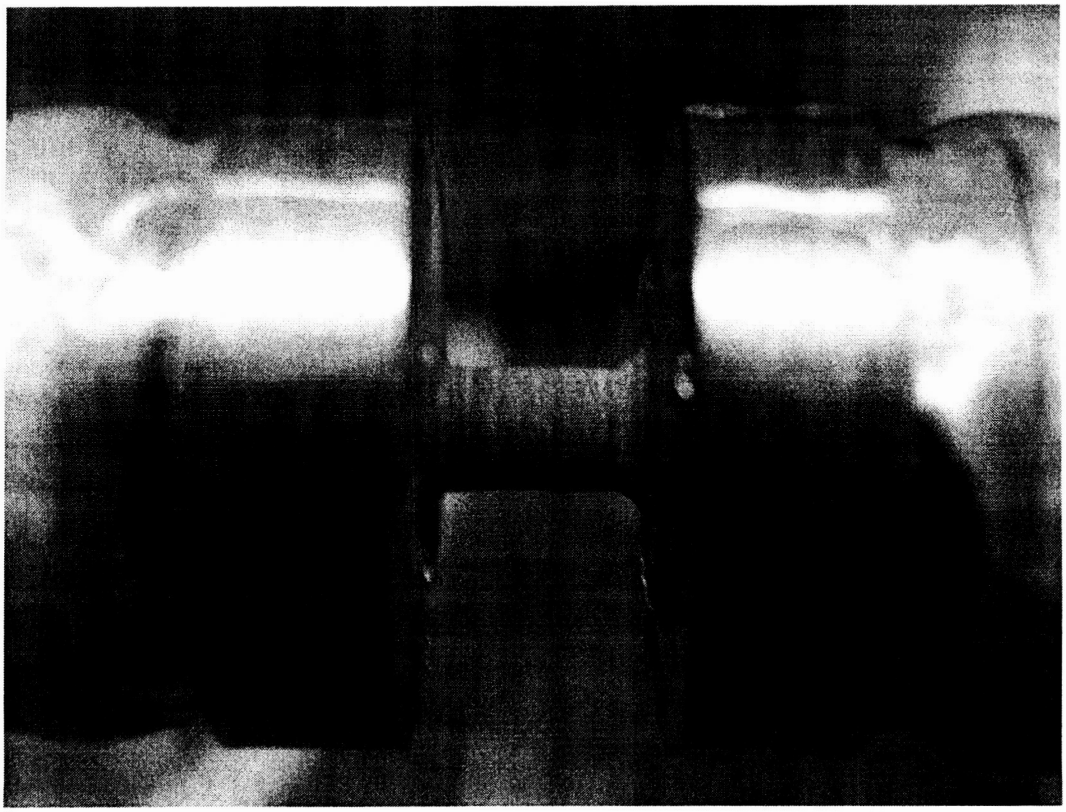


Fig. 25: A short, round PR-520 resin specimen for SHB test.

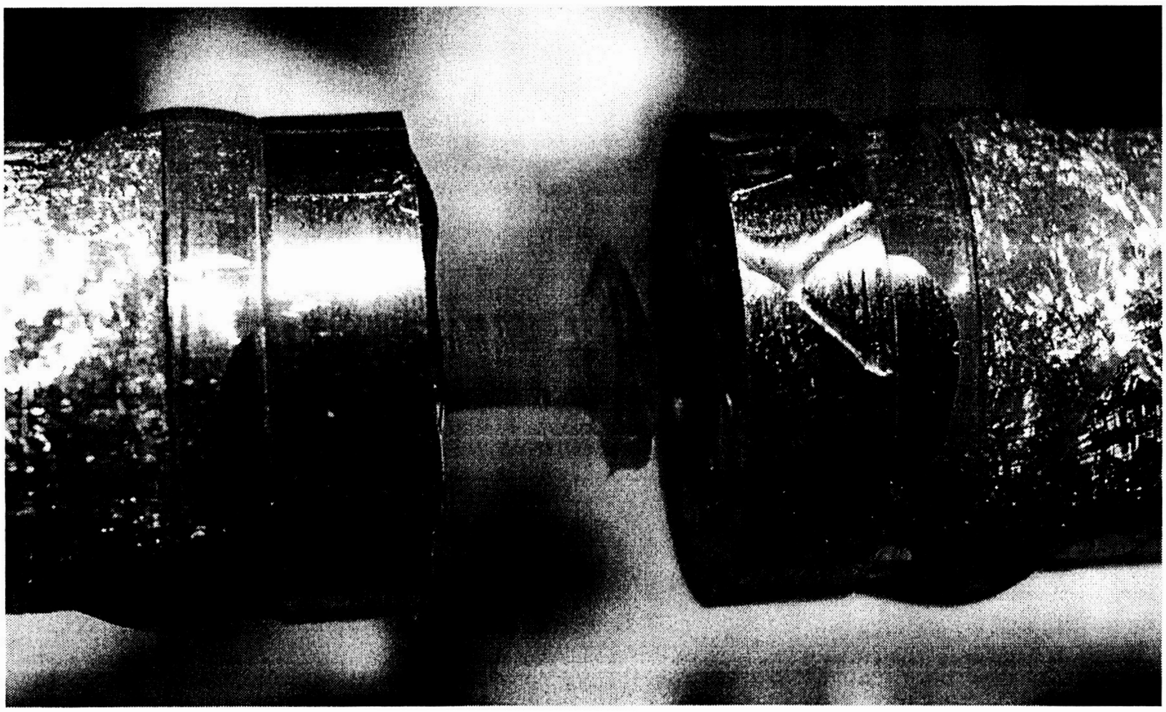
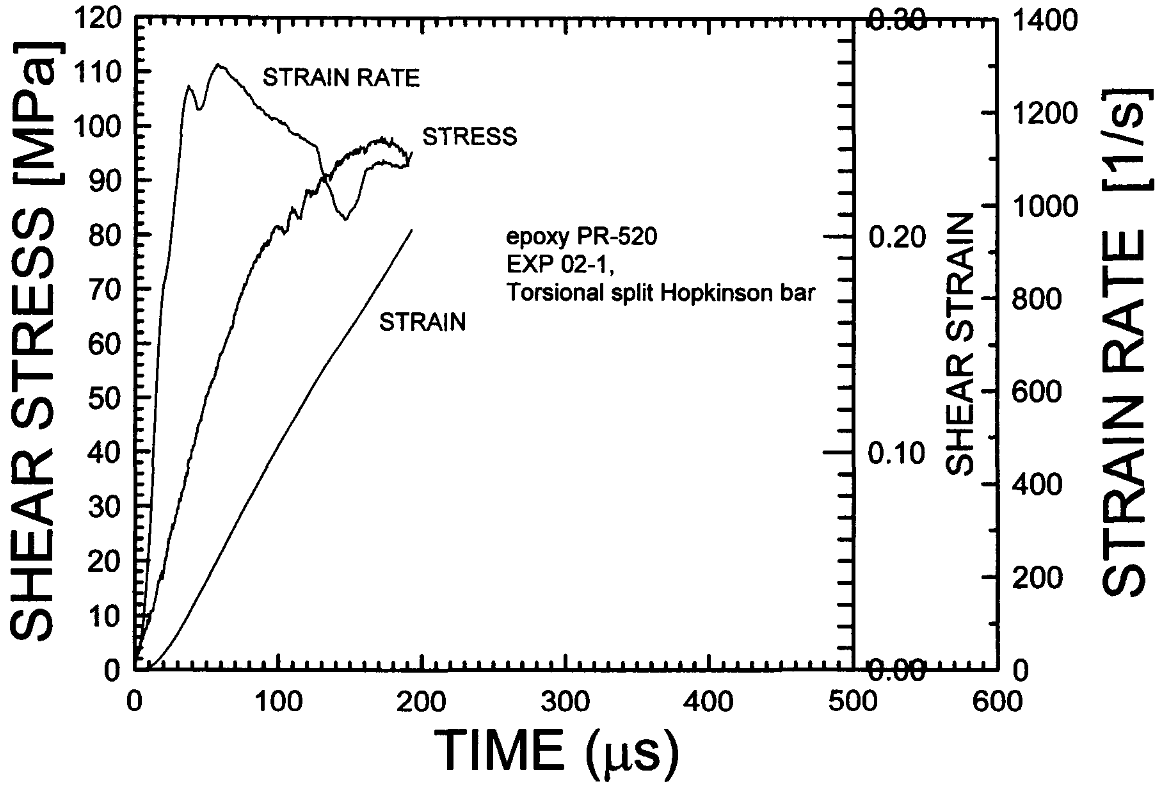


Fig. 26: A fractured short, round E-862 resin specimen for SHB test.

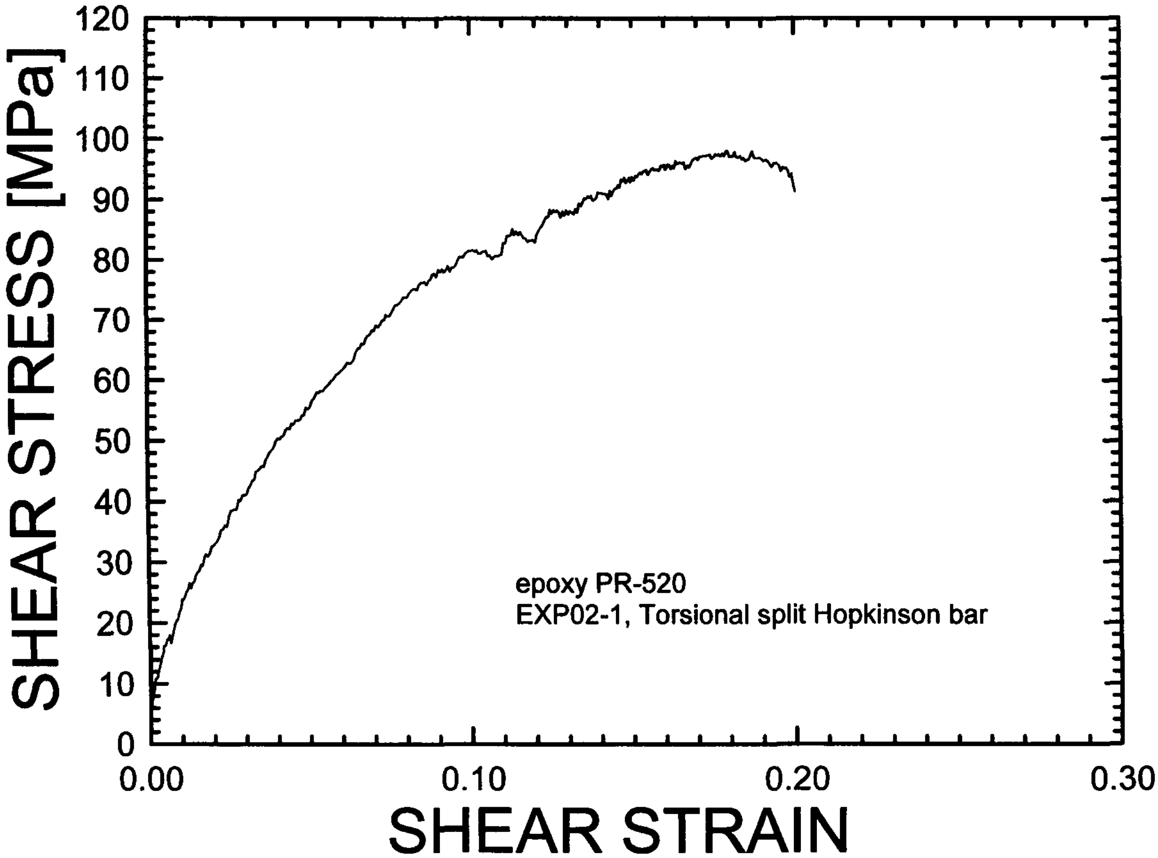
APPENDIX

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.

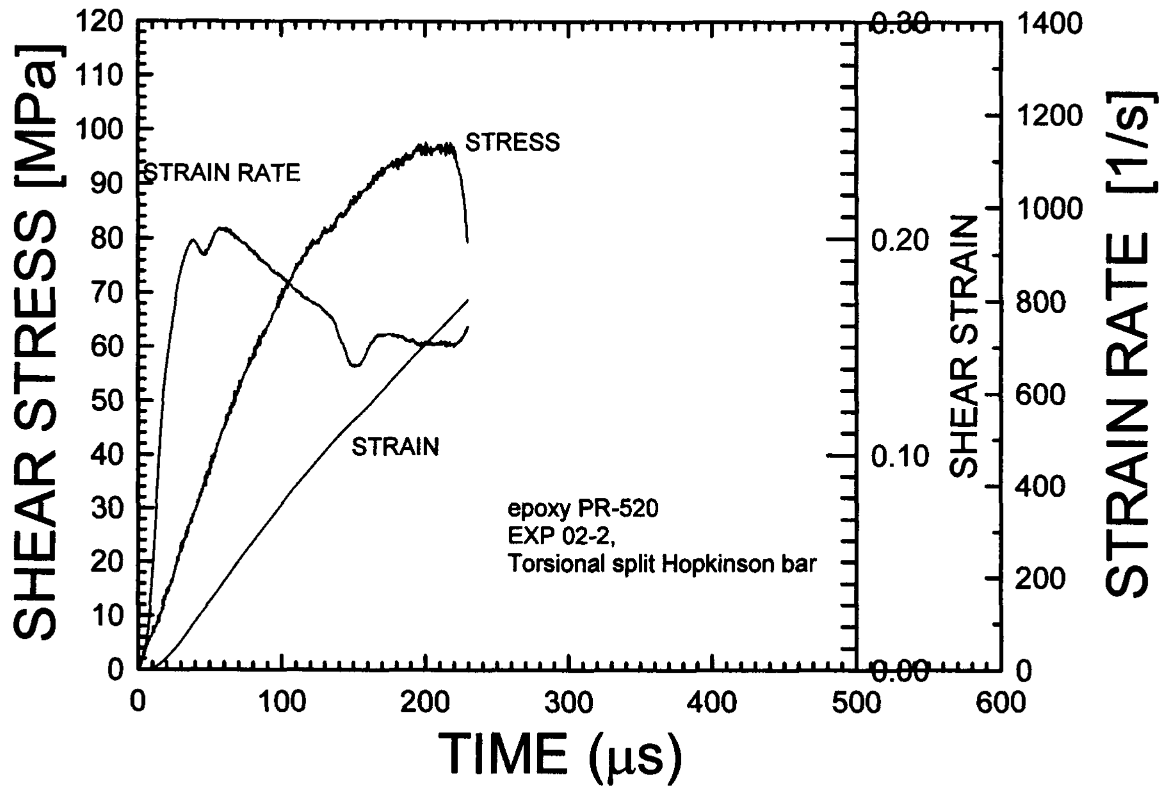
The plots are in the order listed in Table 1.



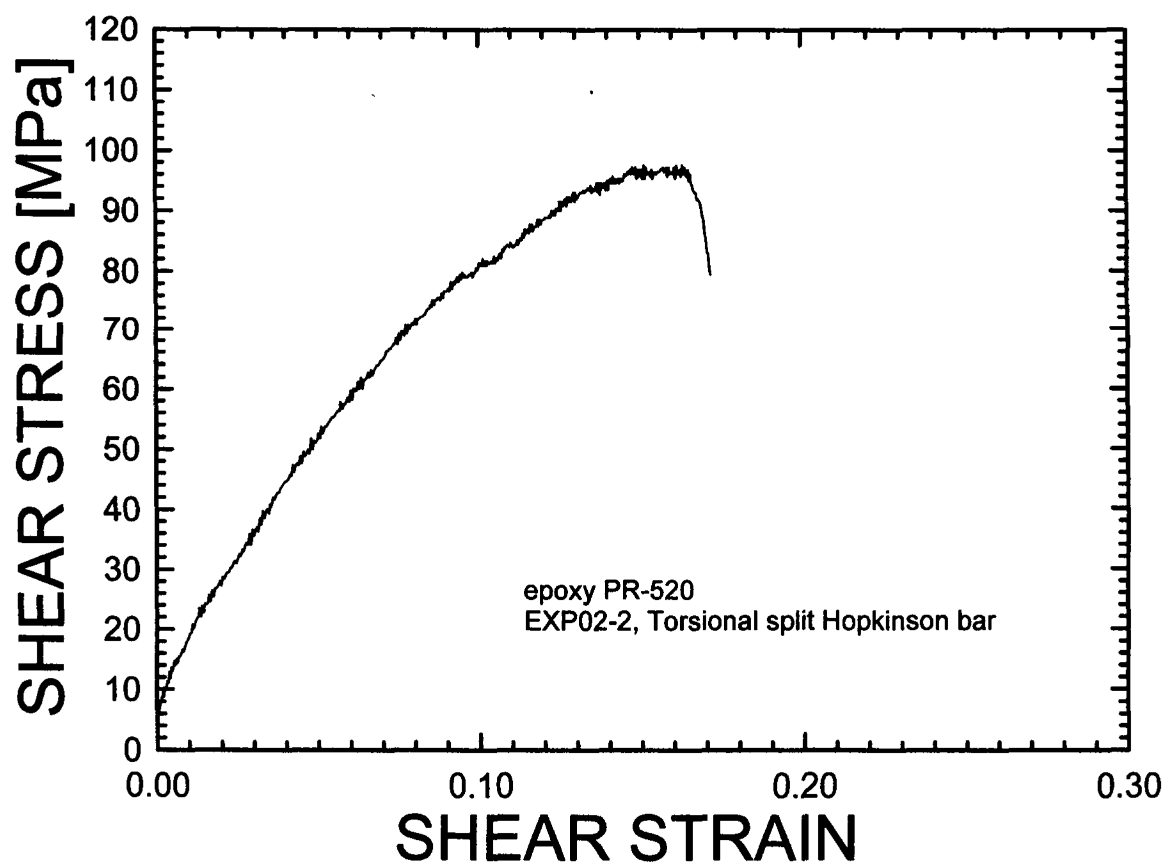
STRAIN RATE
STRESS
STRAIN
epoxy PR-520
EXP 02-1,
Torsional split Hopkinson bar
SHEAR STRESS [MPa]
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)



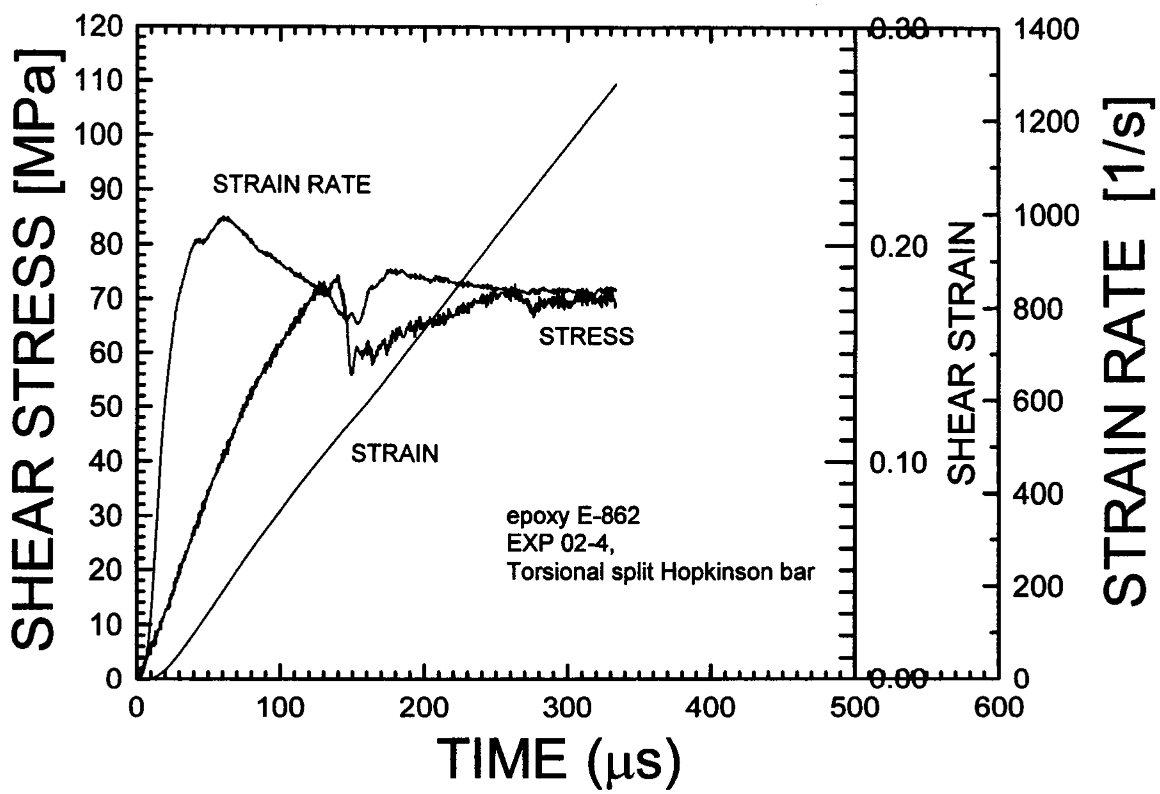
epoxy PR-520
EXP02-1, Torsional split Hopkinson bar
SHEAR STRESS [MPa]
SHEAR STRAIN

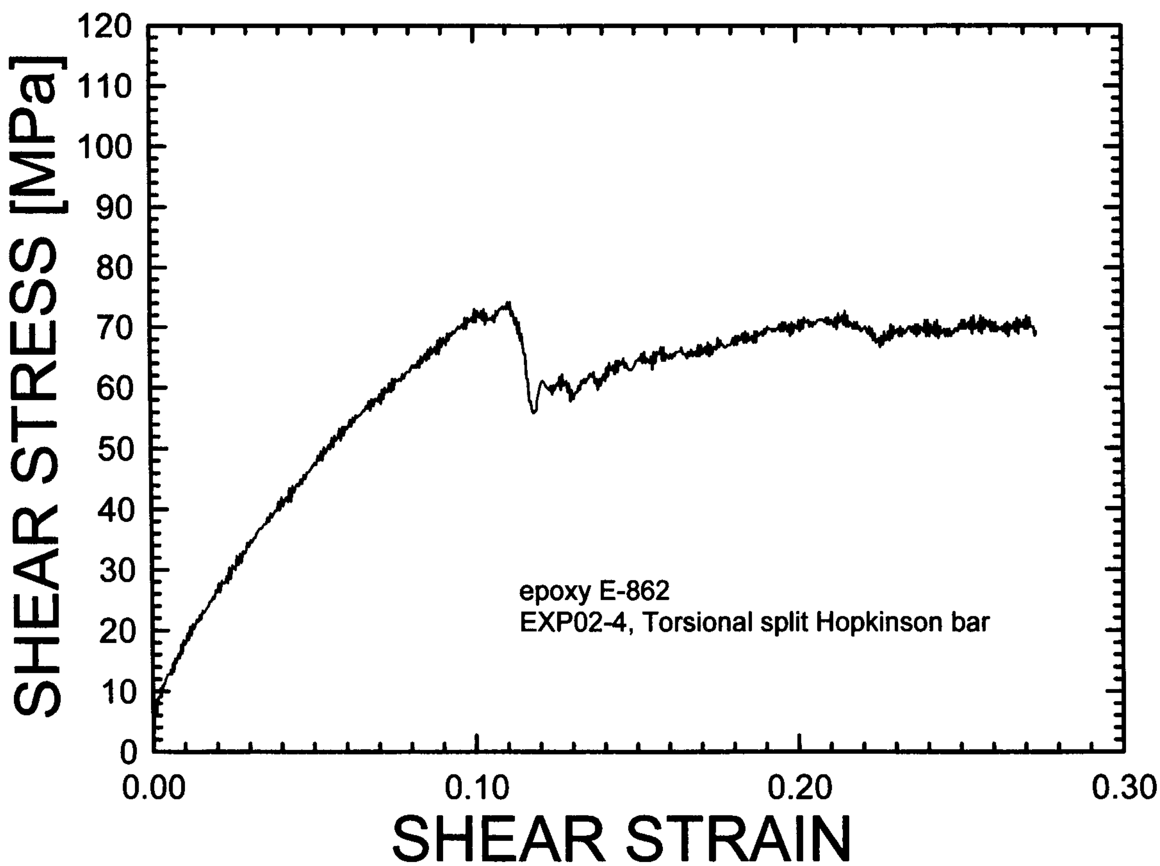


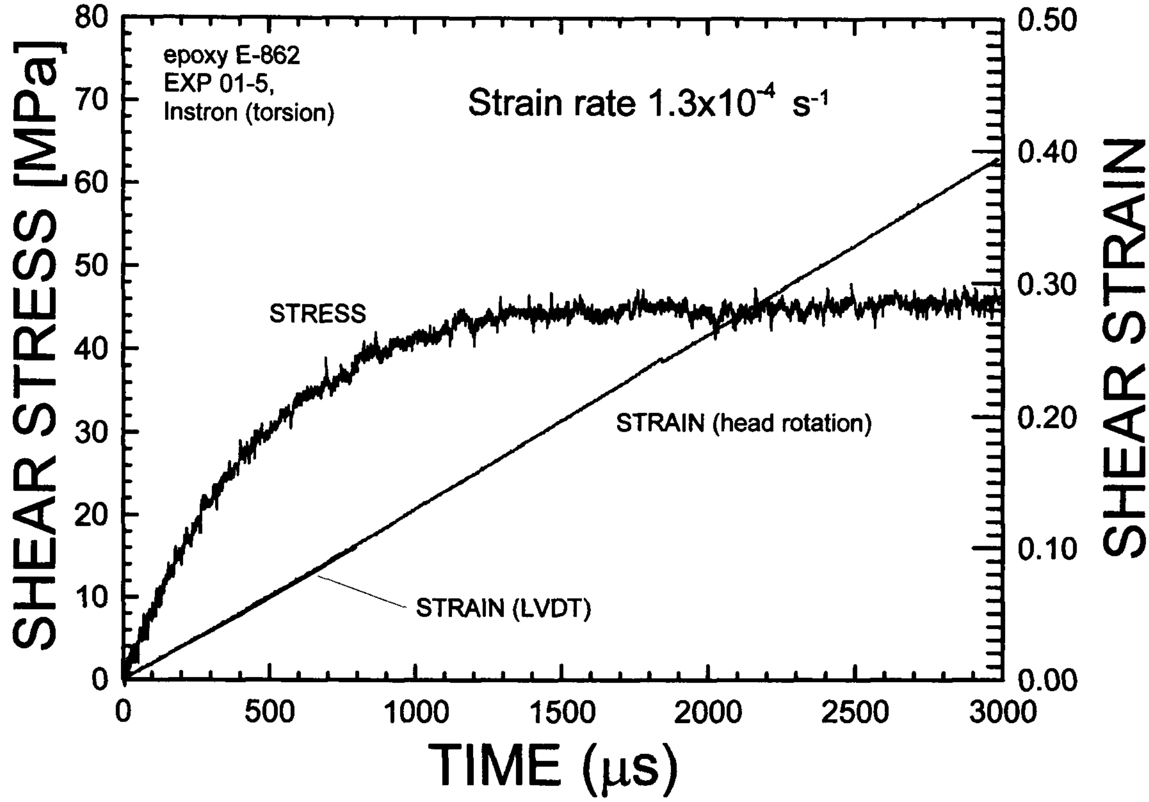
SHEAR STRESS [MPa]
STRAIN RATE
STRESS
STRAIN
epoxy PR-520
EXP 02-2,
Torsional split Hopkinson bar
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)



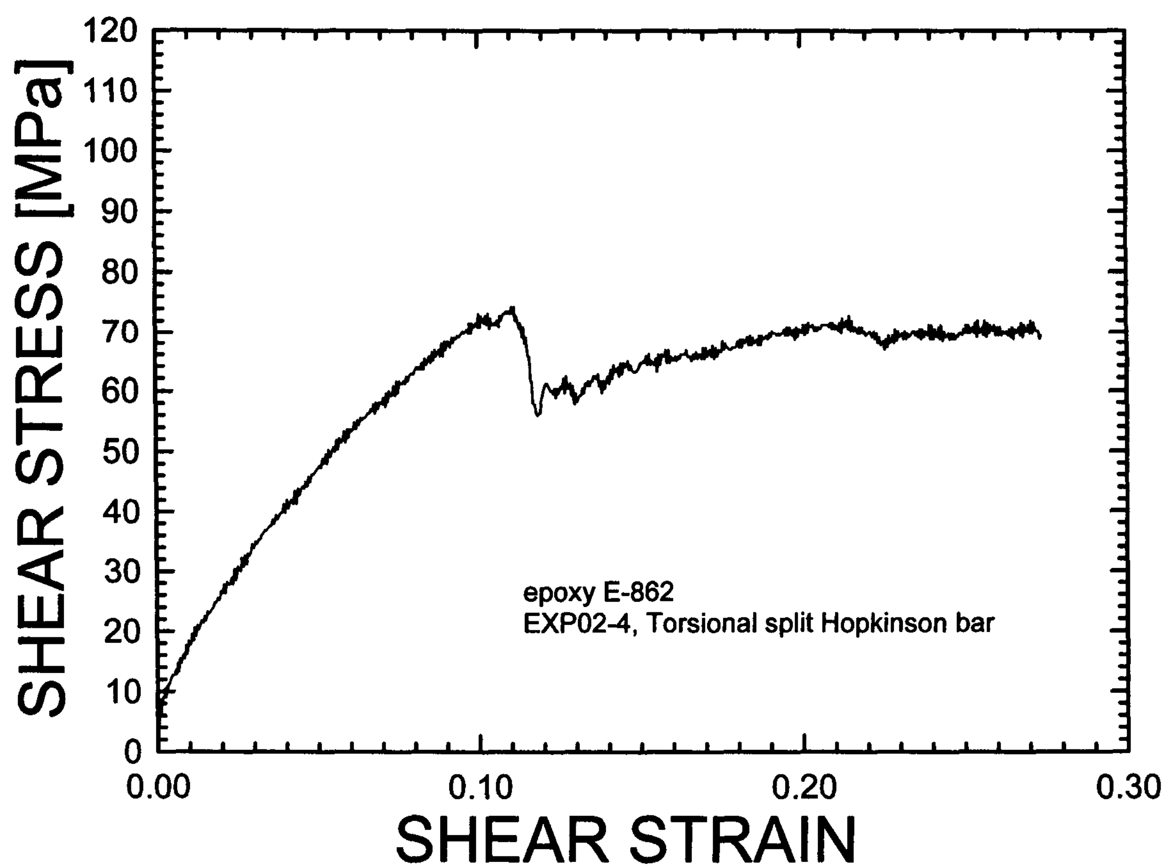
SHEAR STRESS [MPa]
epoxy PR-520
EXP02-2, Torsional split Hopkinson bar
SHEAR STRAIN


SHEAR STRESS [MPa]
STRAIN RATE
STRESS
STRAIN
epoxy E-862
EXP 02-4,
Torsional split Hopkinson bar
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

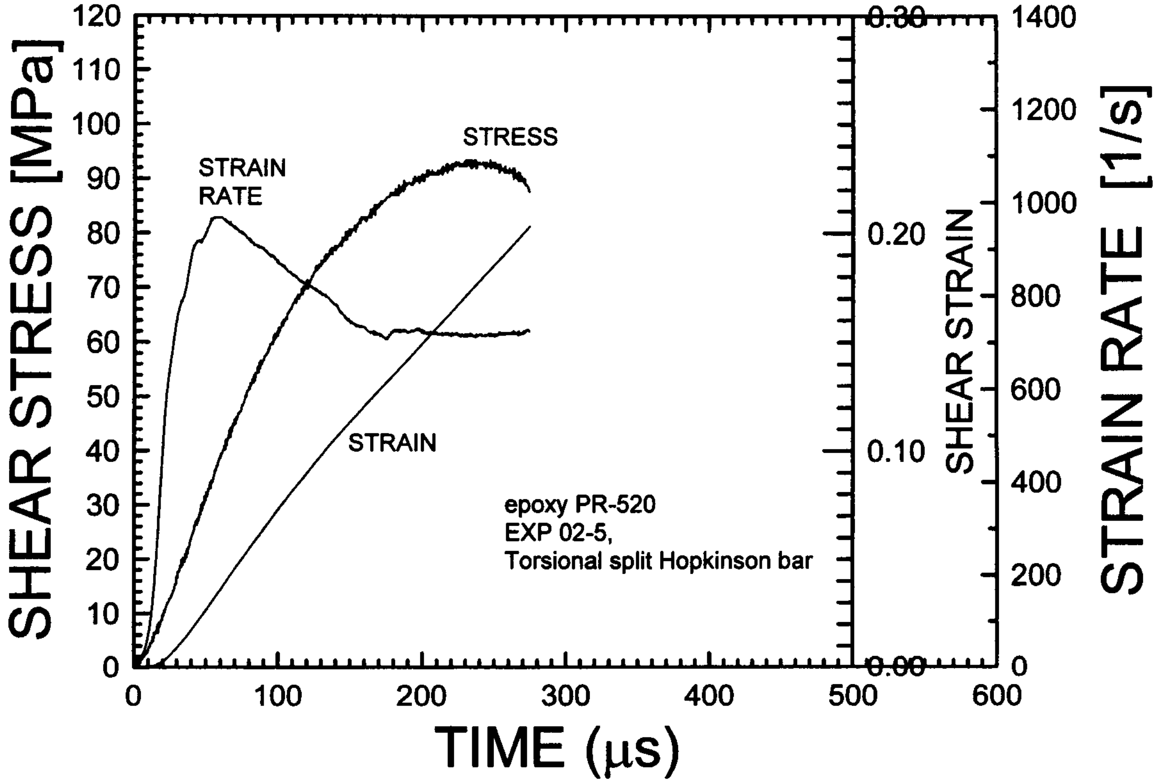

SHEAR STRESS [MPa]
epoxy E-862
EXP02-4, Torsional split Hopkinson bar
SHEAR STRAIN

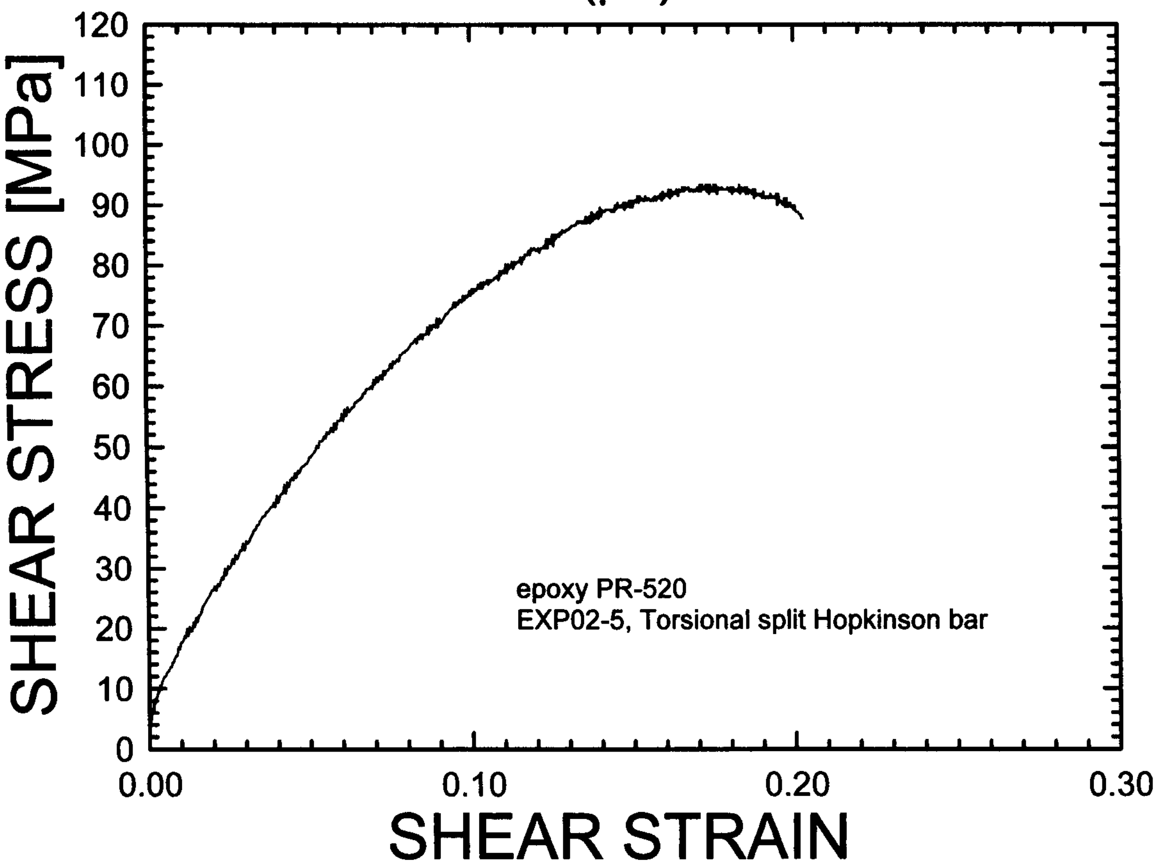


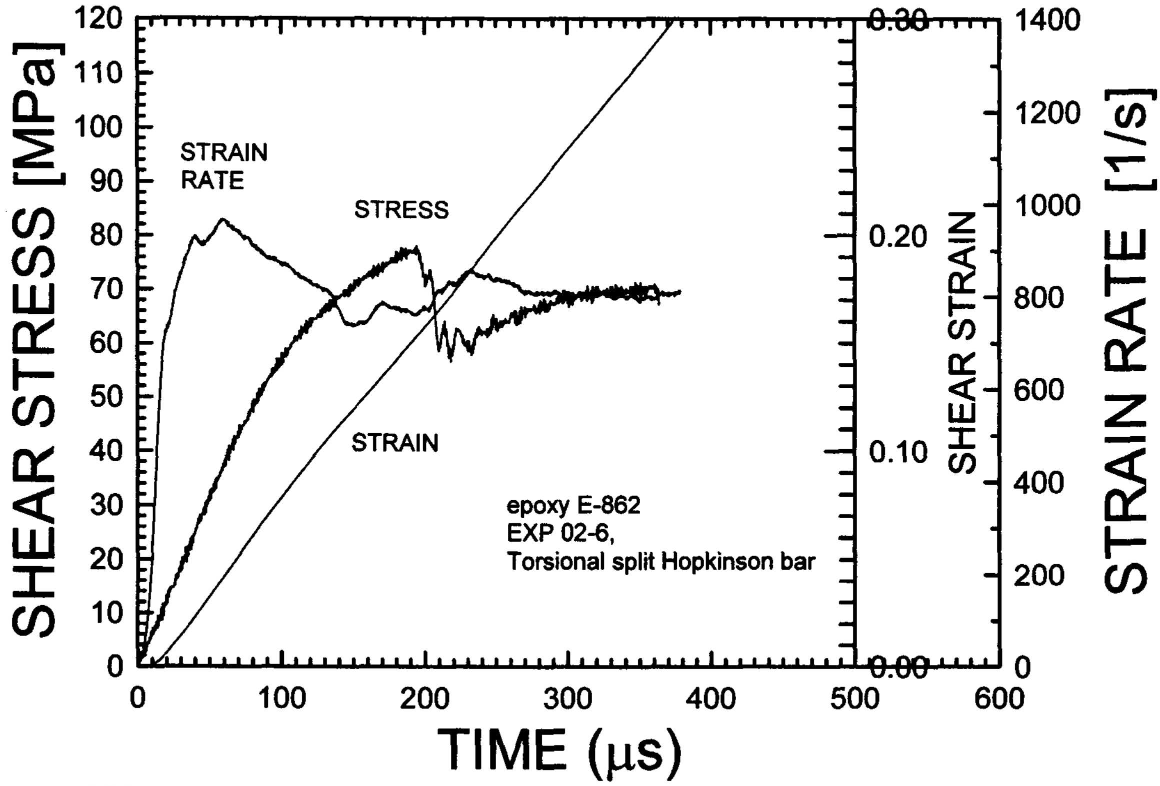
epoxy E-862
EXP 01-5,
Instron (torsion)
Strain rate 1.3x10^{-4} s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)



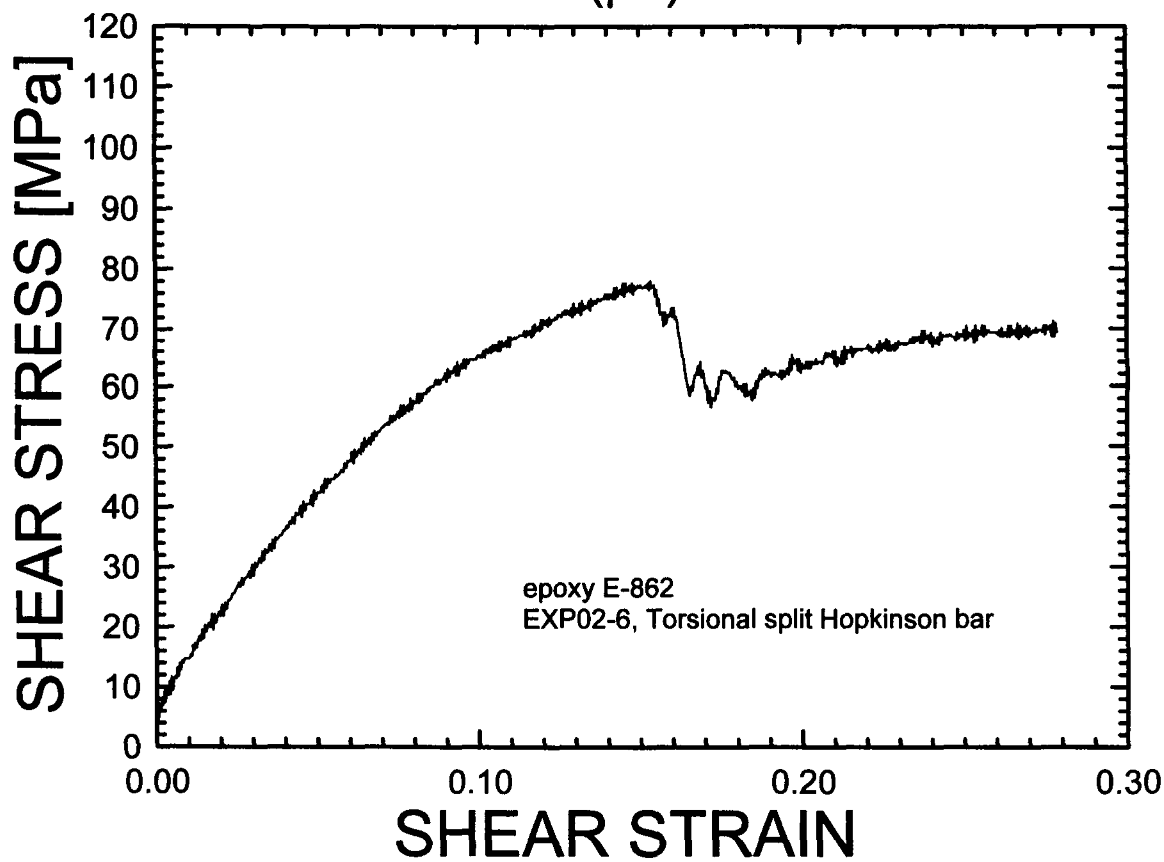
epoxy E-862
EXP02-4, Torsional split Hopkinson bar
SHEAR STRESS [MPa]
SHEAR STRAIN


SHEAR STRESS [MPa]
STRAIN RATE
STRESS
STRAIN
epoxy PR-520
EXP 02-5,
Torsional split Hopkinson bar
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

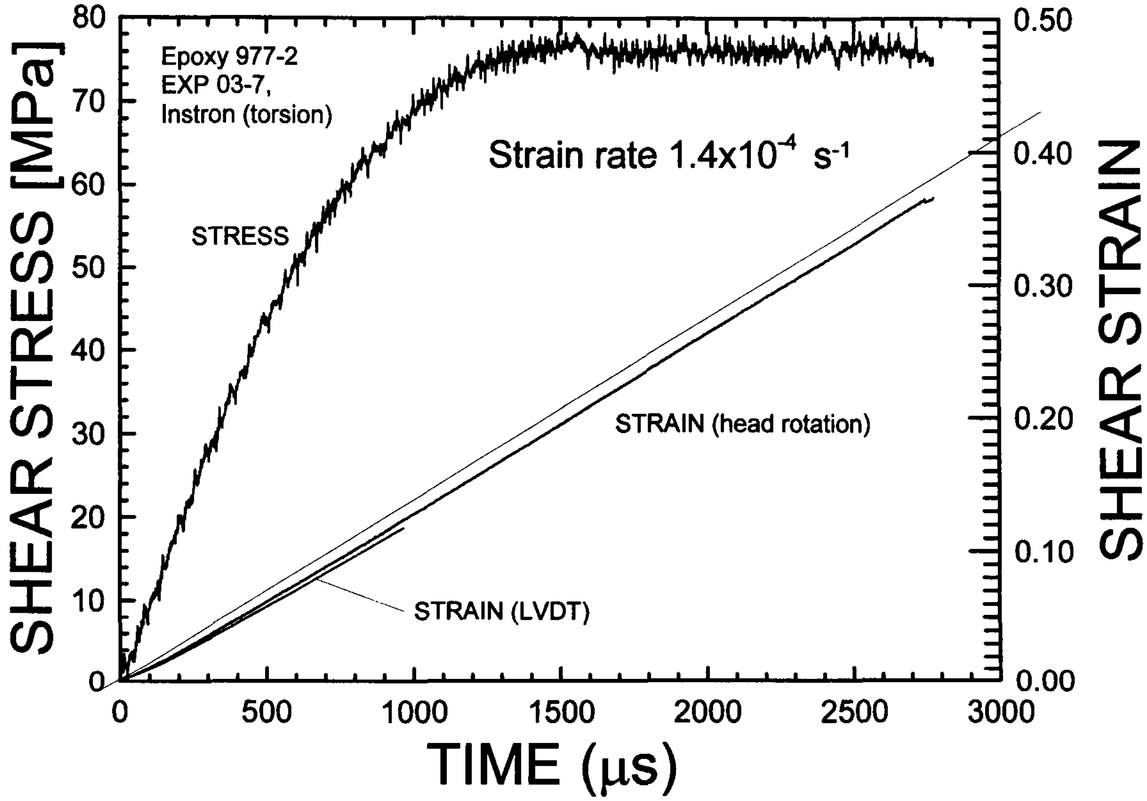

SHEAR STRESS [MPa]
epoxy PR-520
EXP02-5, Torsional split Hopkinson bar
SHEAR STRAIN

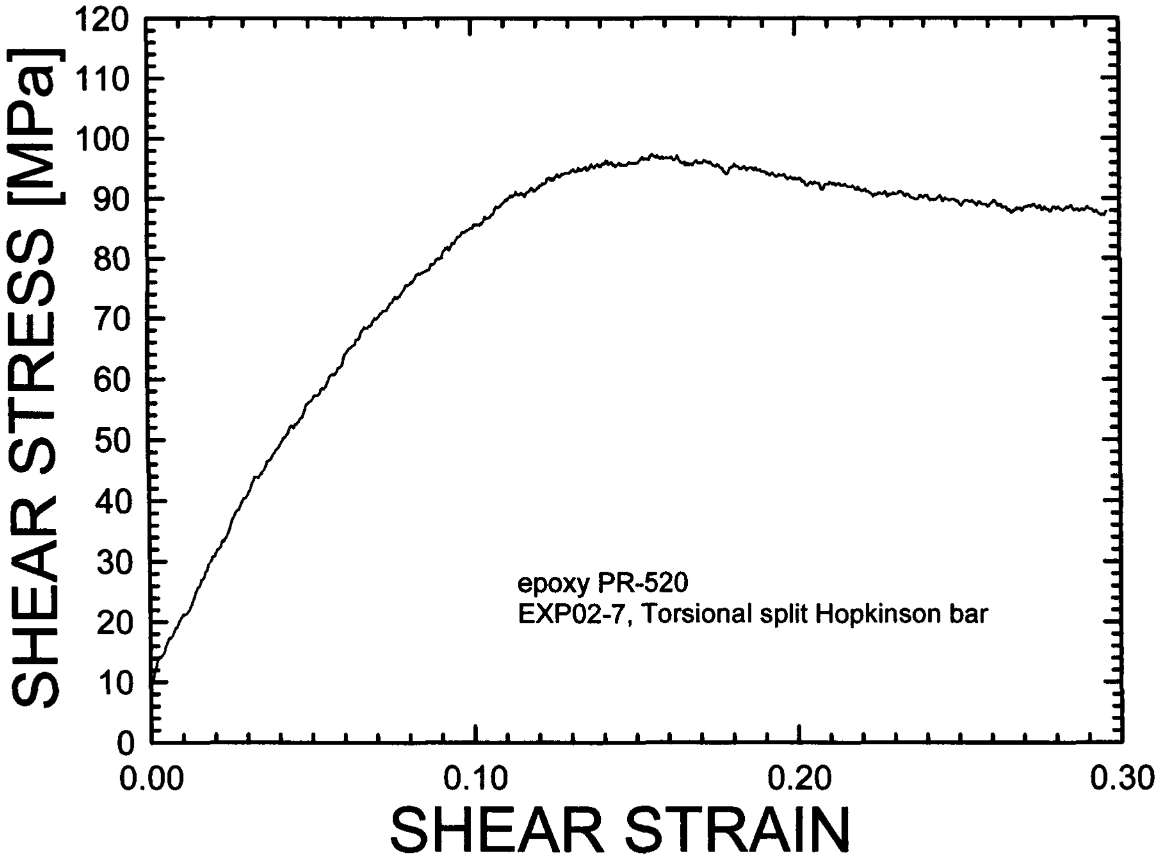


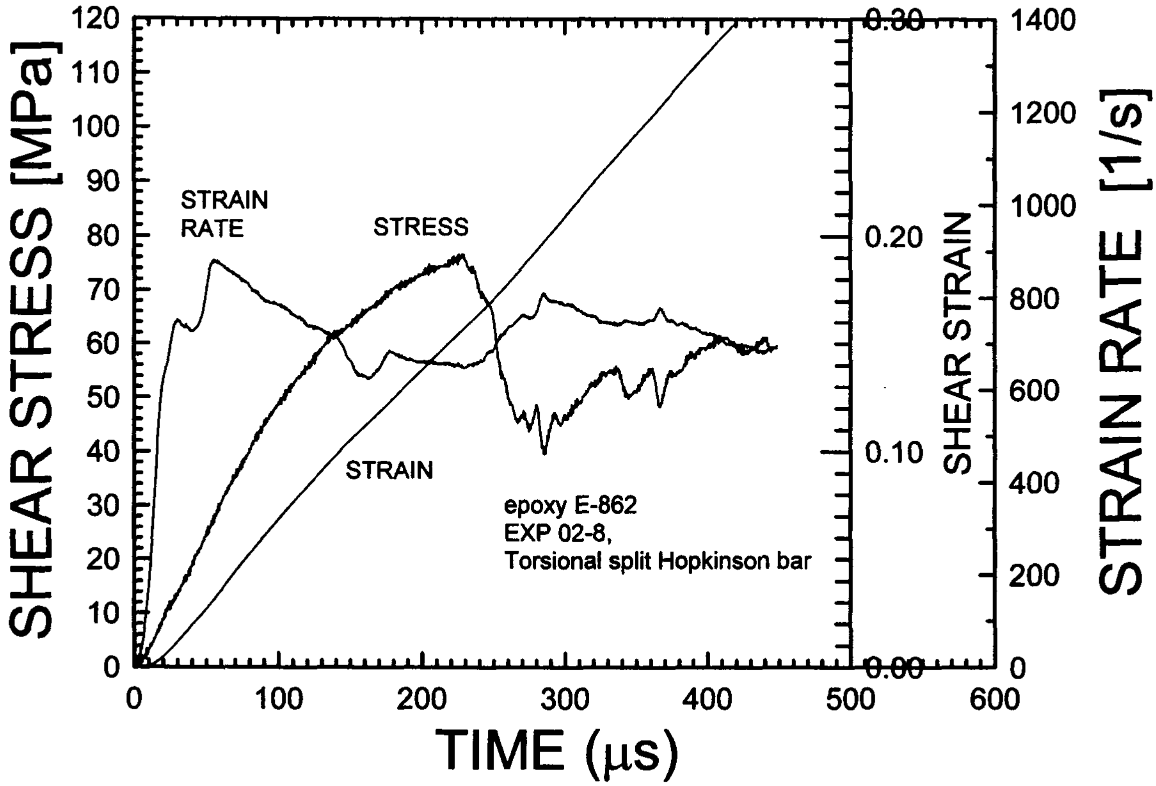
SHEAR STRESS [MPa]
STRAIN RATE
STRESS
STRAIN
epoxy E-862
EXP 02-6,
Torsional split Hopkinson bar
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

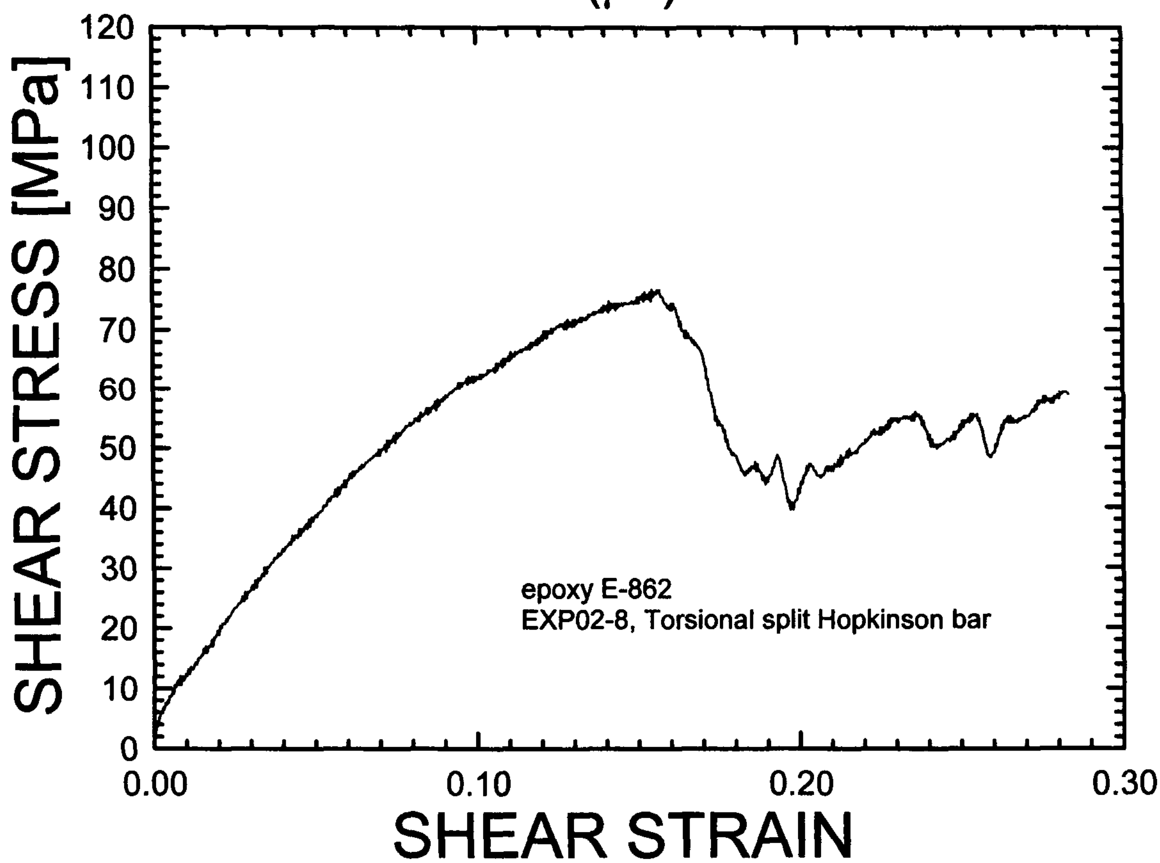


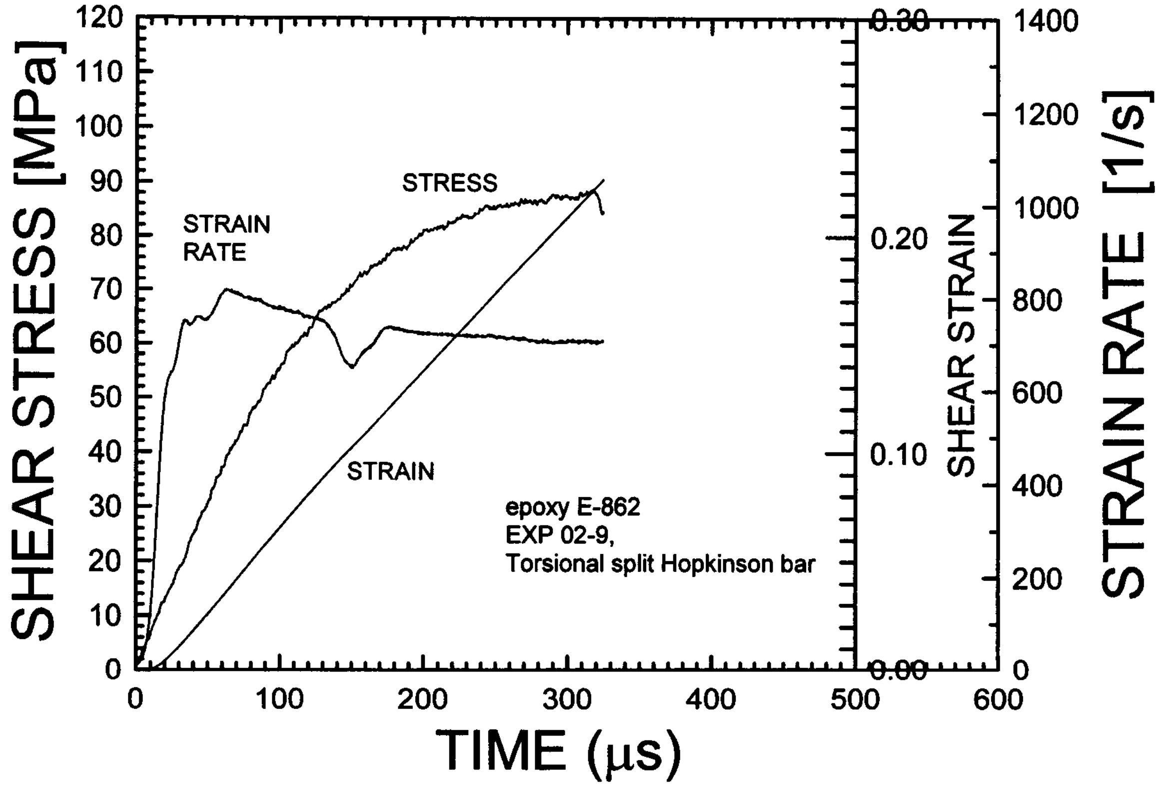
SHEAR STRESS [MPa]
epoxy E-862
EXP02-6, Torsional split Hopkinson bar
SHEAR STRAIN


Epoxy 977-2
EXP 03-7,
Instron (torsion)
Strain rate 1.4x10^-4 s^-1
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)
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

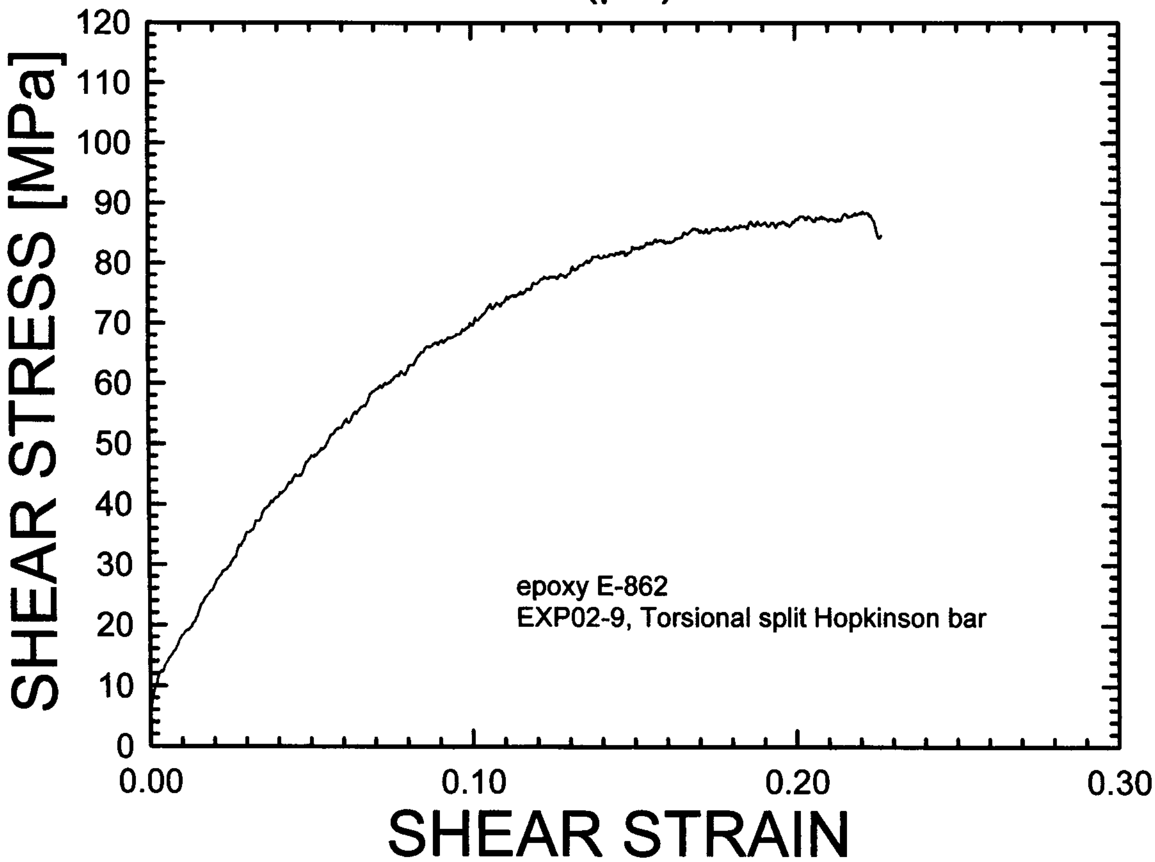

epoxy PR-520
EXP02-7, Torsional split Hopkinson bar
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30


SHEAR STRESS [MPa]
STRAIN RATE
STRESS
STRAIN
epoxy E-862
EXP 02-8,
Torsional split Hopkinson bar
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

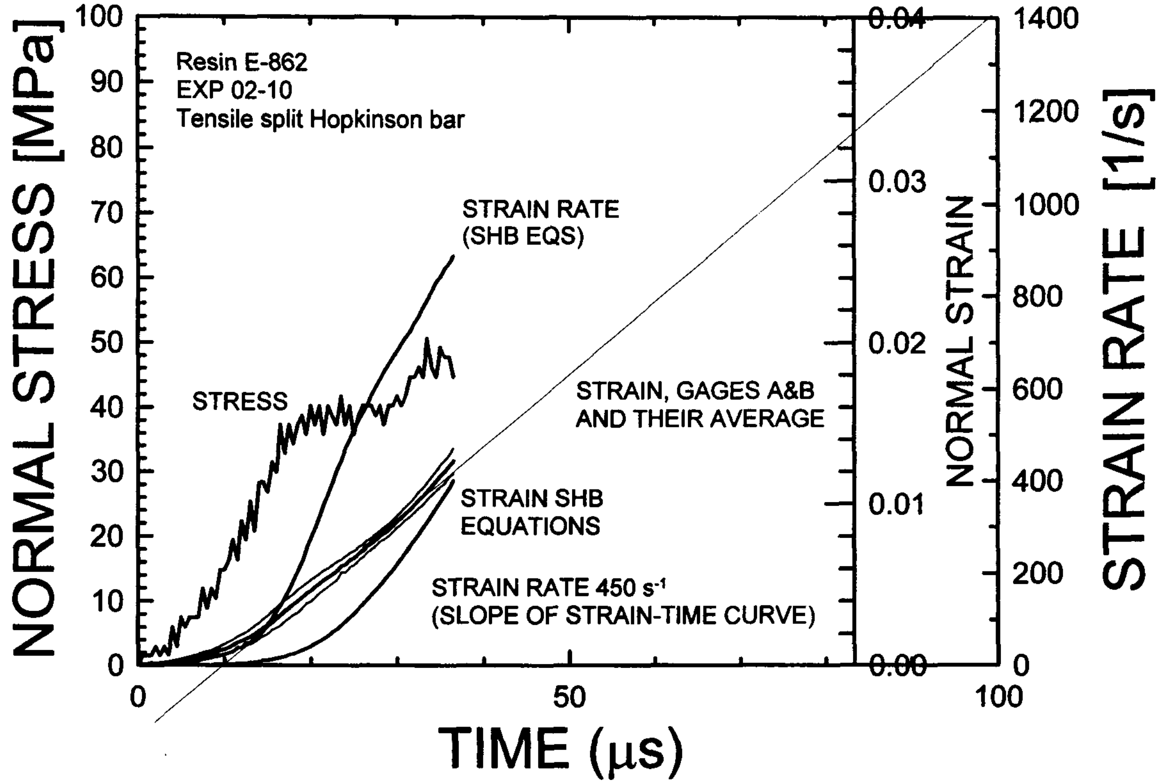

SHEAR STRESS [MPa]
epoxy E-862
EXP02-8, Torsional split Hopkinson bar
SHEAR STRAIN



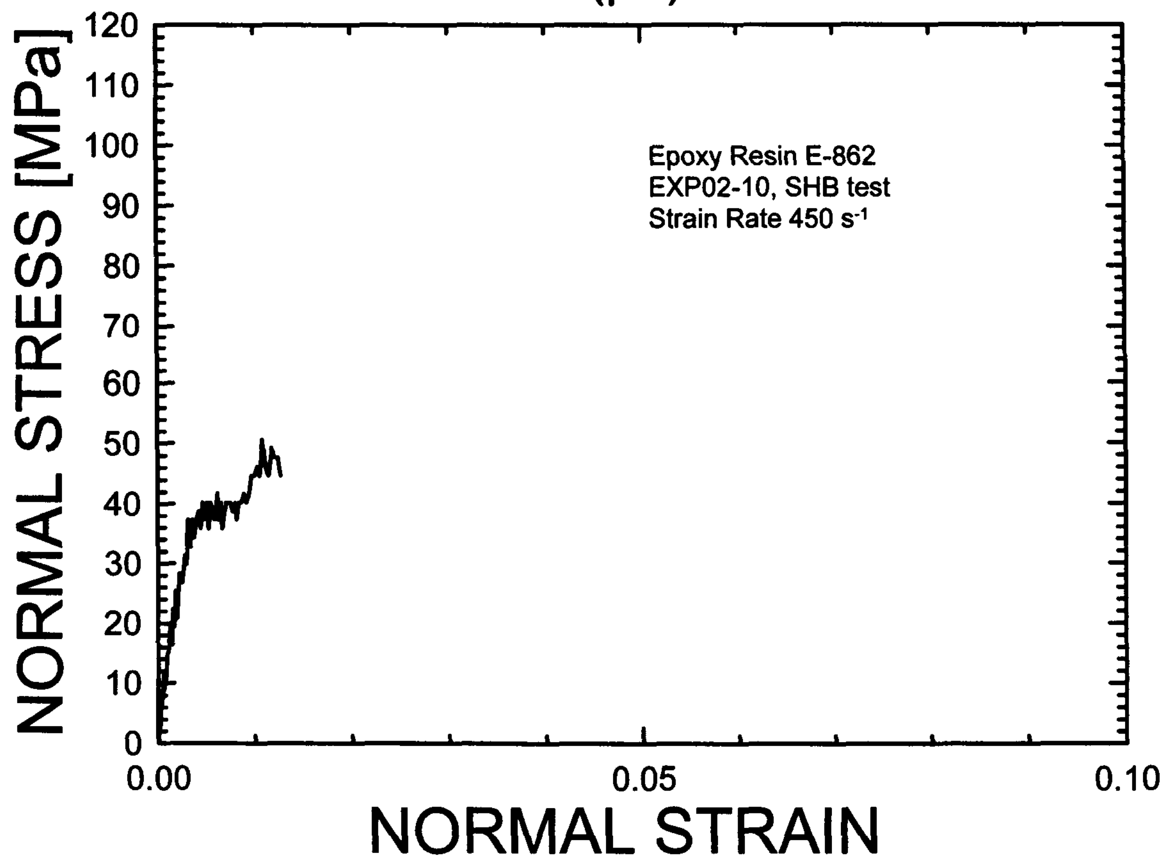
SHEAR STRESS [MPa]
STRAIN RATE
STRESS
STRAIN
epoxy E-862
EXP 02-9,
Torsional split Hopkinson bar
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)



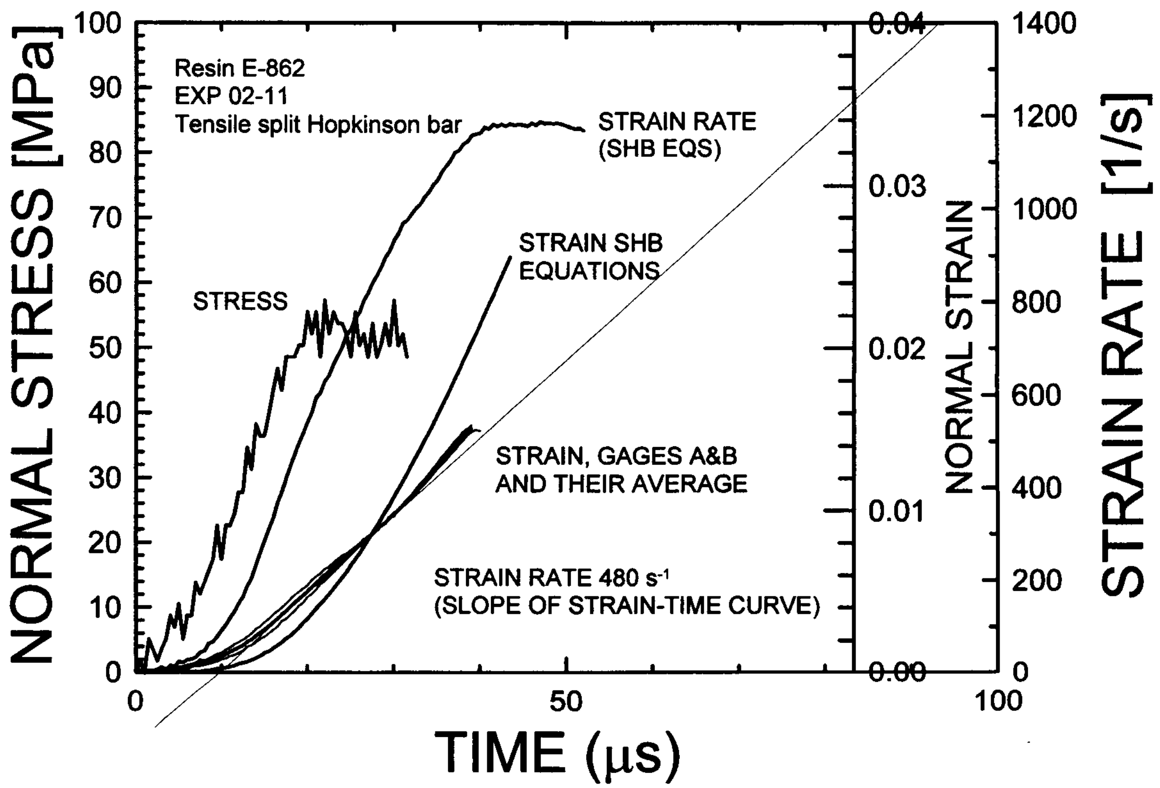
SHEAR STRESS [MPa]
epoxy E-862
EXP02-9, Torsional split Hopkinson bar
SHEAR STRAIN

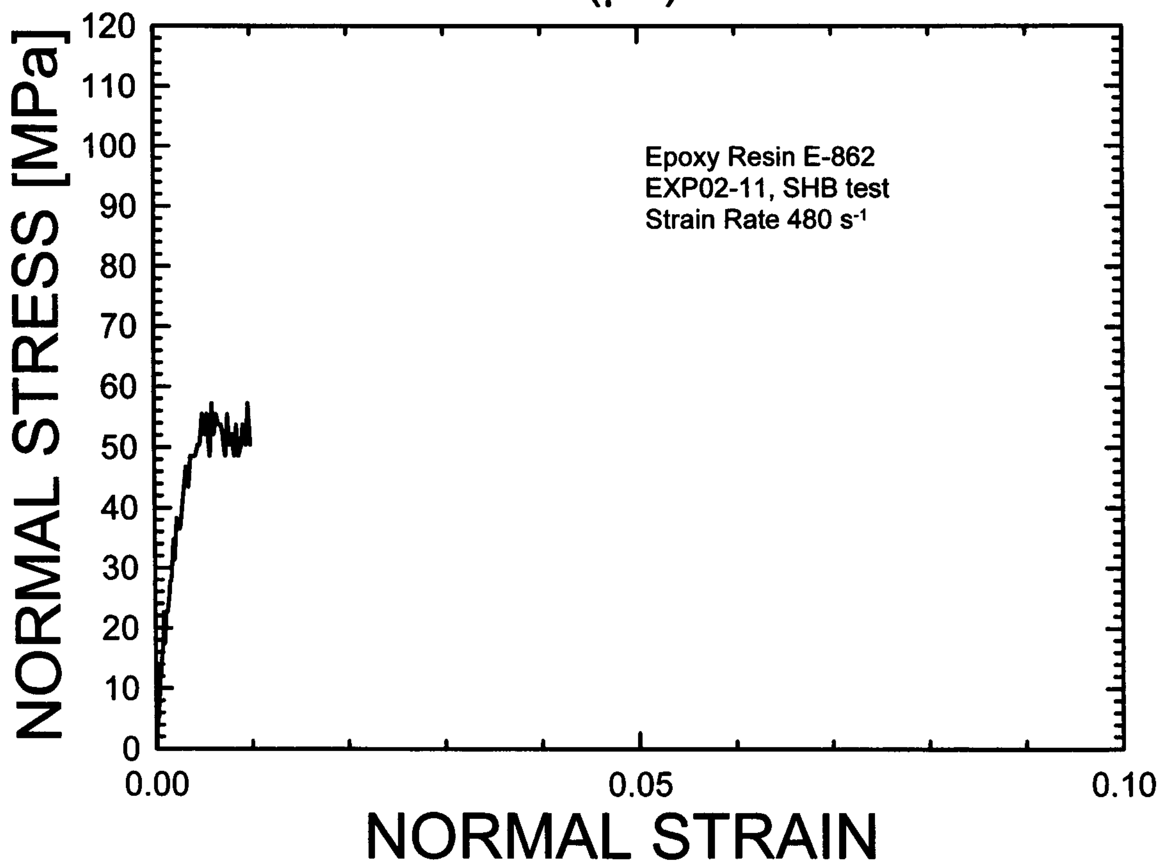


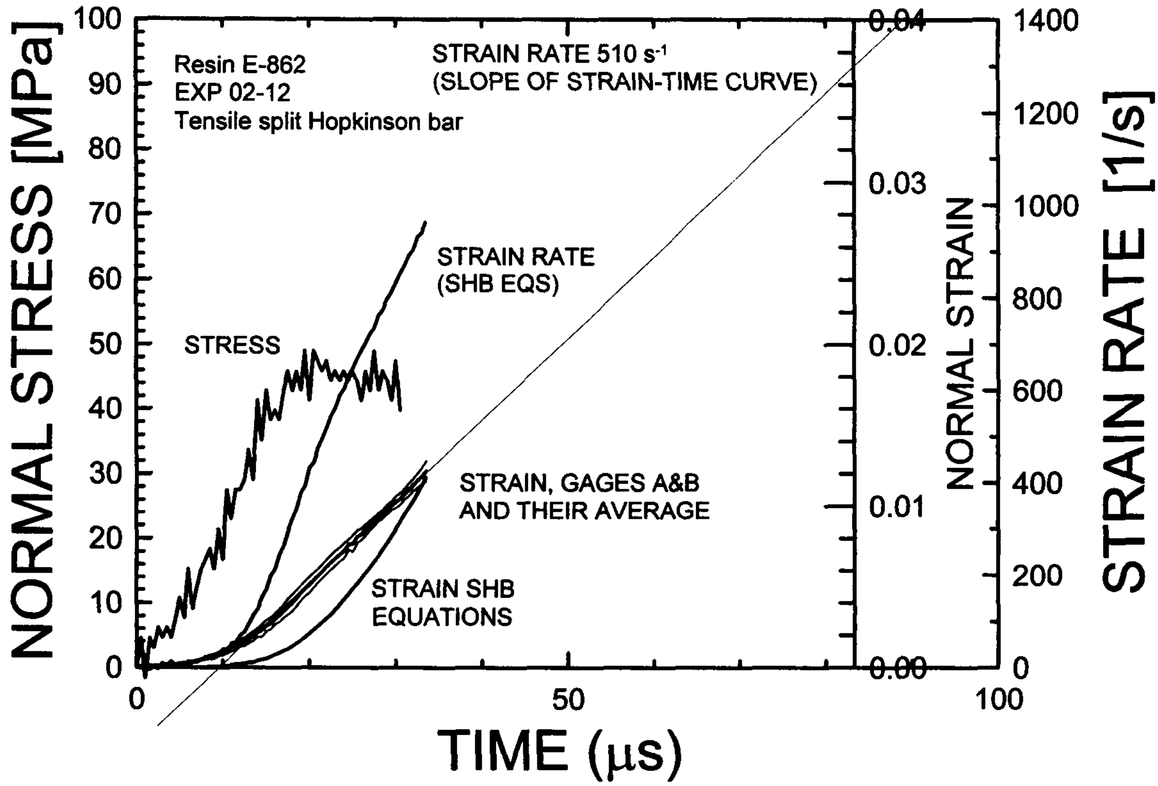
Resin E-862
EXP 02-10
Tensile split Hopkinson bar
STRAIN RATE
(SHB EQS)
STRESS
STRAIN, GAGES A&B
AND THEIR AVERAGE
STRAIN SHB
EQUATIONS
STRAIN RATE 450 s-1
(SLOPE OF STRAIN-TIME CURVE)
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

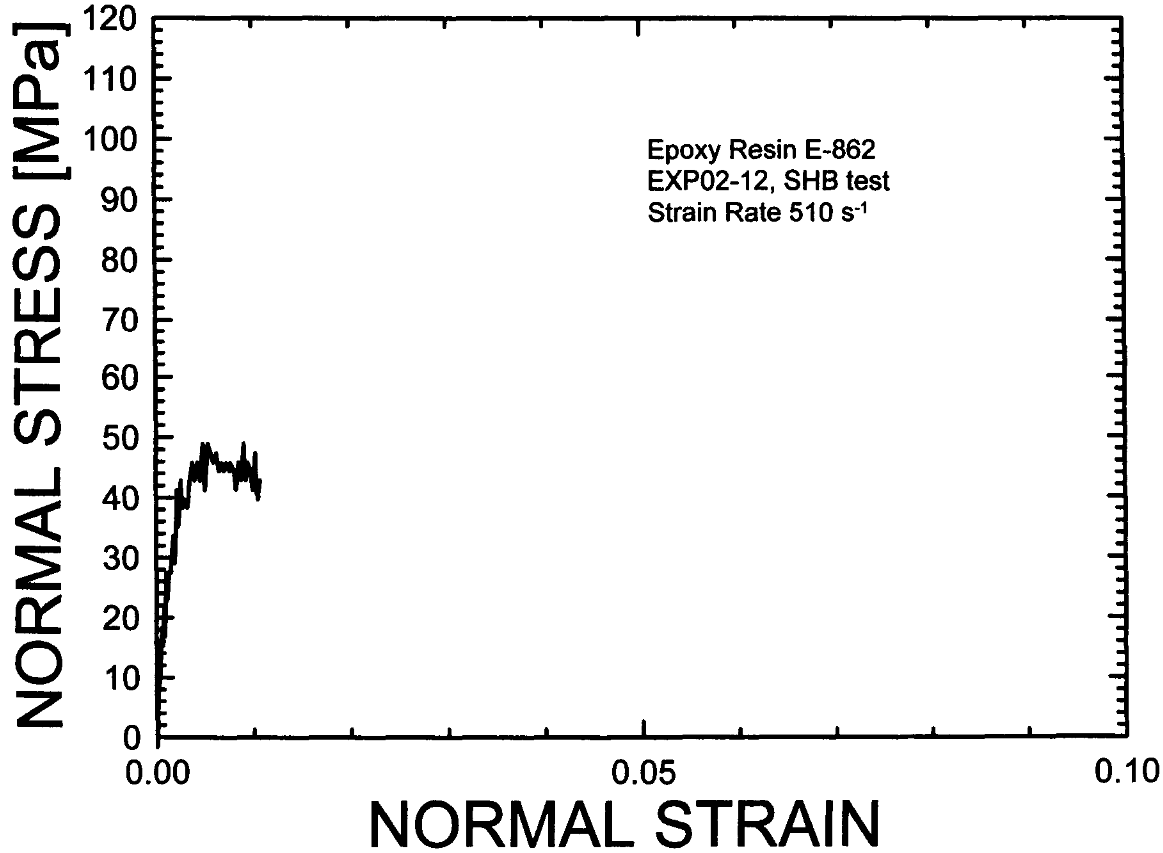


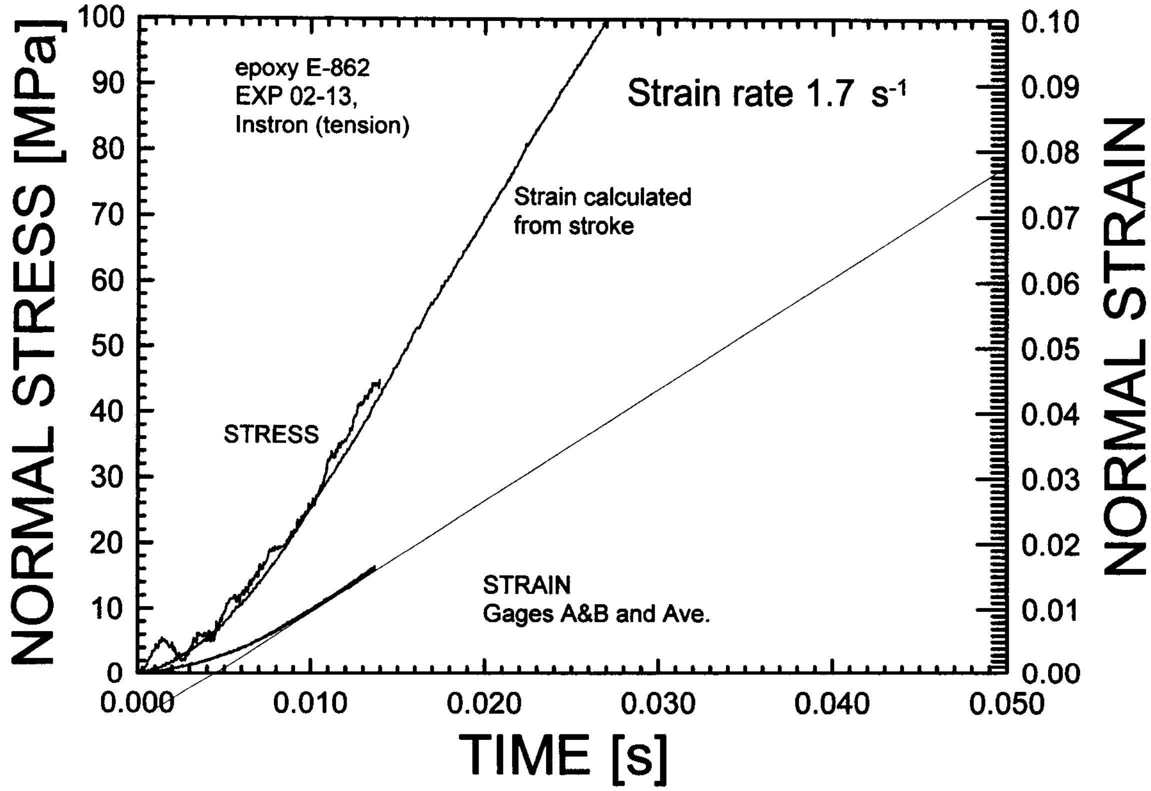
Epoxy Resin E-862
EXP02-10, SHB test
Strain Rate 450 s-1
NORMAL STRESS [MPa]
NORMAL STRAIN

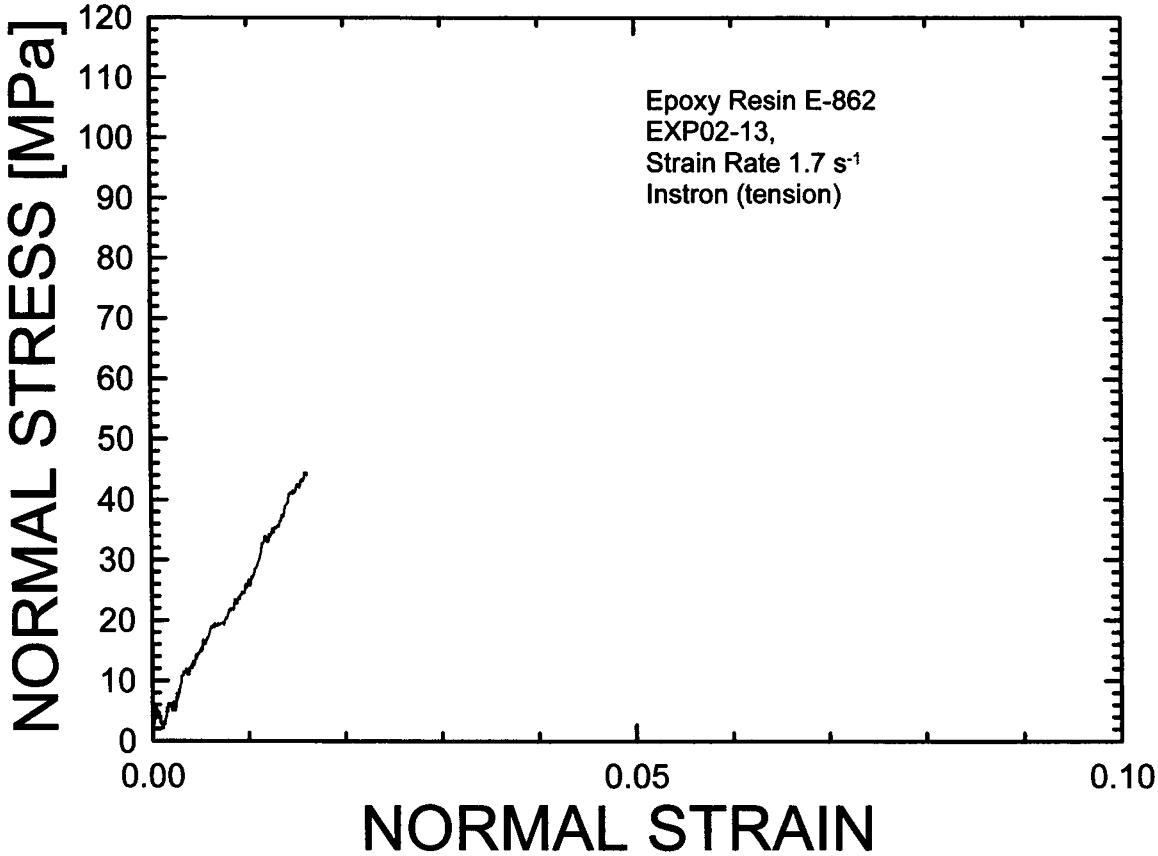

Resin E-862
EXP 02-11
Tensile split Hopkinson bar
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
STRESS
STRAIN, GAGES A&B
AND THEIR AVERAGE
STRAIN RATE 480 s-1
(SLOPE OF STRAIN-TIME CURVE)
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)
0
10
20
30
40
50
60
70
80
90
100
0.00
0.01
0.02
0.03
0.04
200
400
600
800
1000
1200
1400
50
100

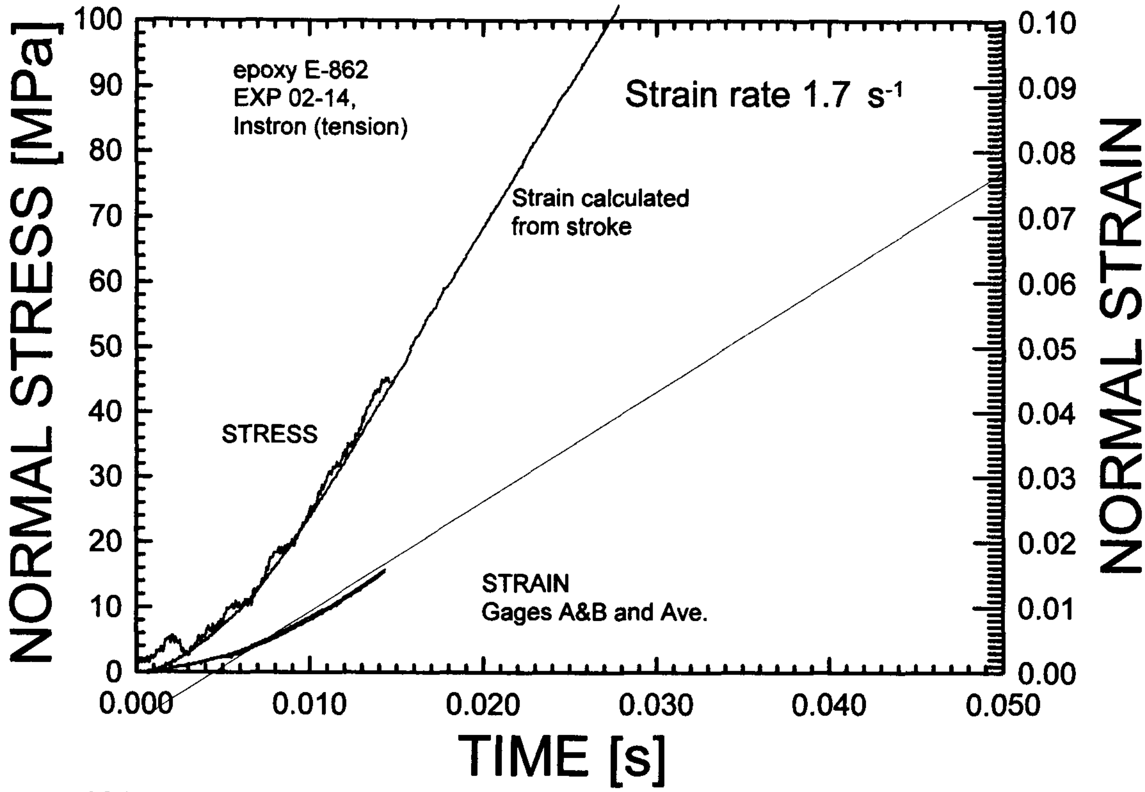

Epoxy Resin E-862
EXP02-11, SHB test
Strain Rate 480 s-1
NORMAL STRESS [MPa]
NORMAL STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.05
0.10

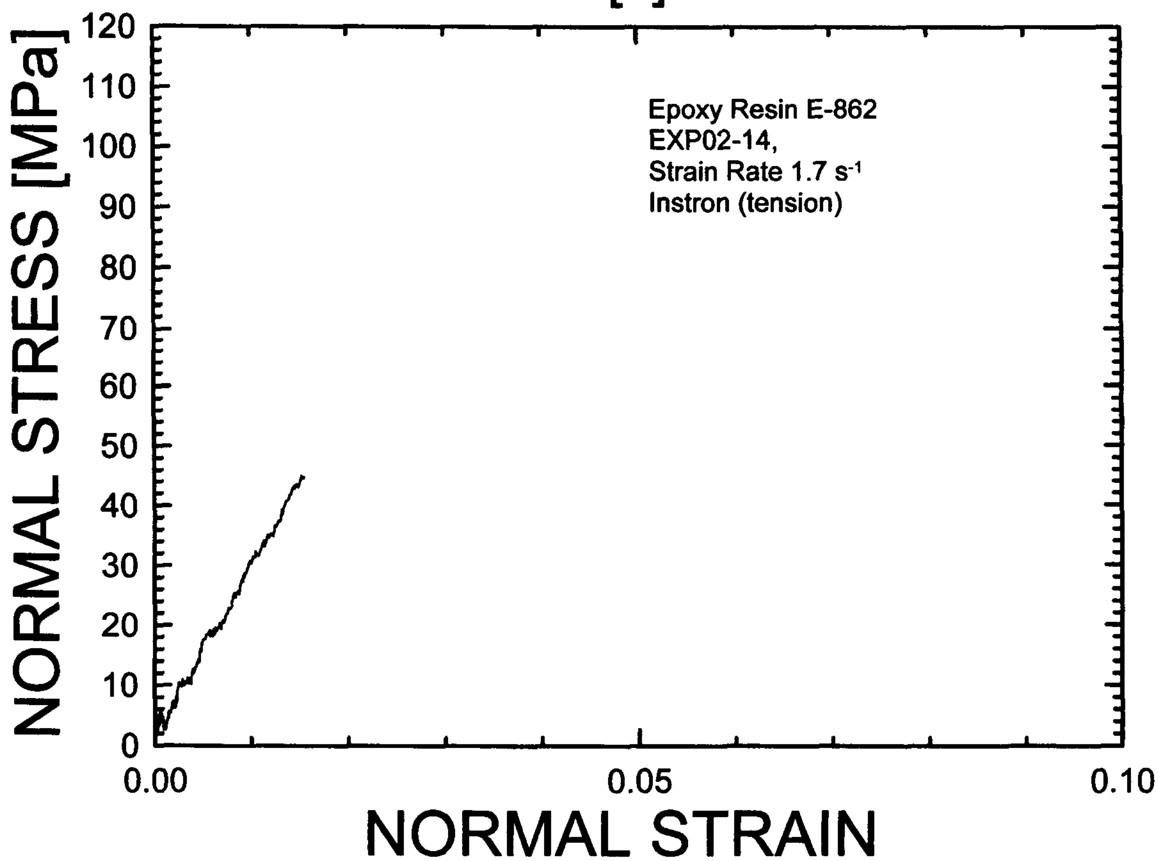

Resin E-862
EXP 02-12
Tensile split Hopkinson bar
STRAIN RATE 510 s-1
(SLOPE OF STRAIN-TIME CURVE)
STRAIN RATE
(SHB EQS)
STRESS
STRAIN, GAGES A&B
AND THEIR AVERAGE
STRAIN SHB
EQUATIONS
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)
0
10
20
30
40
50
60
70
80
90
100
0.00
0.01
0.02
0.03
0.04
200
400
600
800
1000
1200
1400

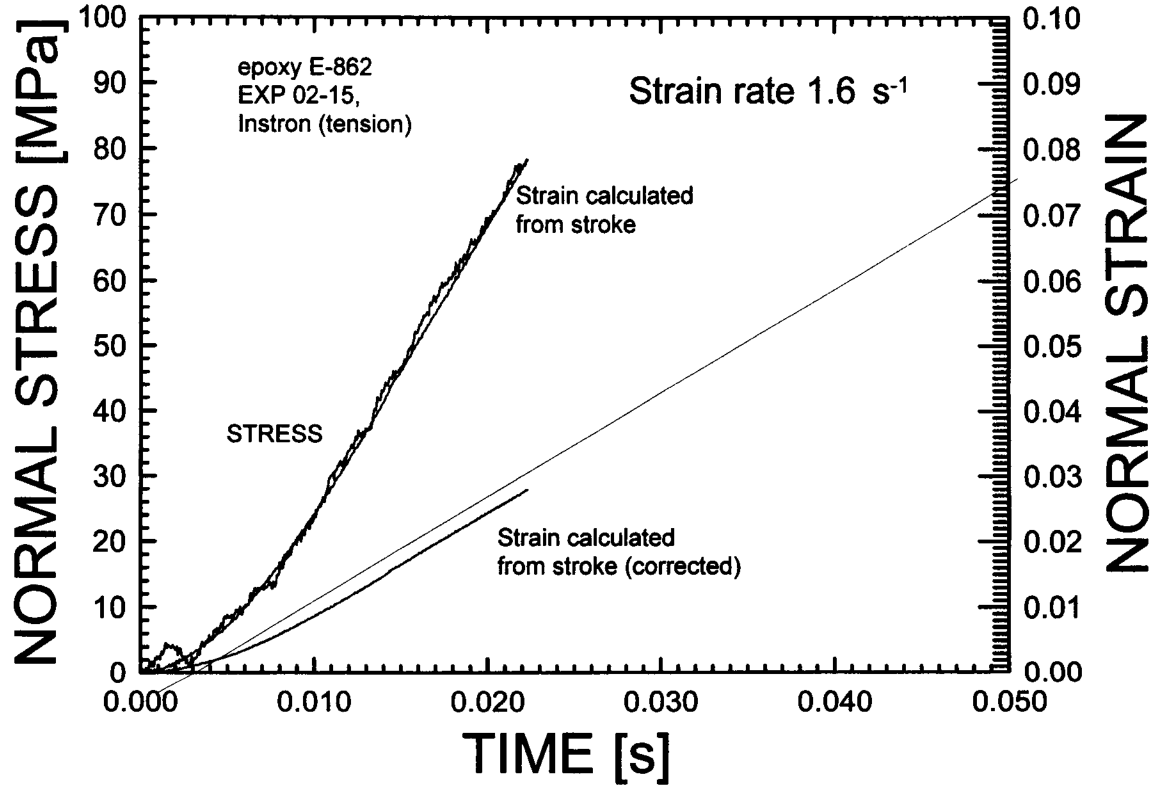

Epoxy Resin E-862
EXP02-12, SHB test
Strain Rate 510 s-1
NORMAL STRESS [MPa]
NORMAL STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.05
0.10

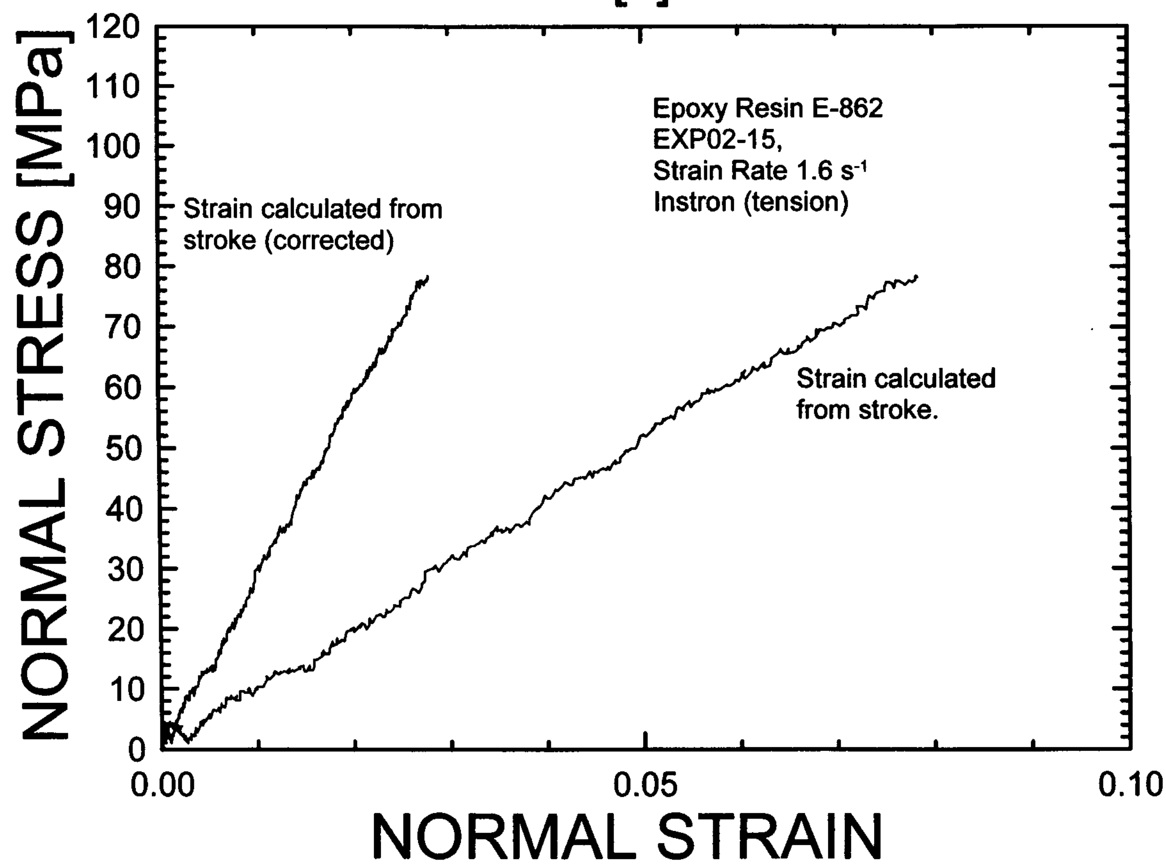

epoxy E-862
EXP 02-13,
Instron (tension)
Strain rate 1.7 s^{-1}
Strain calculated
from stroke
STRESS
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]

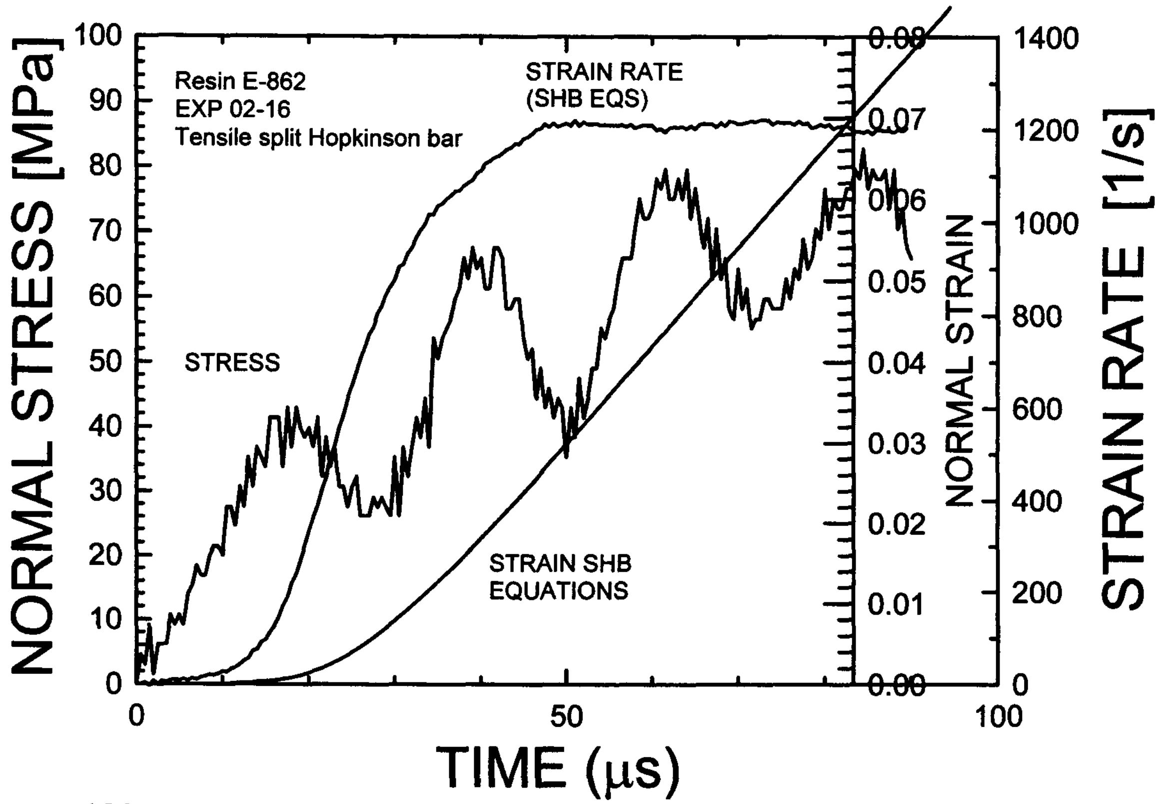

Epoxy Resin E-862
EXP02-13,
Strain Rate 1.7 s^{-1}
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN


epoxy E-862
EXP 02-14,
Instron (tension)
Strain rate 1.7 s^{-1}
Strain calculated from stroke
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

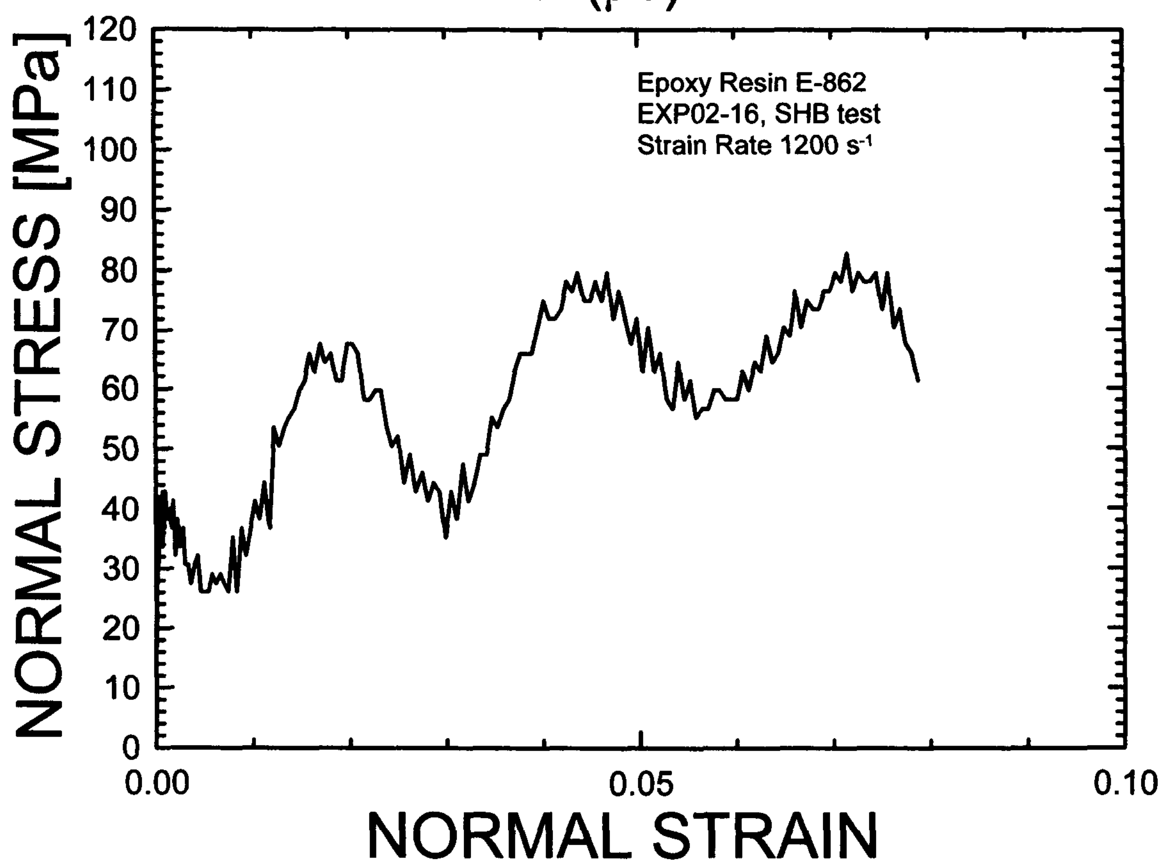

Epoxy Resin E-862
EXP02-14,
Strain Rate 1.7 s^{-1}
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN
120
110
100
90
80
70
60
50
40
30
20
10
0
0.00
0.05
0.10


NORMAL STRESS [MPa]
epoxy E-862
EXP 02-15,
Instron (tension)
Strain rate 1.6 s^{-1}
Strain calculated from stroke
STRESS
Strain calculated from stroke (corrected)
TIME [s]
NORMAL STRAIN

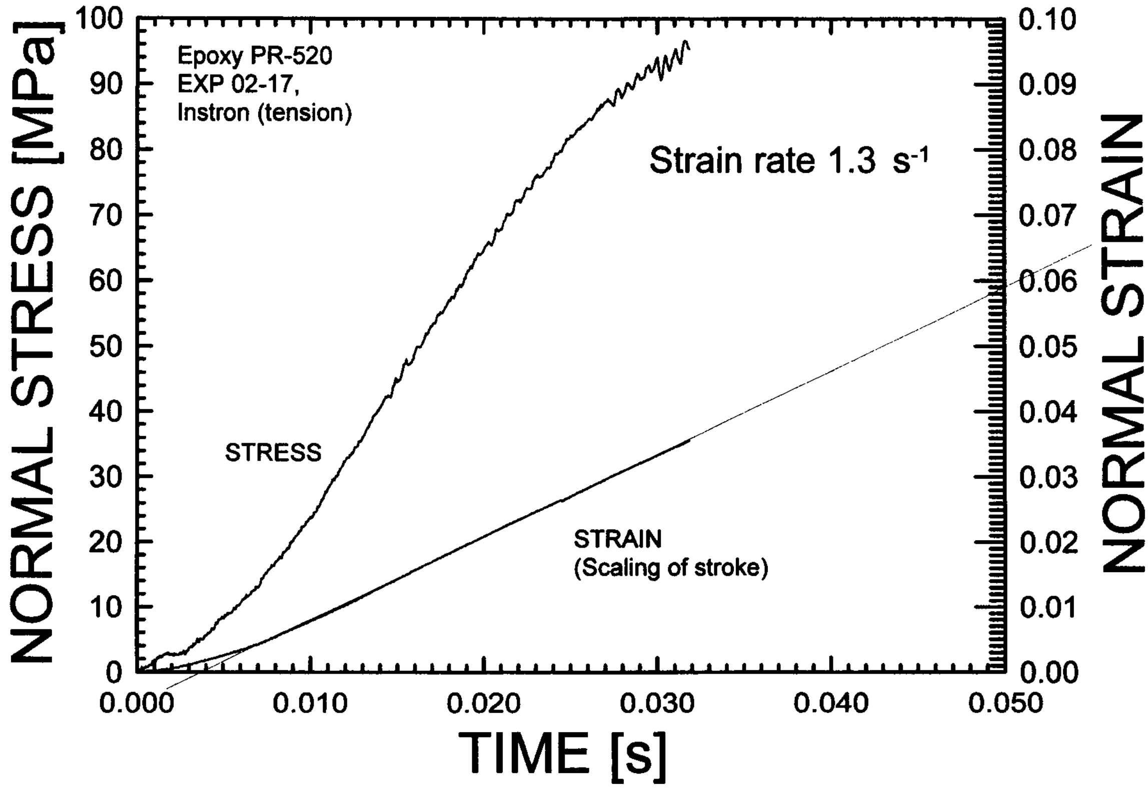

NORMAL STRESS [MPa]
Epoxy Resin E-862
EXP02-15,
Strain Rate 1.6 s^{-1}
Instron (tension)
Strain calculated from stroke (corrected)
Strain calculated from stroke.
NORMAL STRAIN

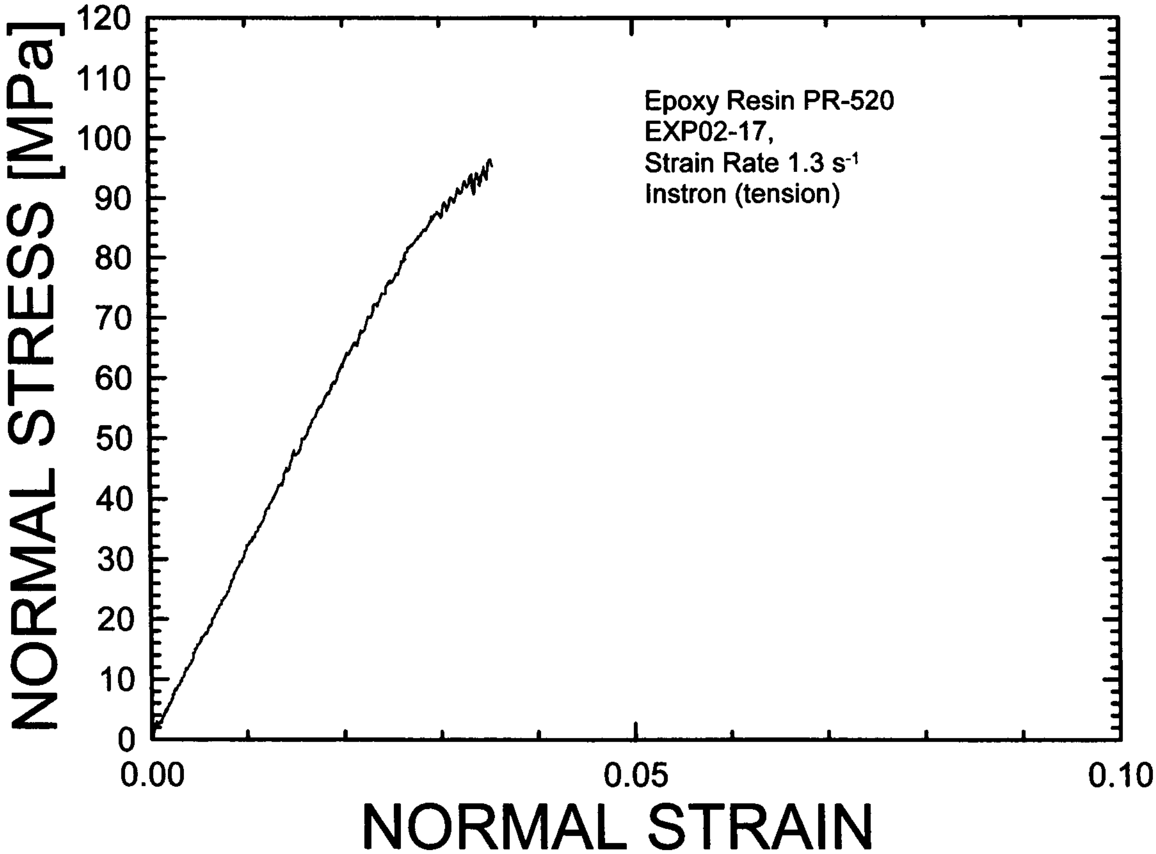


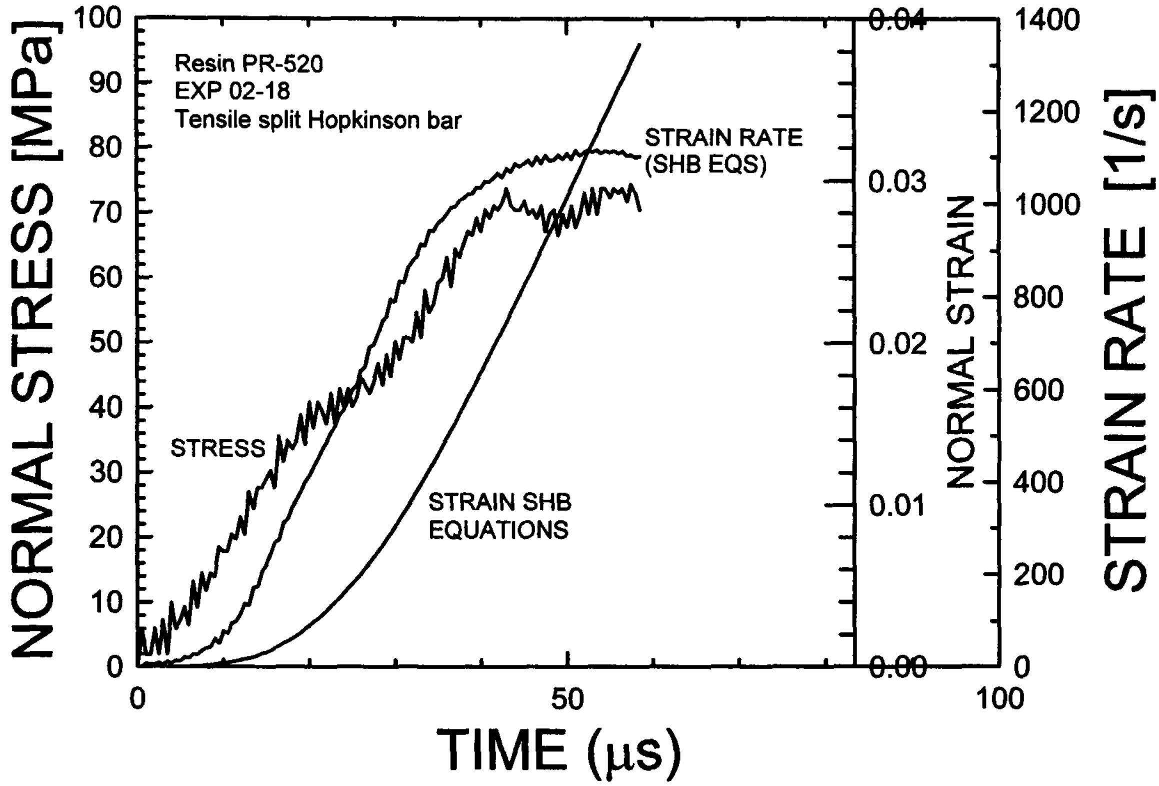
Resin E-862
EXP 02-16
Tensile split Hopkinson bar
STRAIN RATE
(SHB EQS)
STRESS
STRAIN SHB
EQUATIONS
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)



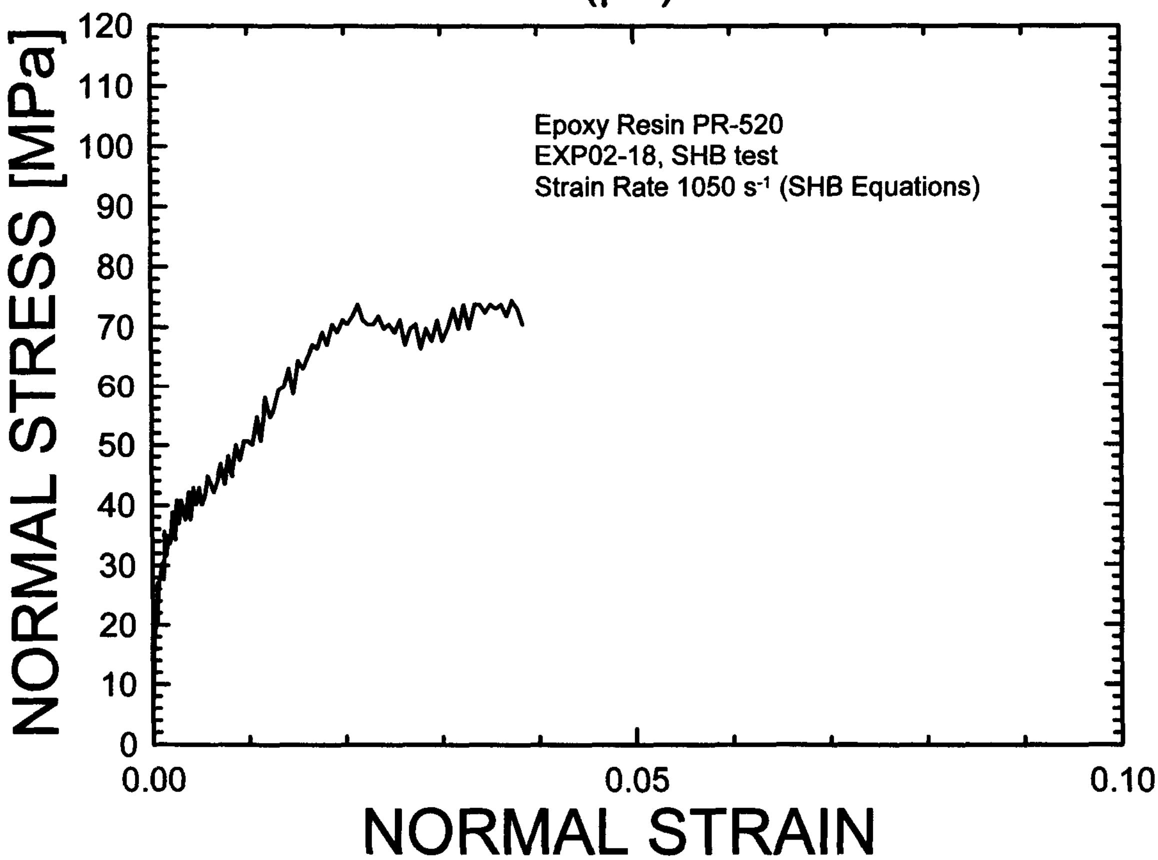
Epoxy Resin E-862
EXP02-16, SHB test
Strain Rate 1200 s-1
NORMAL STRESS [MPa]
NORMAL STRAIN


Epoxy PR-520
EXP 02-17,
Instron (tension)
Strain rate 1.3 s-1
STRESS
STRAIN
(Scaling of stroke)
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

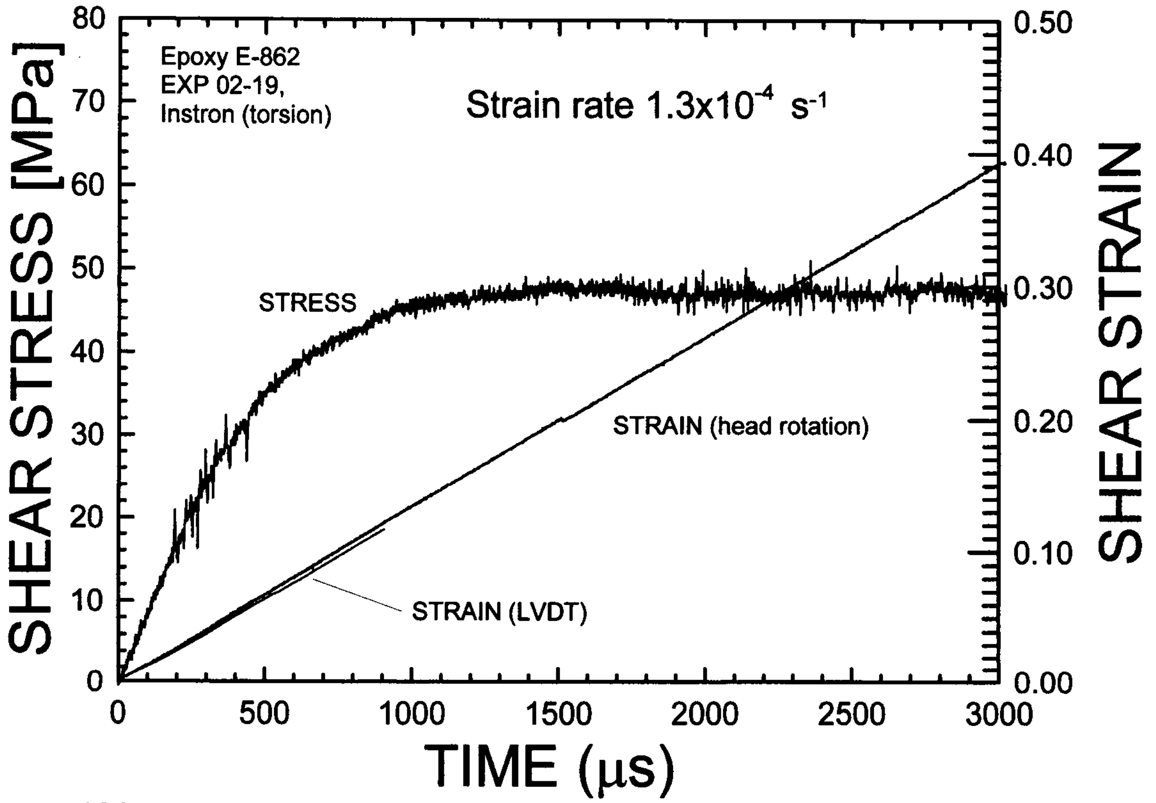

Epoxy Resin PR-520
EXP02-17,
Strain Rate 1.3 s-1
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN
120
110
100
90
80
70
60
50
40
30
20
10
0
0.00
0.05
0.10

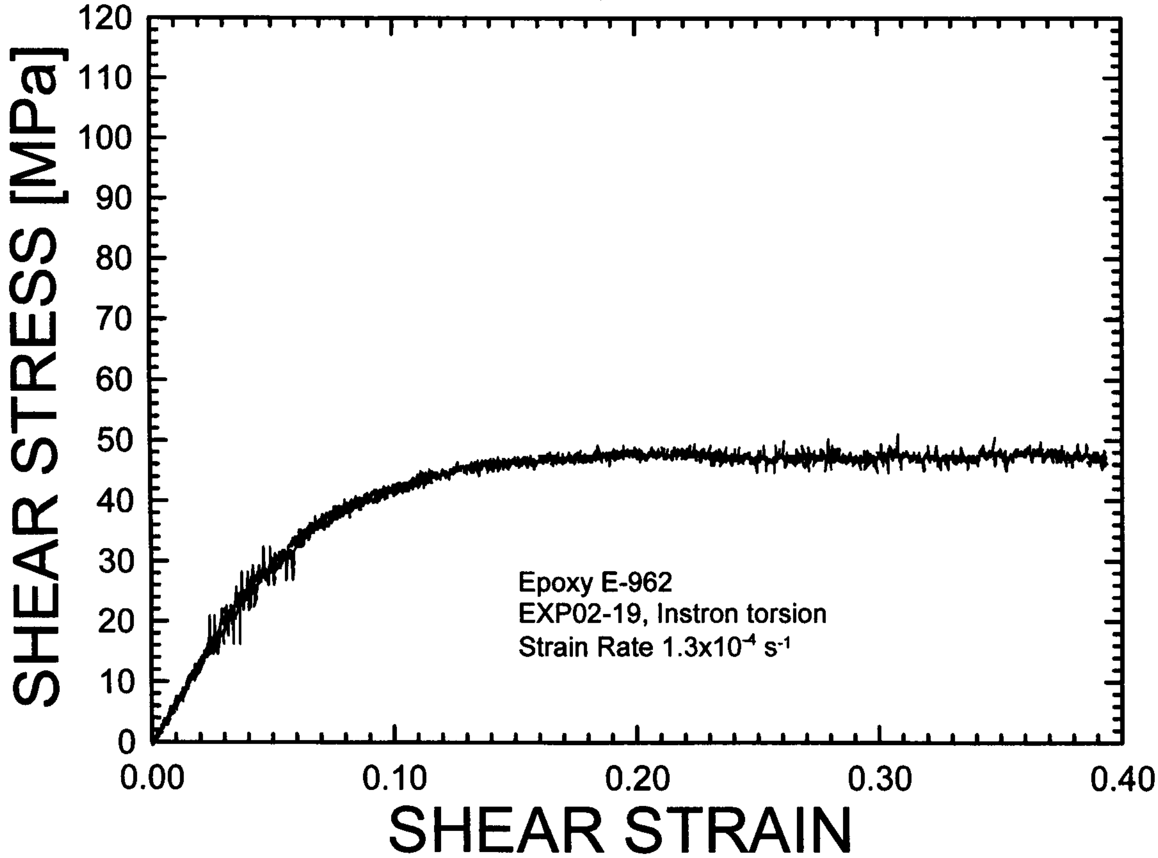


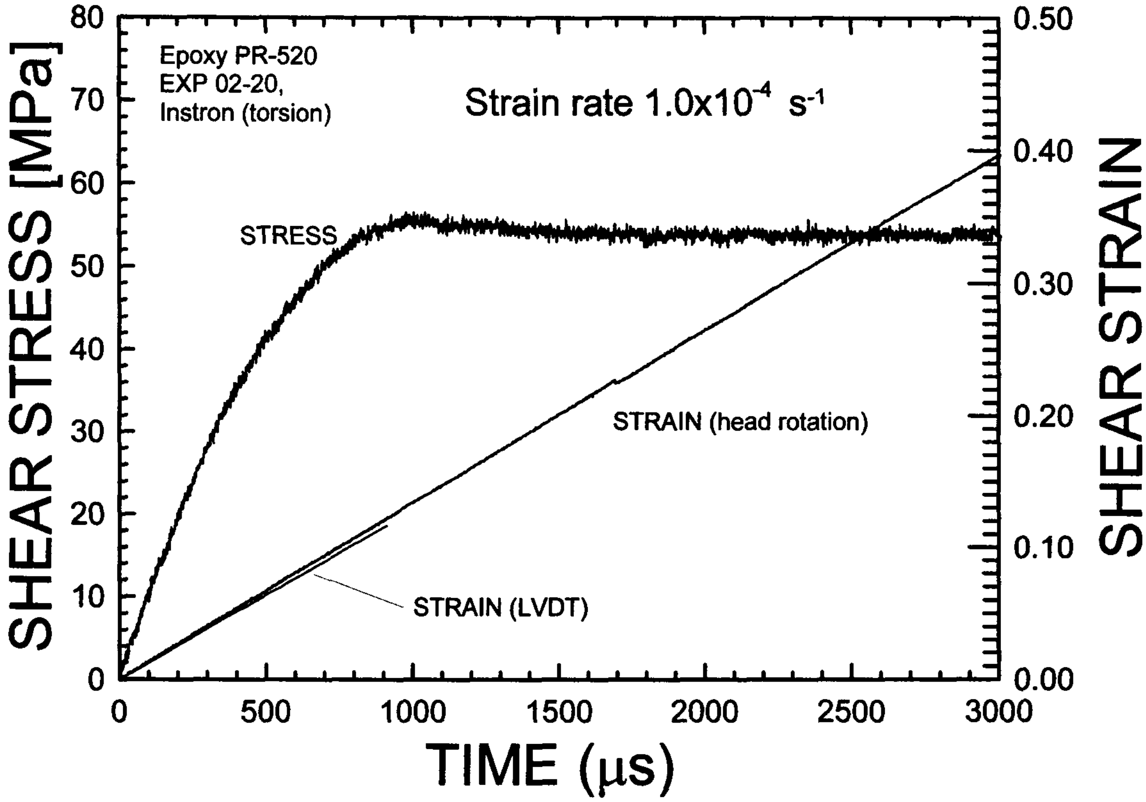
Resin PR-520
EXP 02-18
Tensile split Hopkinson bar
STRAIN RATE
(SHB EQS)
STRESS
STRAIN SHB
EQUATIONS
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

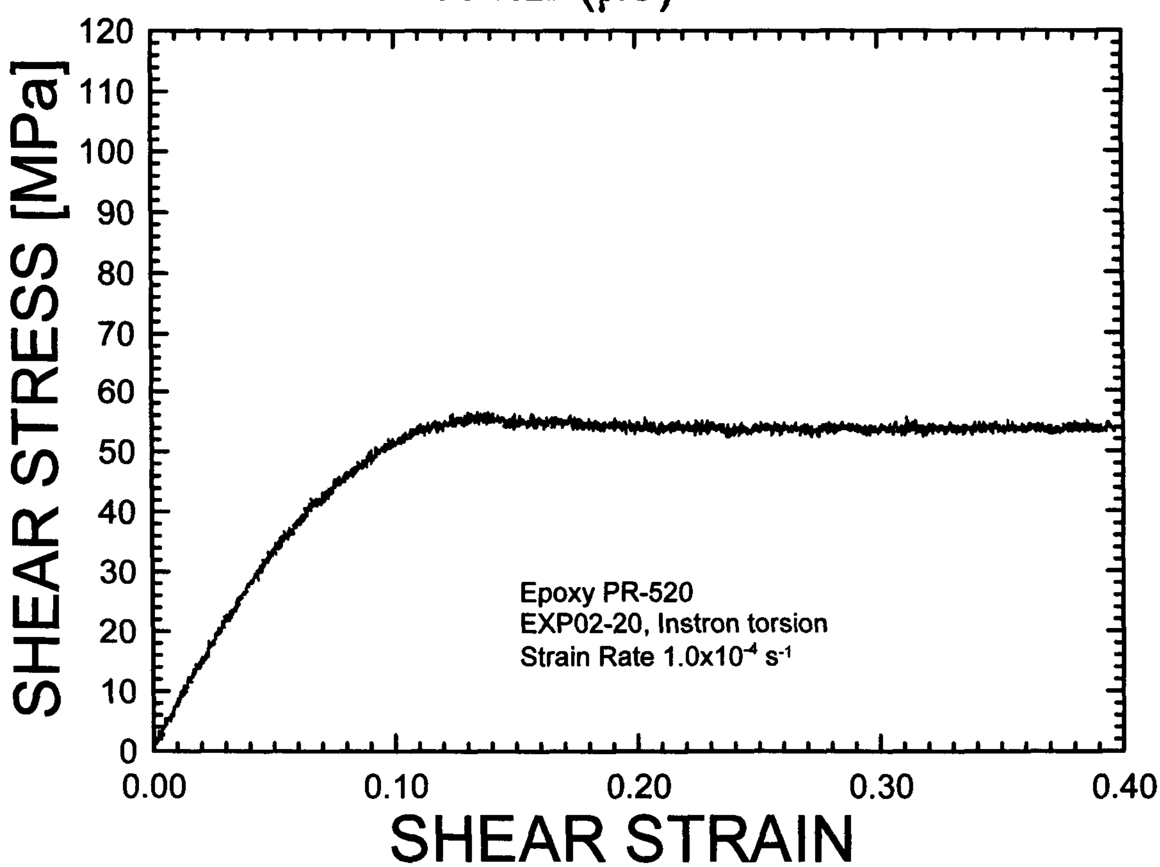


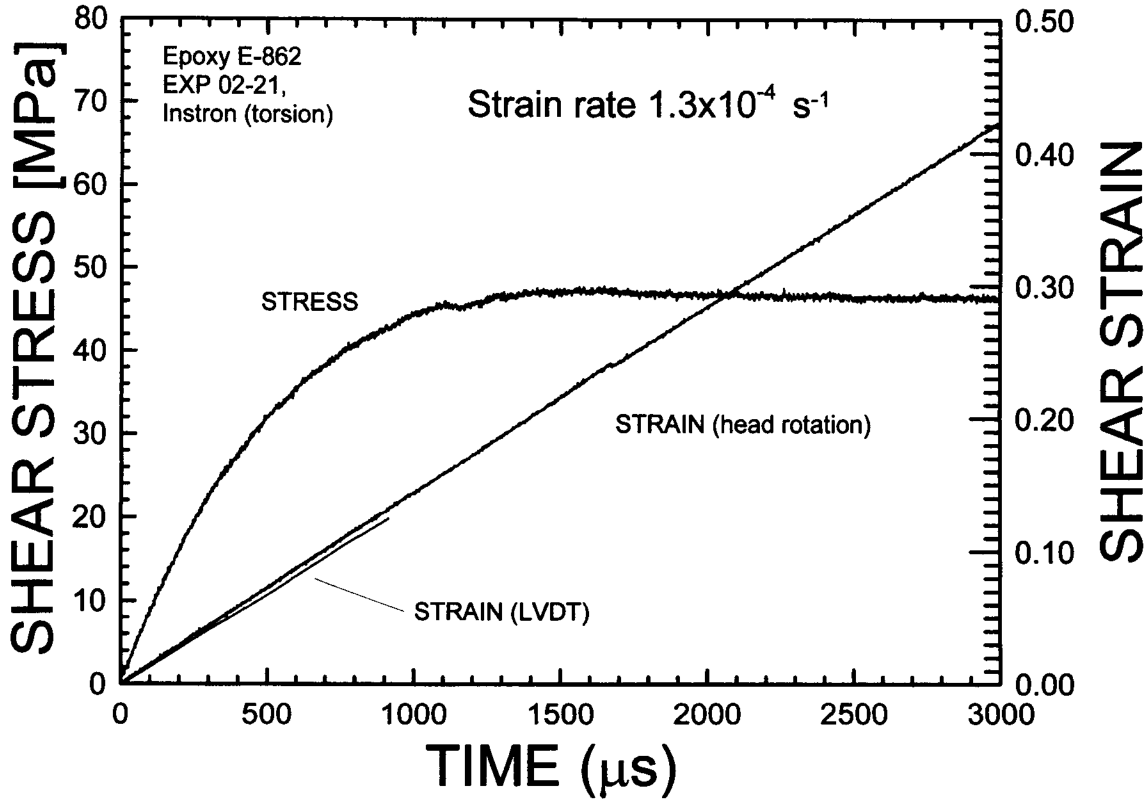
Epoxy Resin PR-520
EXP02-18, SHB test
Strain Rate 1050 s-1 (SHB Equations)
NORMAL STRESS [MPa]
NORMAL STRAIN

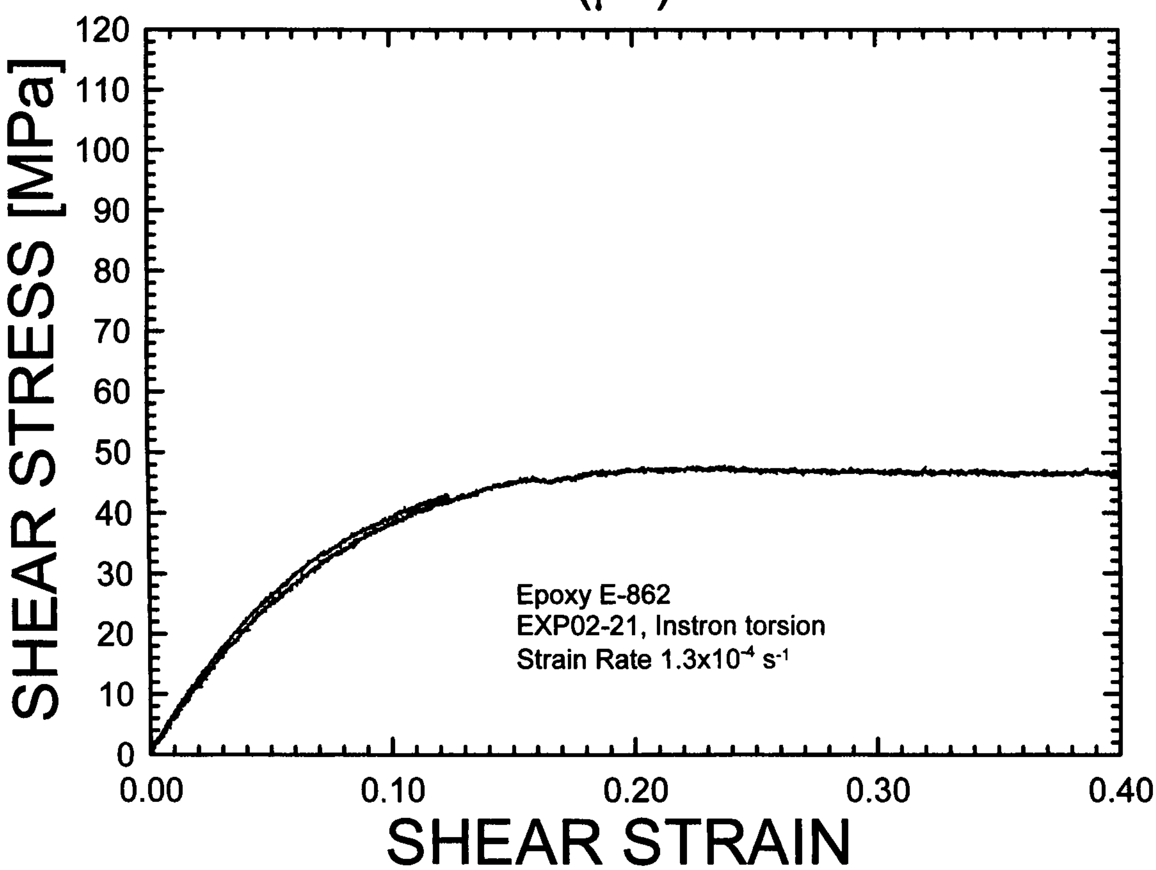

Epoxy E-862
EXP 02-19,
Instron (torsion)
Strain rate 1.3x10^{-4} s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)

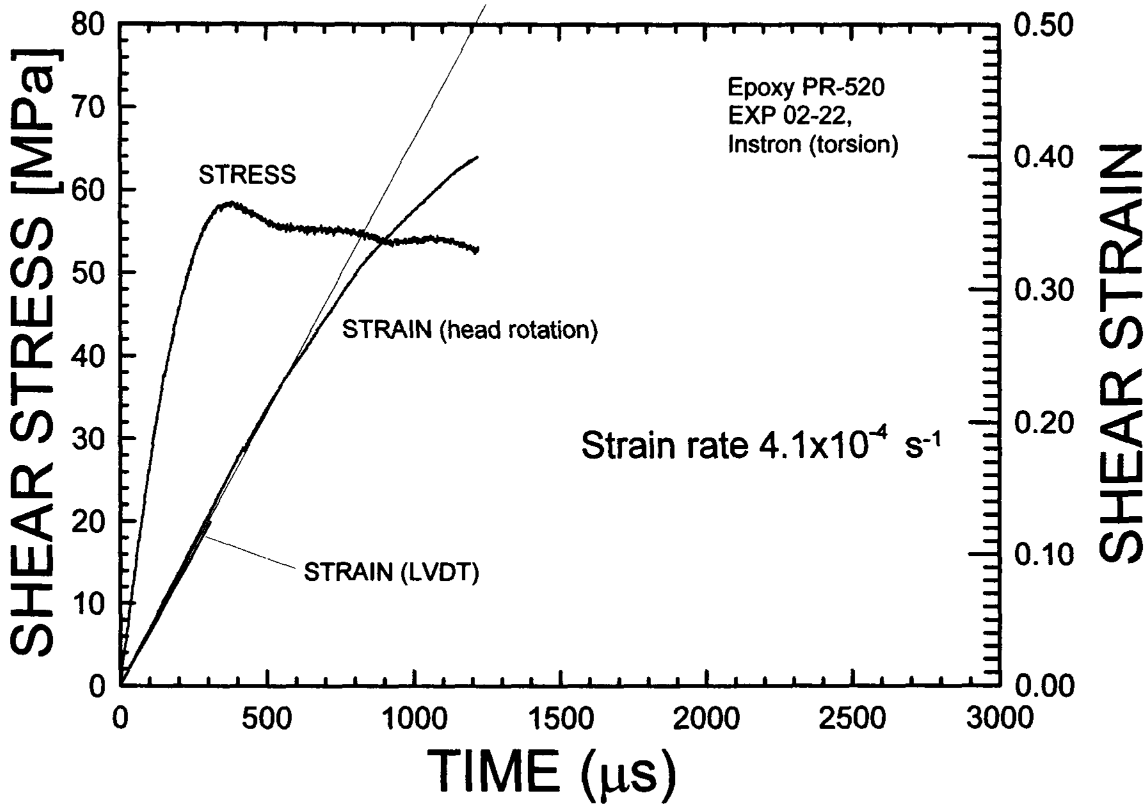

Epoxy E-962
EXP02-19, Instron torsion
Strain Rate 1.3x10^{-4} s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN

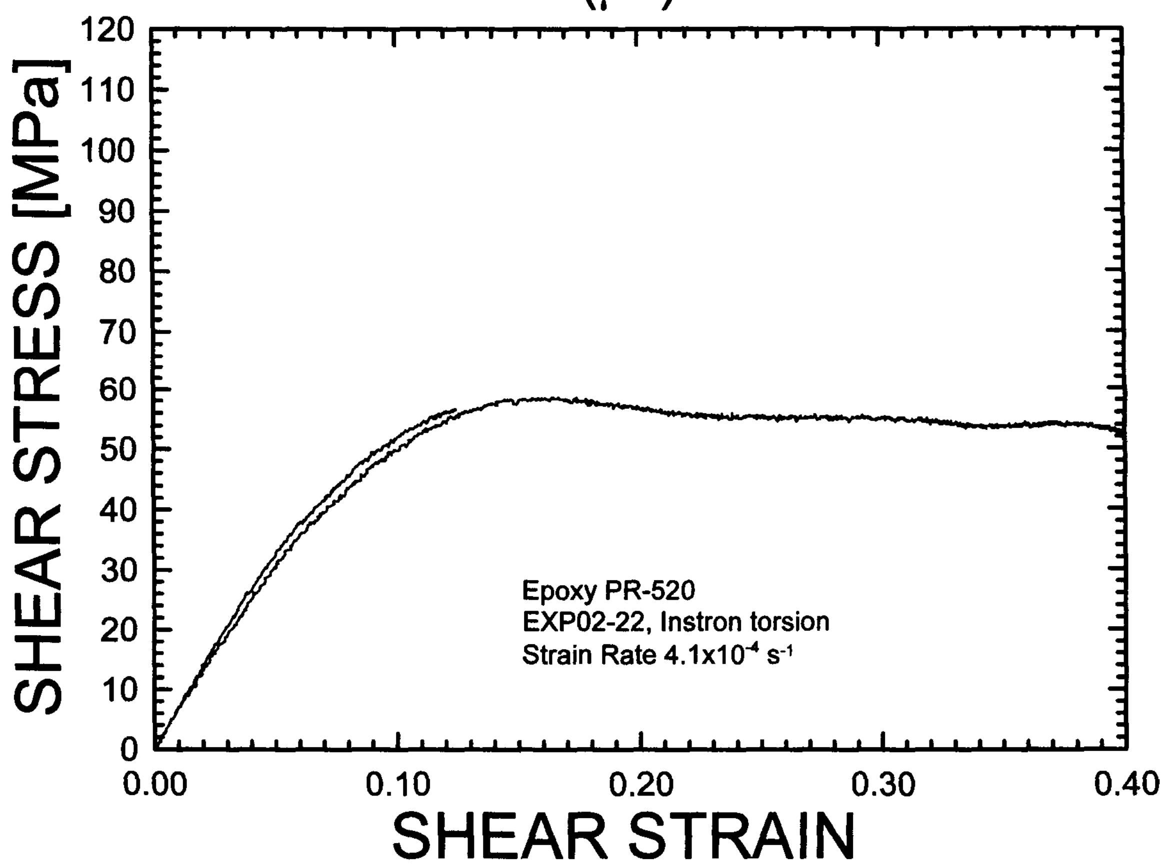

Epoxy PR-520
EXP 02-20,
Instron (torsion)
Strain rate 1.0x10^{-4} s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)
0
10
20
30
40
50
60
70
80
0.00
0.10
0.20
0.30
0.40
0.50
0
500
1000
1500
2000
2500
3000

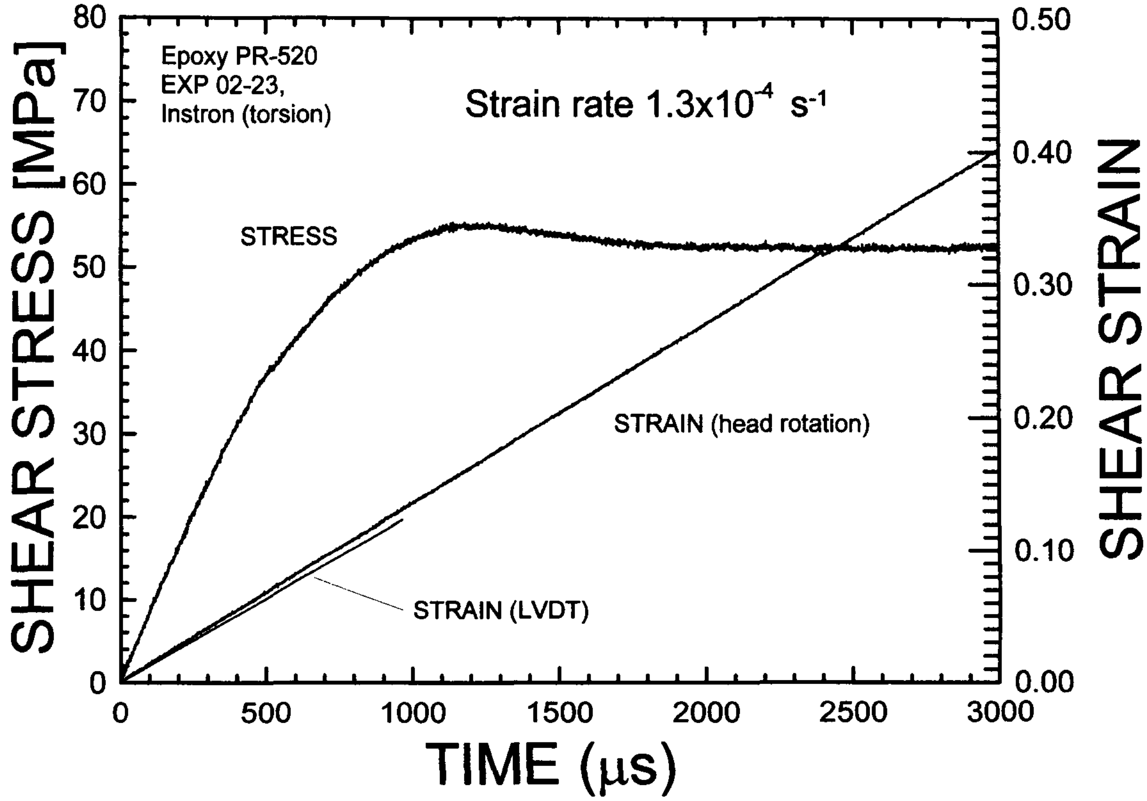

Epoxy PR-520
EXP02-20, Instron torsion
Strain Rate 1.0x10^{-4} s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40


Epoxy E-862
EXP 02-21,
Instron (torsion)
Strain rate 1.3x10^{-4} s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)
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

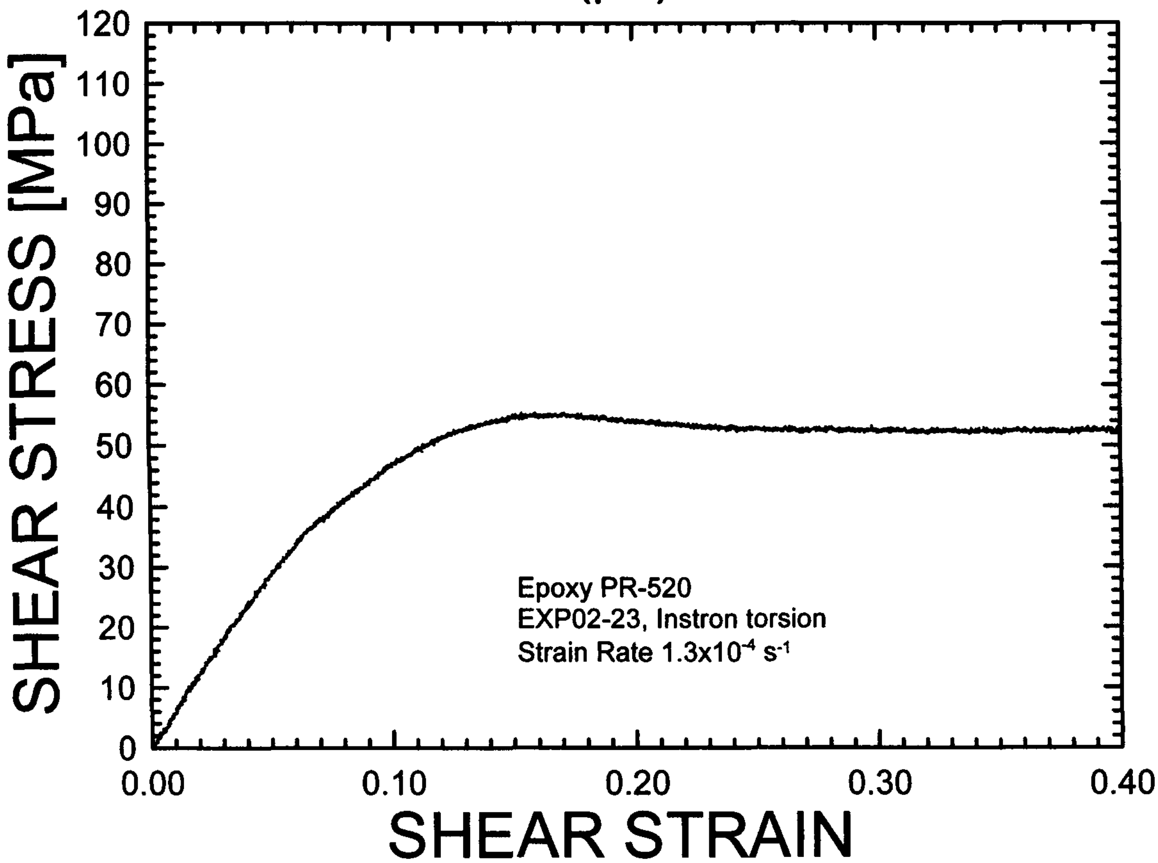

Epoxy E-862
EXP02-21, Instron torsion
Strain Rate 1.3x10^{-4} s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40


SHEAR STRESS [MPa]
TIME (μs)
SHEAR STRAIN
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
Epoxy PR-520
EXP 02-22,
Instron (torsion)
Strain rate 4.1x10^-4 s^-1
0
500
1000
1500
2000
2500
3000
0
10
20
30
40
50
60
70
80
0.00
0.10
0.20
0.30
0.40
0.50

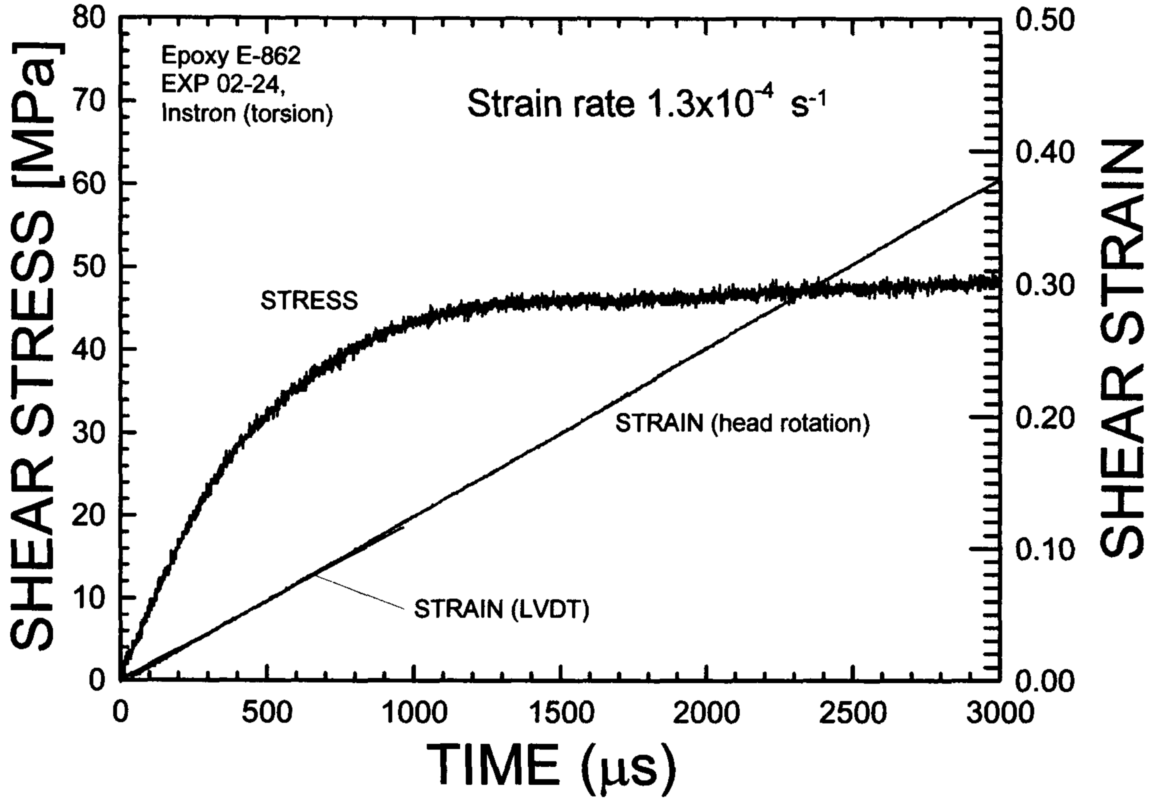

SHEAR STRESS [MPa]
SHEAR STRAIN
Epoxy PR-520
EXP02-22, Instron torsion
Strain Rate 4.1x10^-4 s^-1
0.00
0.10
0.20
0.30
0.40
0
10
20
30
40
50
60
70
80
90
100
110
120

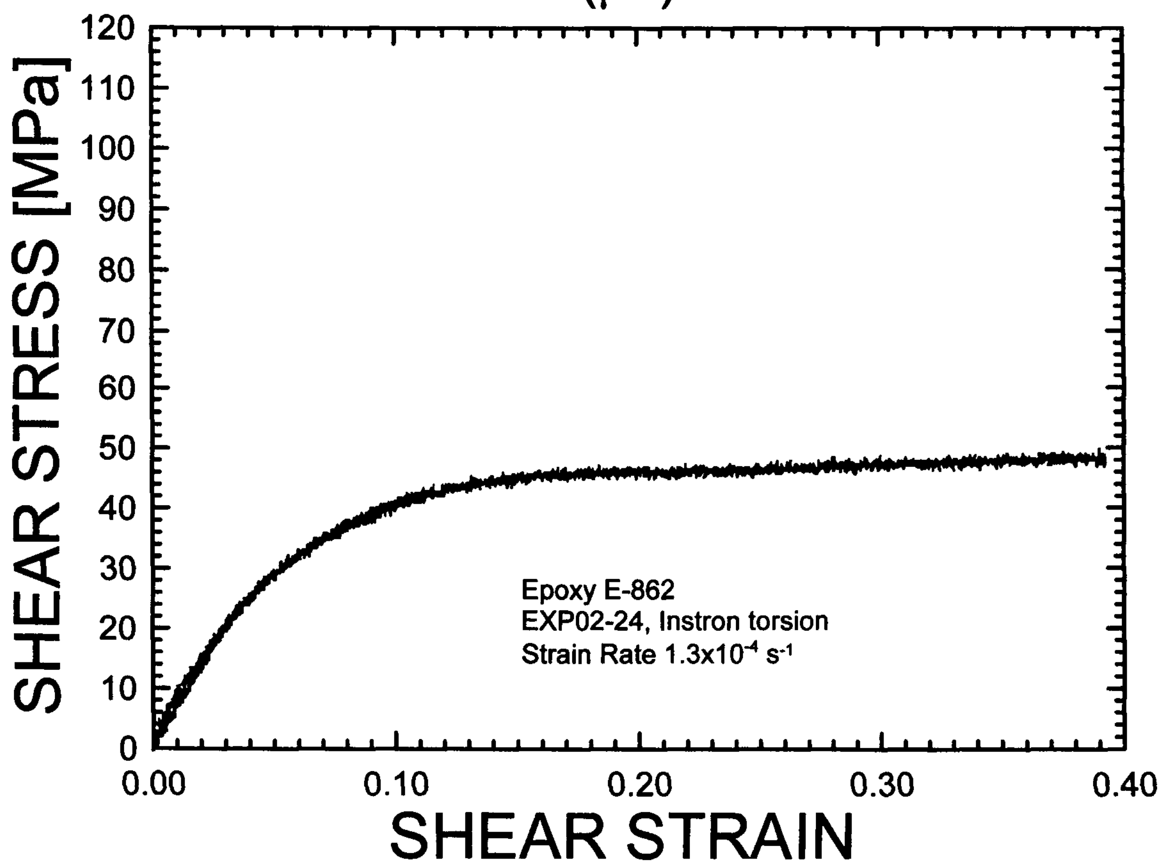


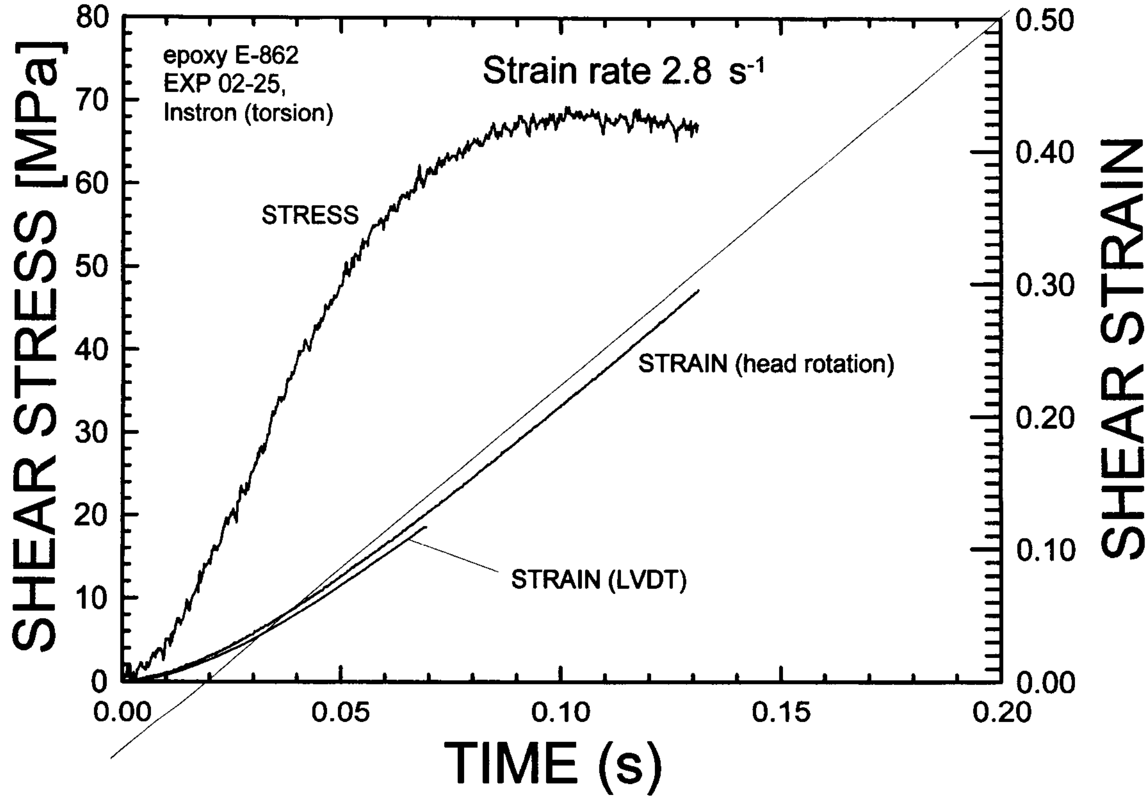
Epoxy PR-520
EXP 02-23,
Instron (torsion)
Strain rate 1.3x10-4 s-1
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)
0
10
20
30
40
50
60
70
80
0.00
0.10
0.20
0.30
0.40
0.50
500
1000
1500
2000
2500
3000

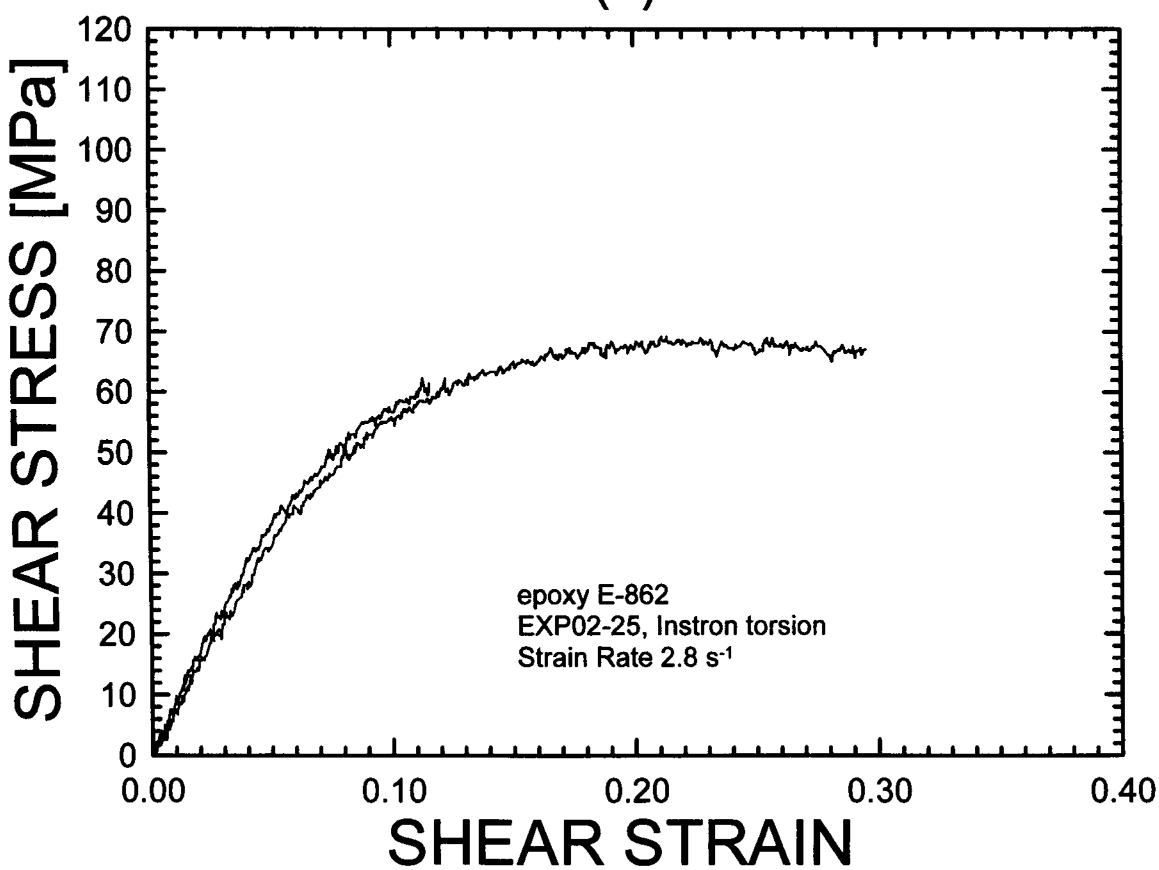


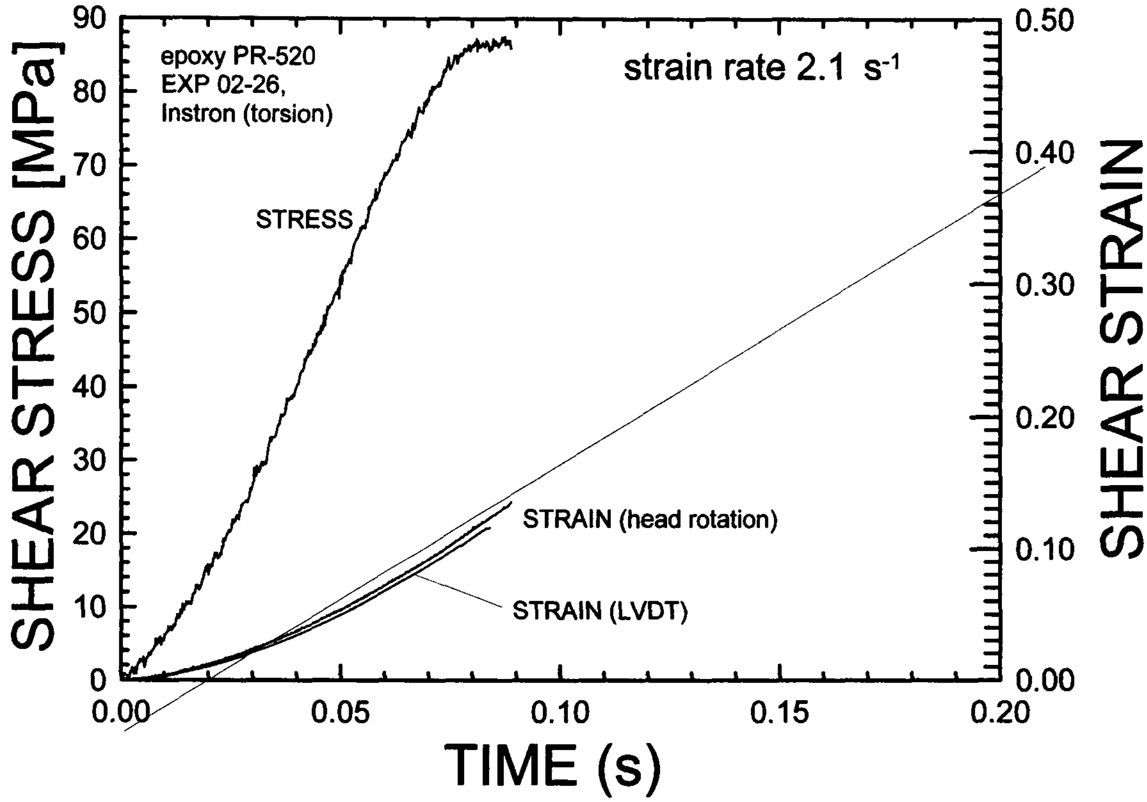
Epoxy PR-520
EXP02-23, Instron torsion
Strain Rate 1.3x10-4 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40

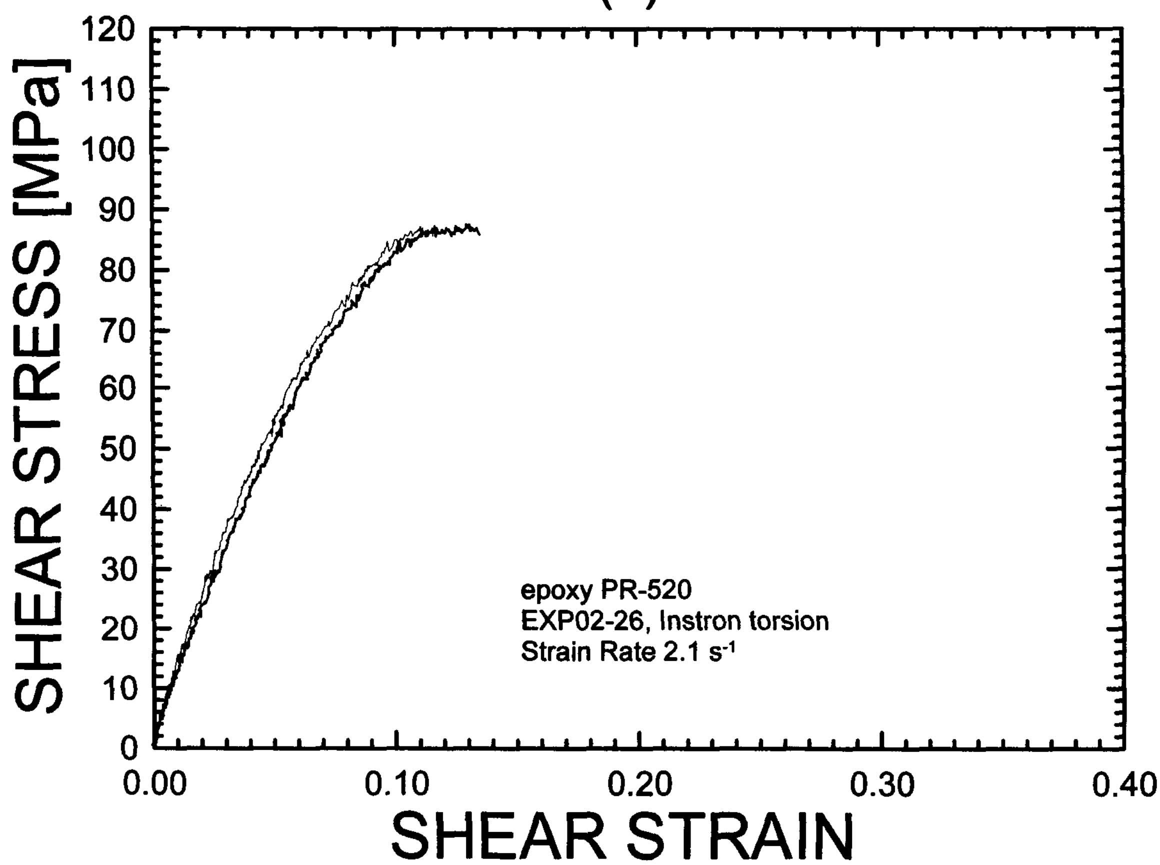

Epoxy E-862
EXP 02-24,
Instron (torsion)
Strain rate 1.3x10^-4 s^-1
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)

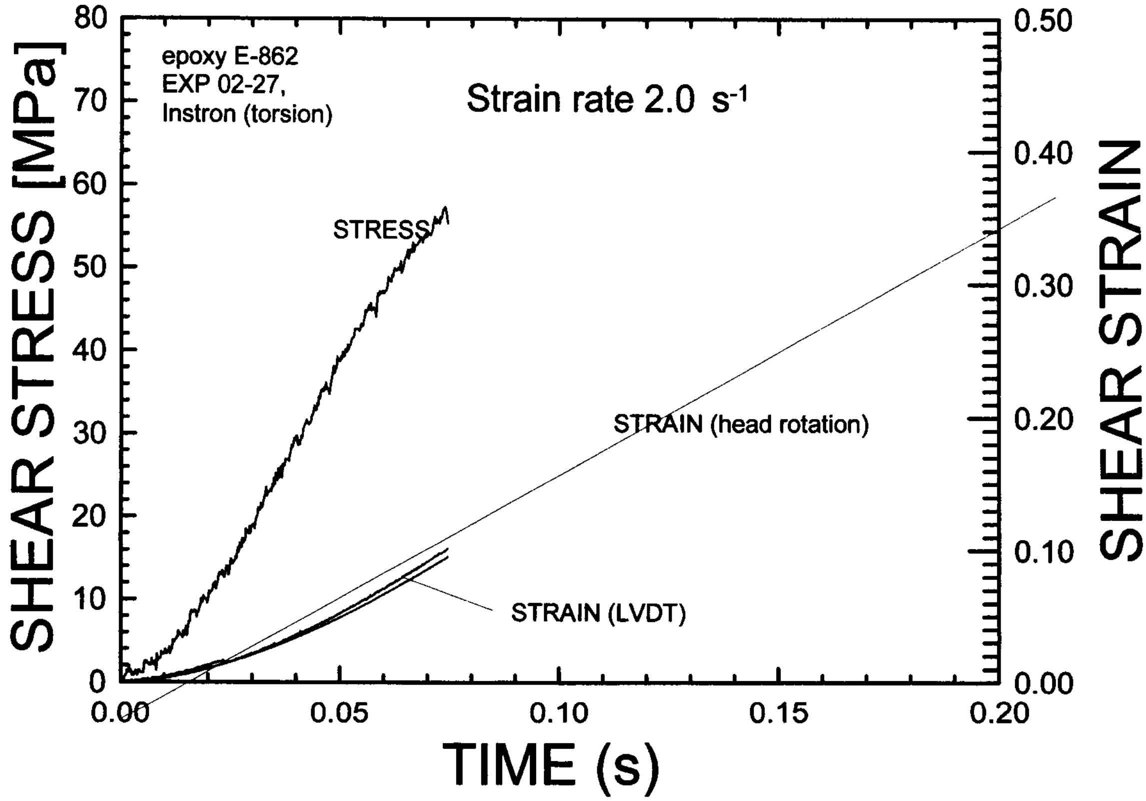

Epoxy E-862
EXP02-24, Instron torsion
Strain Rate 1.3x10^-4 s^-1
SHEAR STRESS [MPa]
SHEAR STRAIN

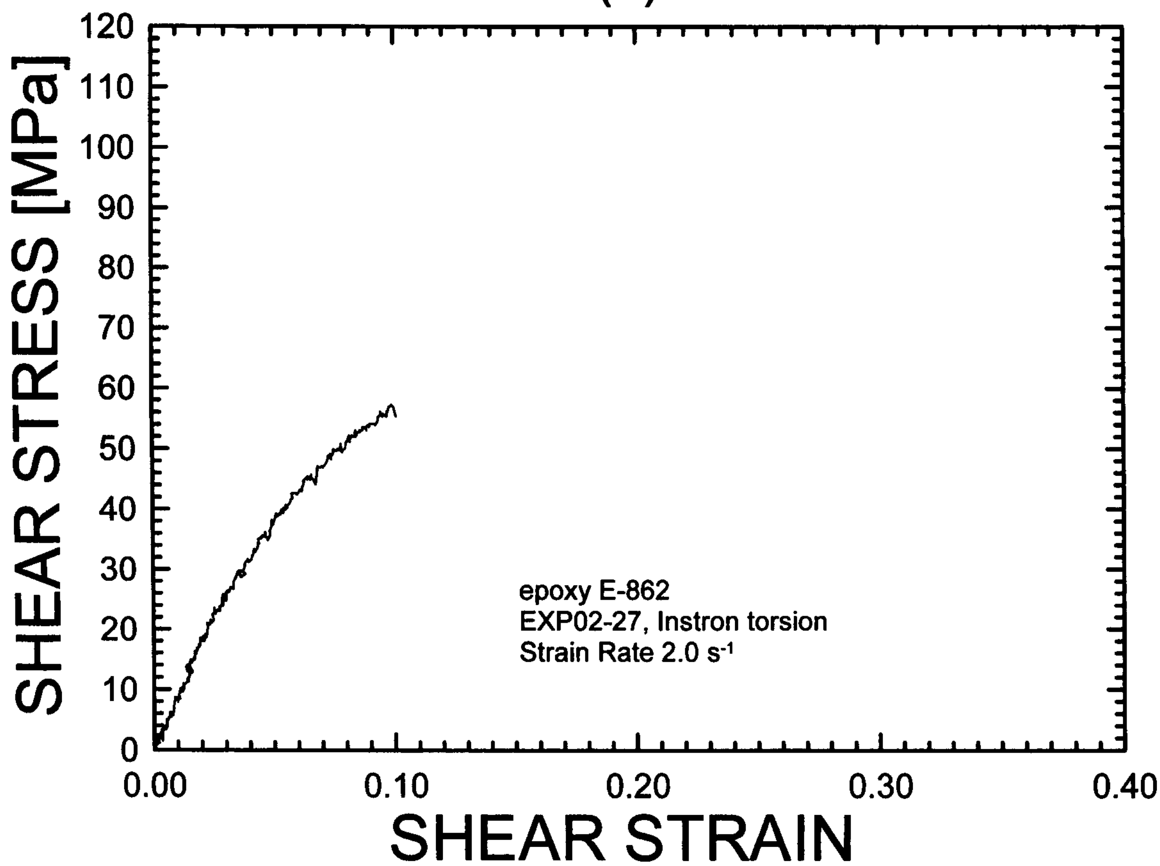

epoxy E-862
EXP 02-25,
Instron (torsion)
Strain rate 2.8 s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0
10
20
30
40
50
60
70
80
0.00
0.05
0.10
0.15
0.20
0.00
0.10
0.20
0.30
0.40
0.50

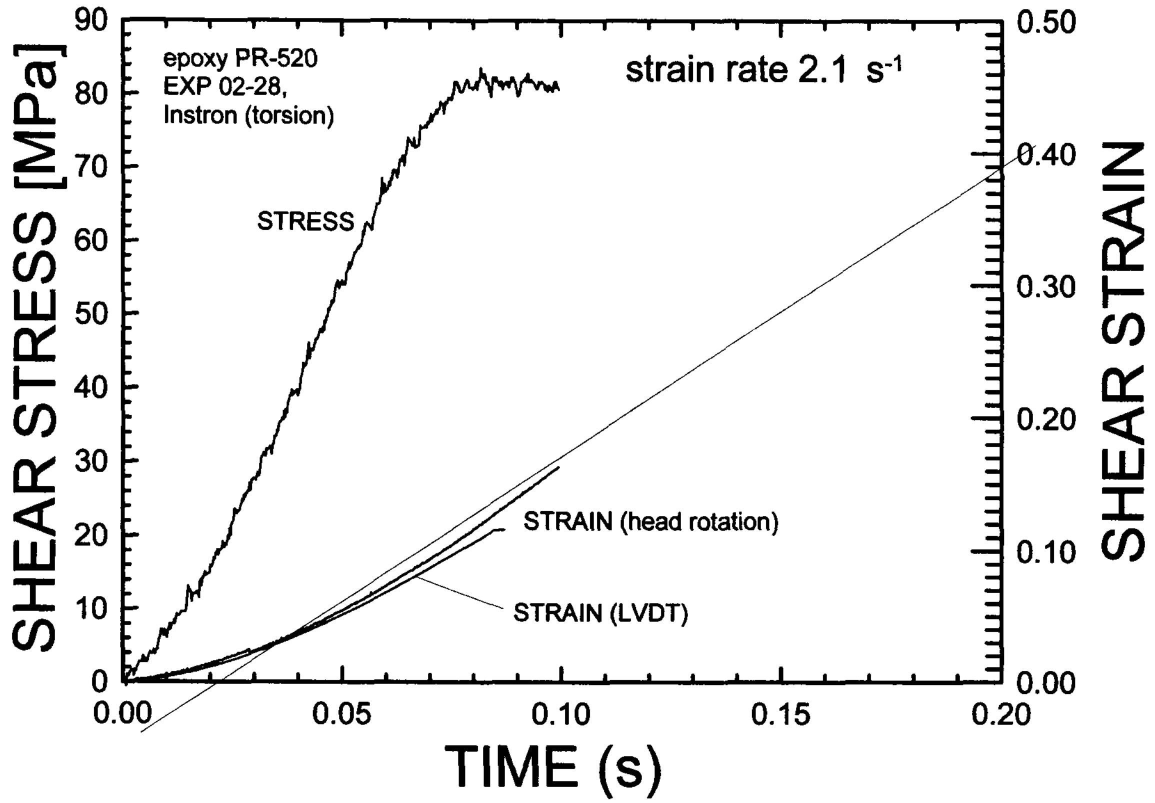

epoxy E-862
EXP02-25, Instron torsion
Strain Rate 2.8 s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40

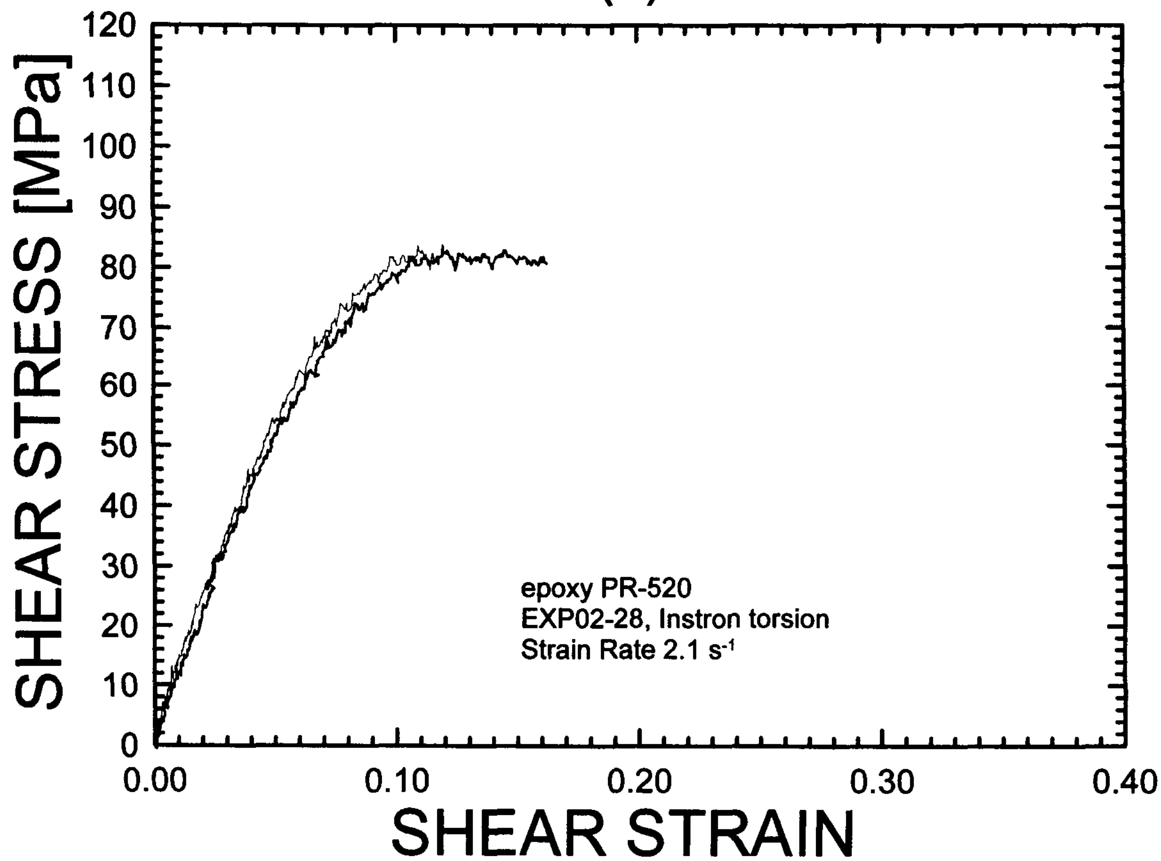

epoxy PR-520
EXP 02-26,
Instron (torsion)
strain rate 2.1 s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)

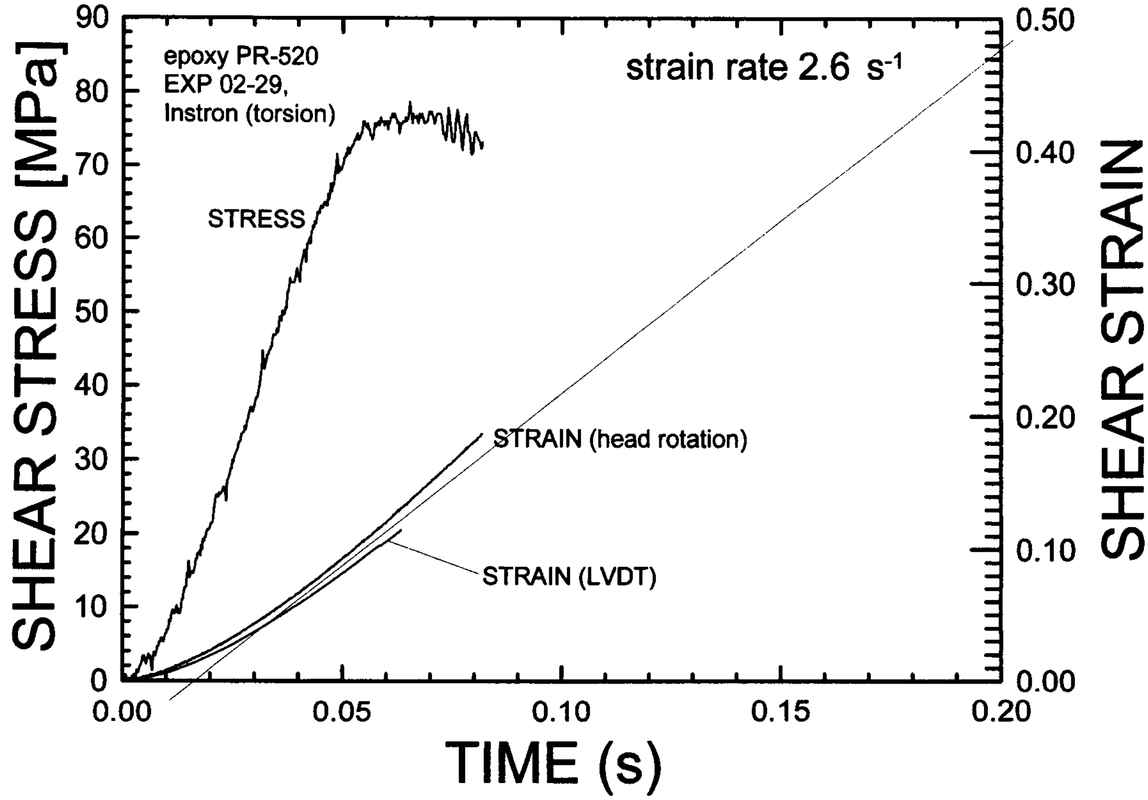

epoxy PR-520
EXP02-26, Instron torsion
Strain Rate 2.1 s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN


epoxy E-862
EXP 02-27,
Instron (torsion)
Strain rate 2.0 s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)

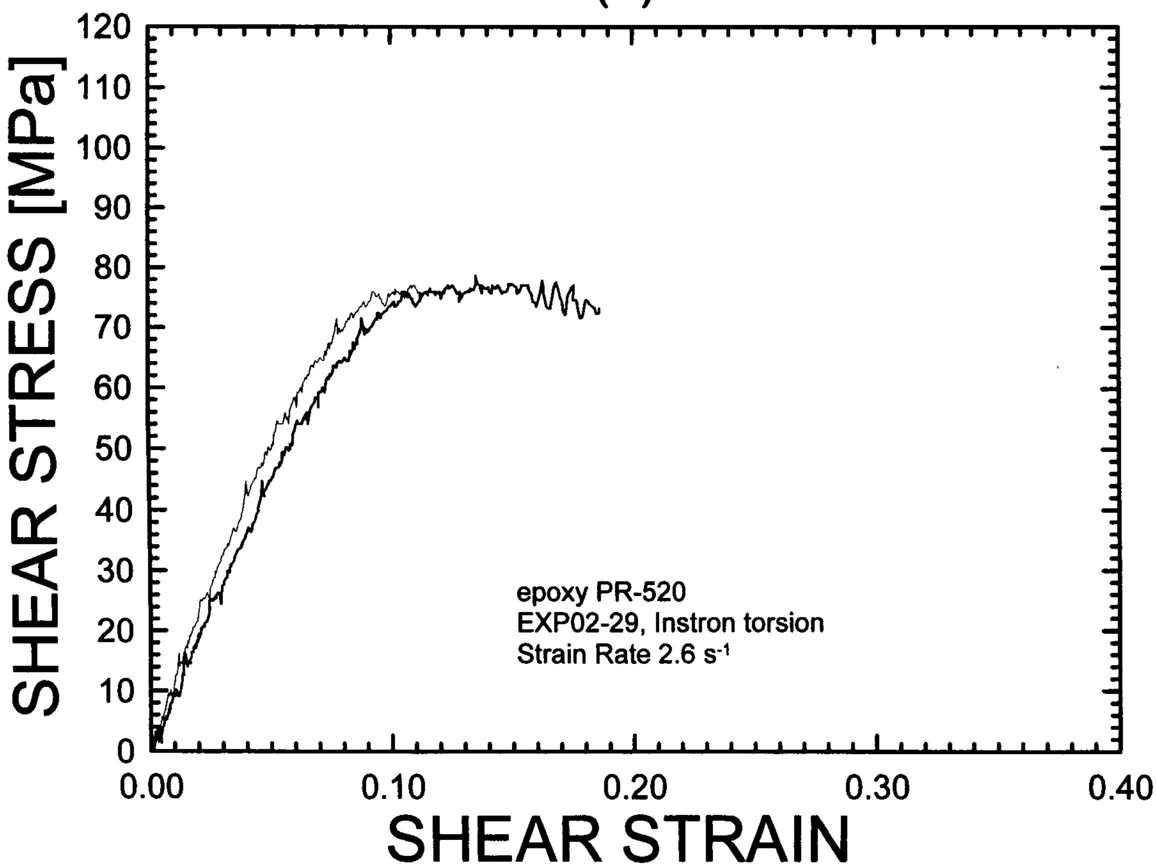

epoxy E-862
EXP02-27, Instron torsion
Strain Rate 2.0 s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN


epoxy PR-520
EXP 02-28,
Instron (torsion)
strain rate 2.1 s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0
10
20
30
40
50
60
70
80
90
0.00
0.10
0.20
0.30
0.40
0.50
0.00
0.05
0.10
0.15
0.20

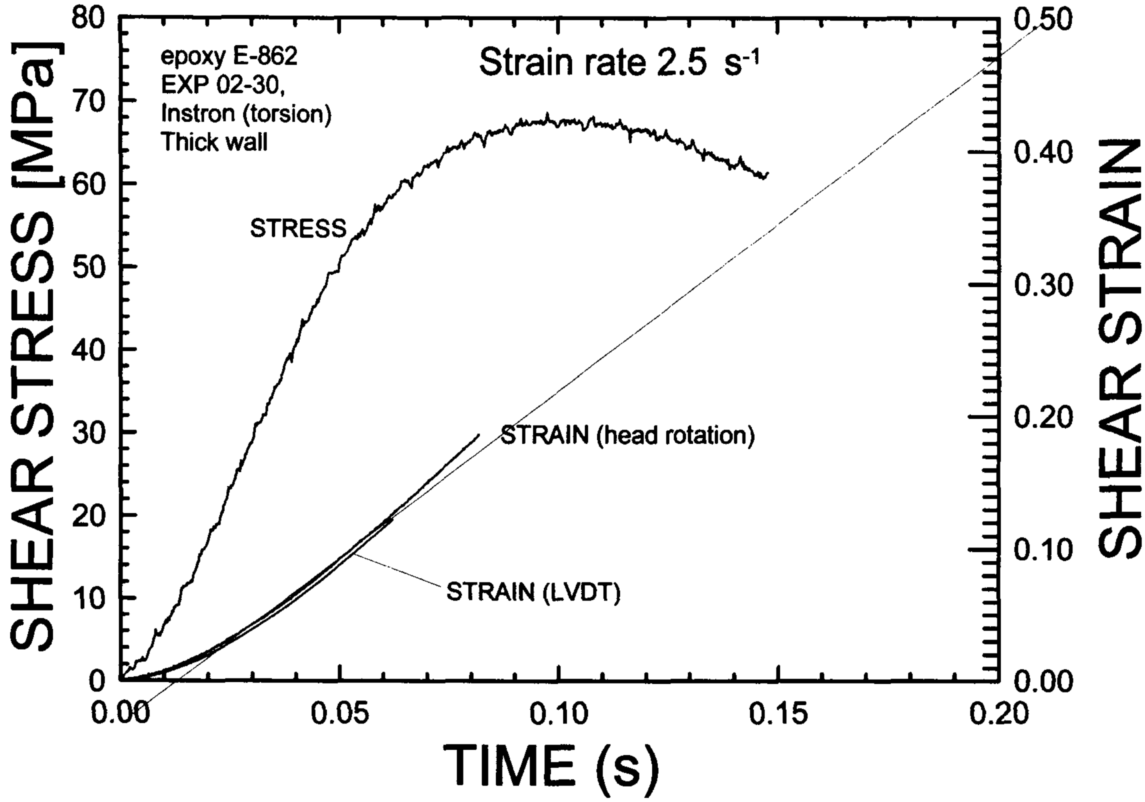

epoxy PR-520
EXP02-28, Instron torsion
Strain Rate 2.1 s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40



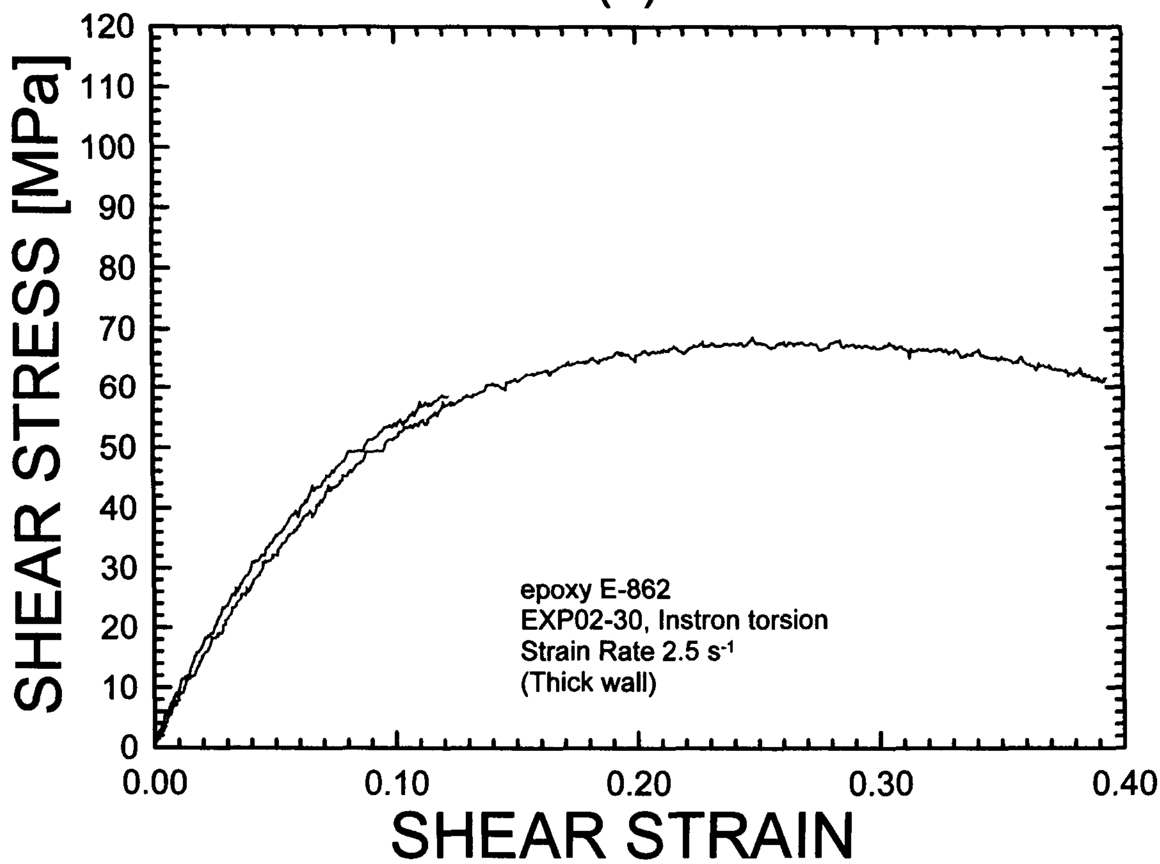
epoxy PR-520
EXP 02-29,
Instron (torsion)
strain rate 2.6 s-1
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)



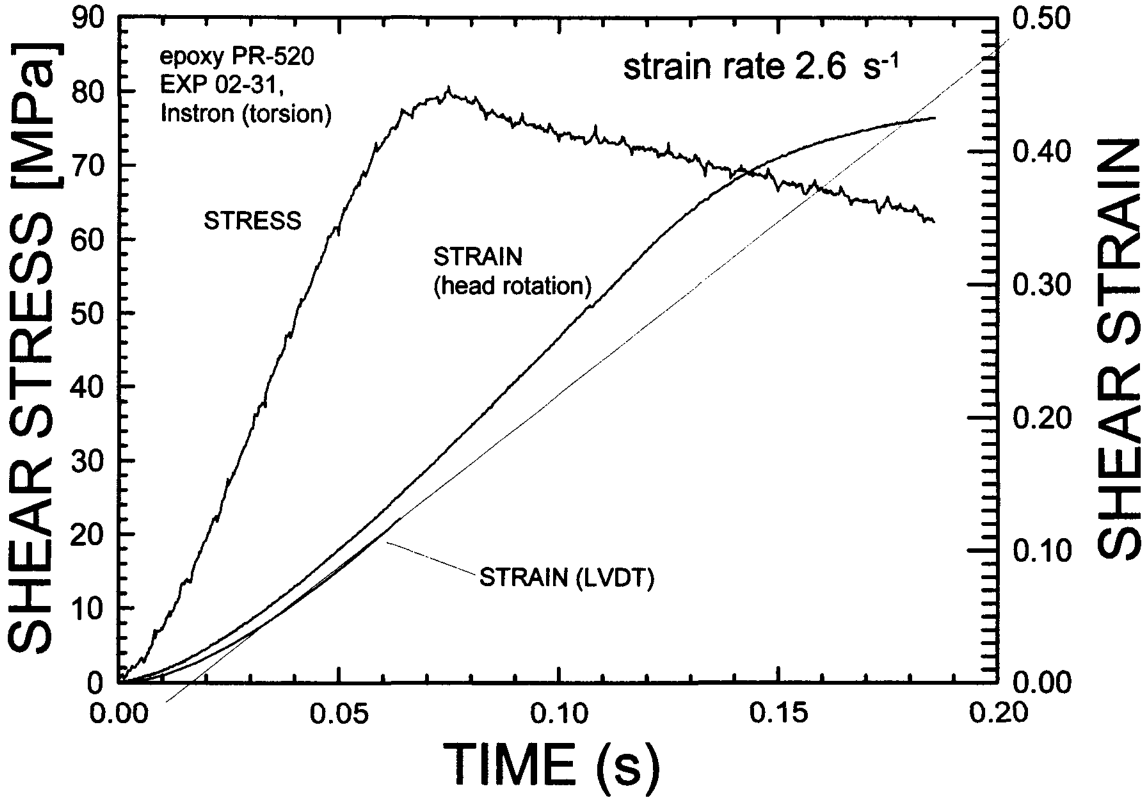
epoxy PR-520
EXP02-29, Instron torsion
Strain Rate 2.6 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN

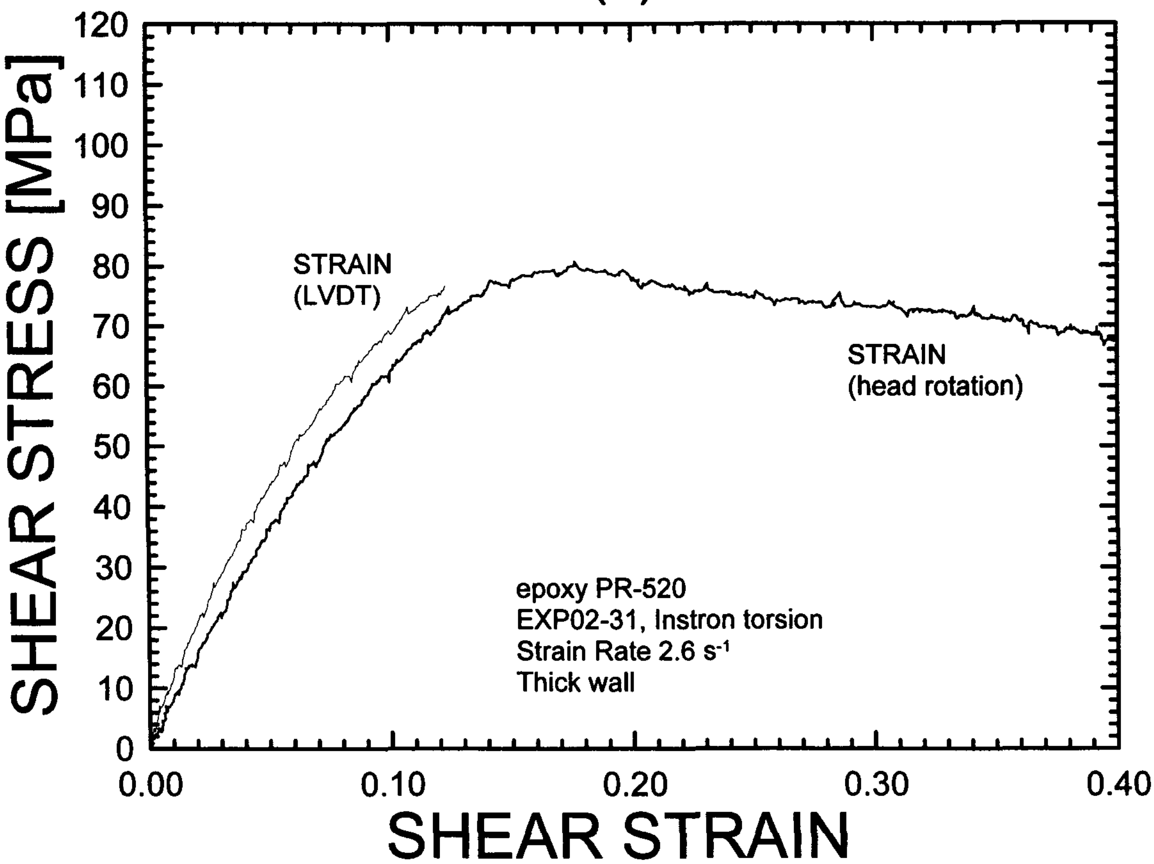


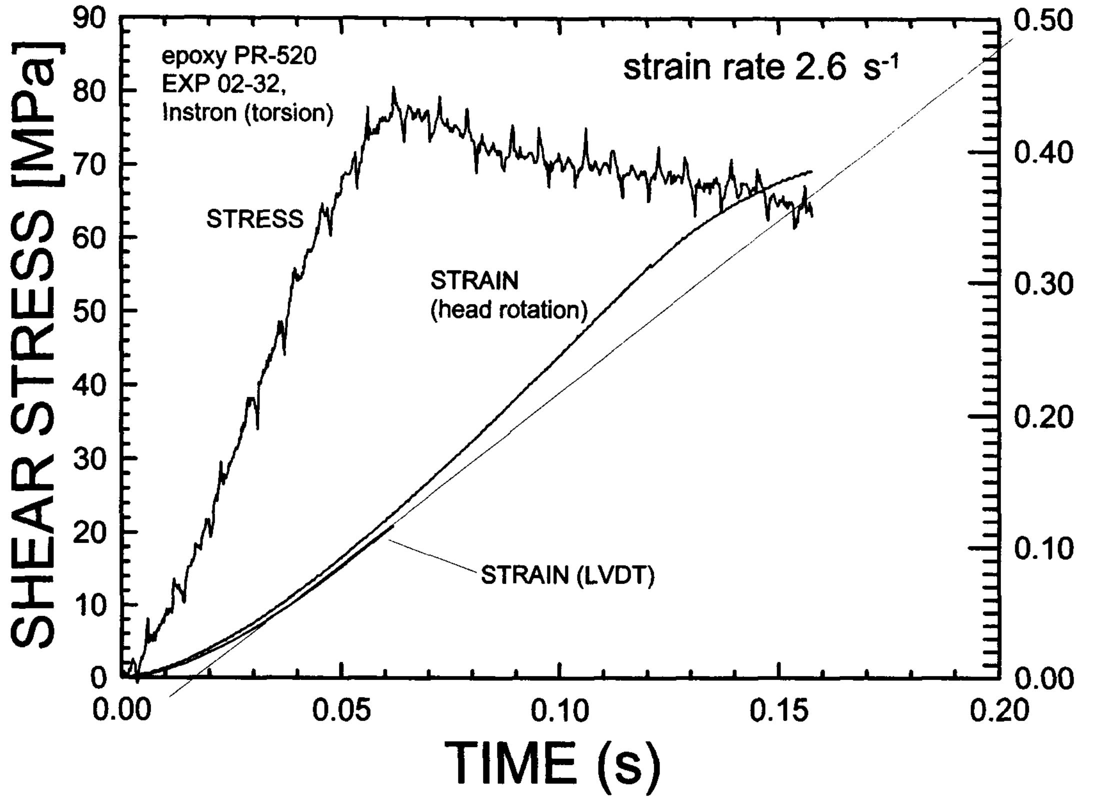
epoxy E-862
EXP 02-30,
Instron (torsion)
Thick wall
Strain rate 2.5 s-1
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0
10
20
30
40
50
60
70
80
0.00
0.05
0.10
0.15
0.20
0.00
0.10
0.20
0.30
0.40
0.50

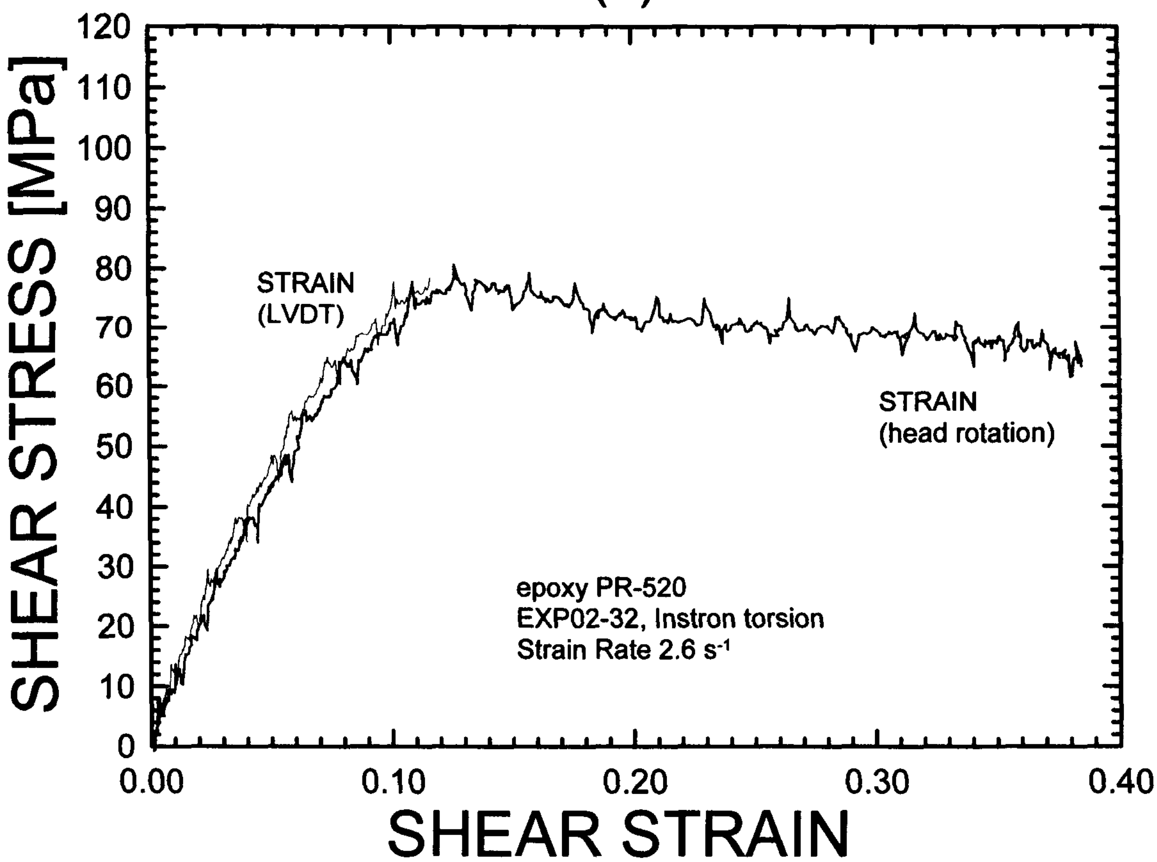


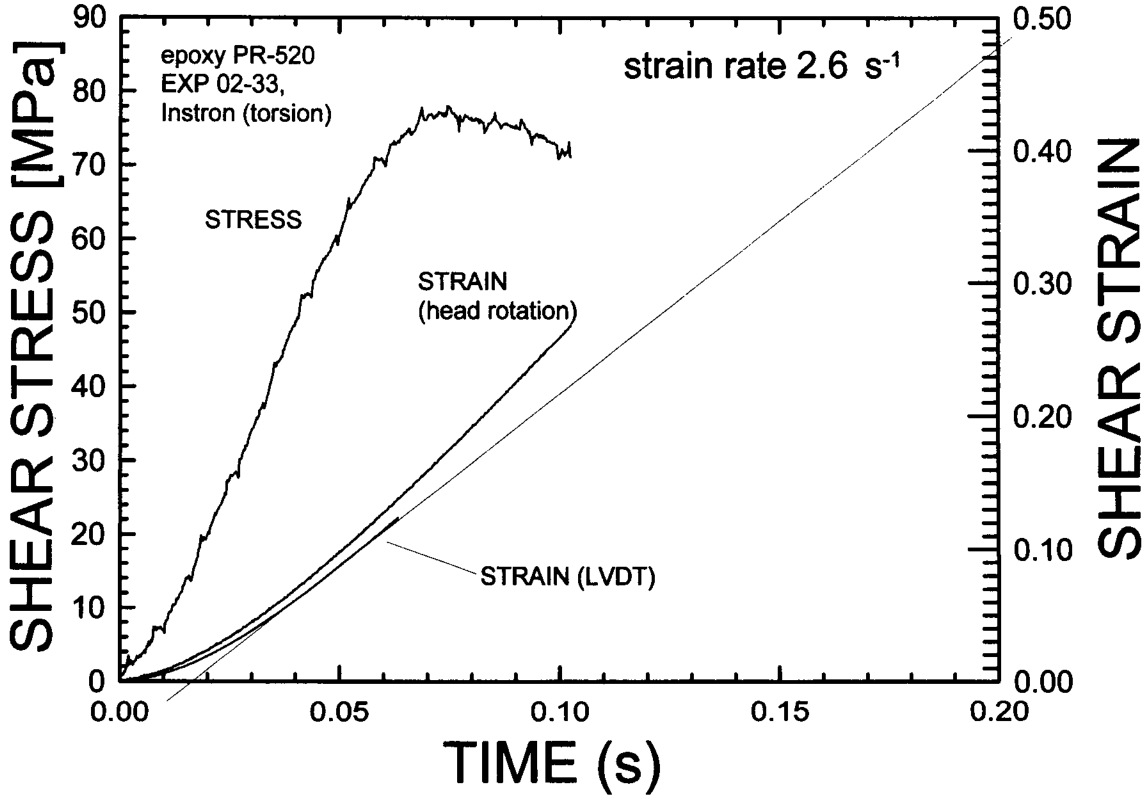
epoxy E-862
EXP02-30, Instron torsion
Strain Rate 2.5 s-1
(Thick wall)
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40


epoxy PR-520
EXP 02-31,
Instron (torsion)
strain rate 2.6 s-1
STRESS
STRAIN
(head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)

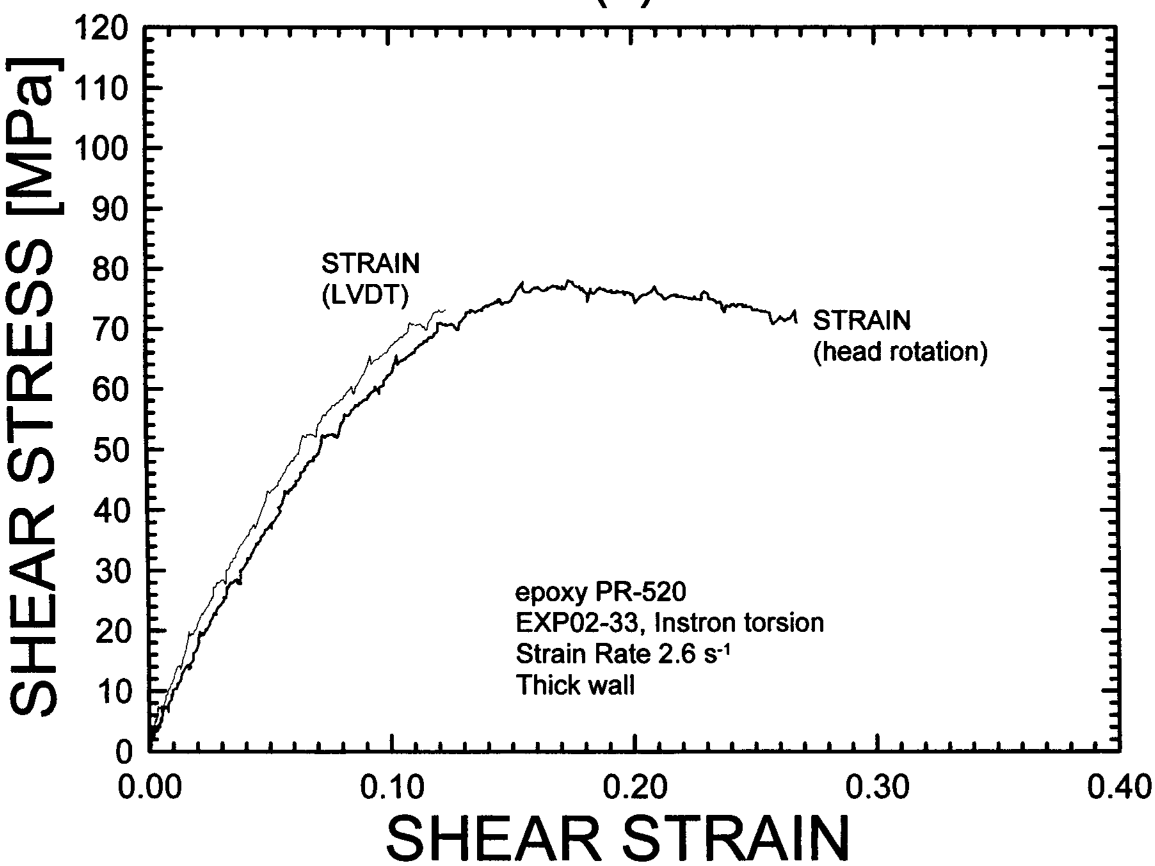

STRAIN
(LVDT)
STRAIN
(head rotation)
epoxy PR-520
EXP02-31, Instron torsion
Strain Rate 2.6 s-1
Thick wall
SHEAR STRESS [MPa]
SHEAR STRAIN


epoxy PR-520
EXP 02-32,
Instron (torsion)
strain rate 2.6 s^{-1}
STRESS
STRAIN
(head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)

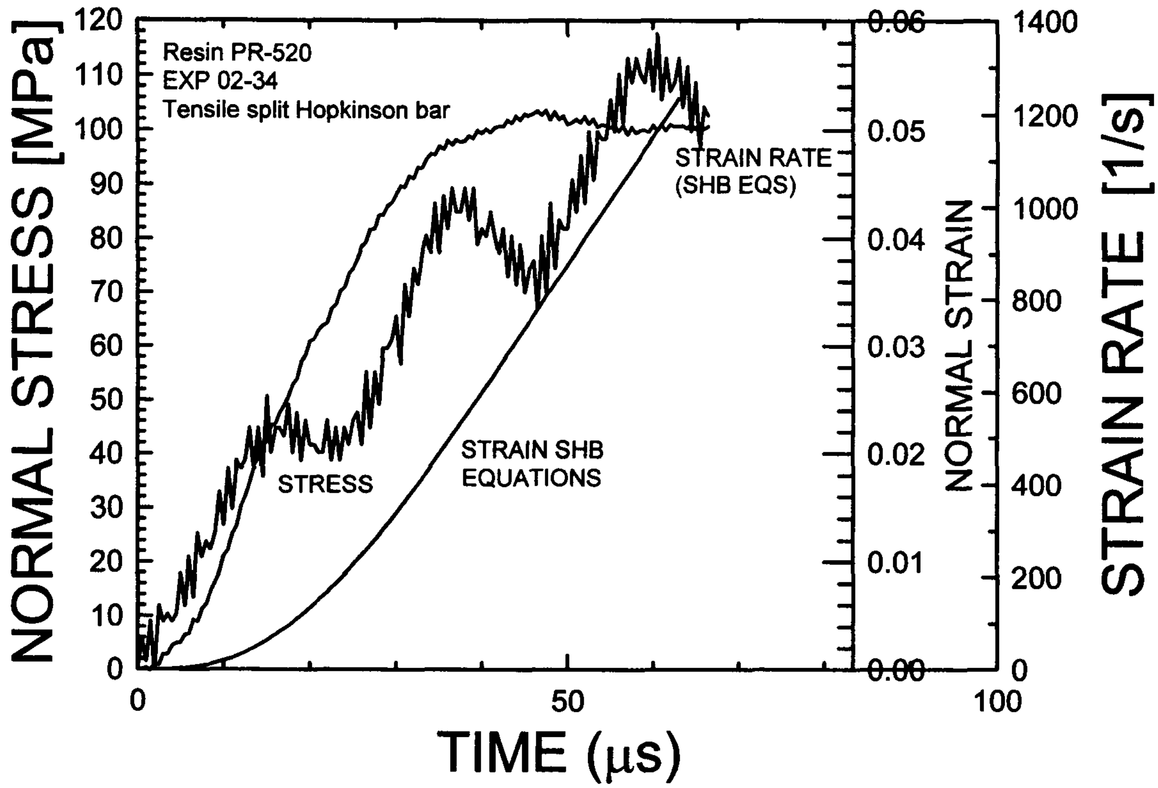

STRAIN
(LVDT)
STRAIN
(head rotation)
epoxy PR-520
EXP02-32, Instron torsion
Strain Rate 2.6 s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN

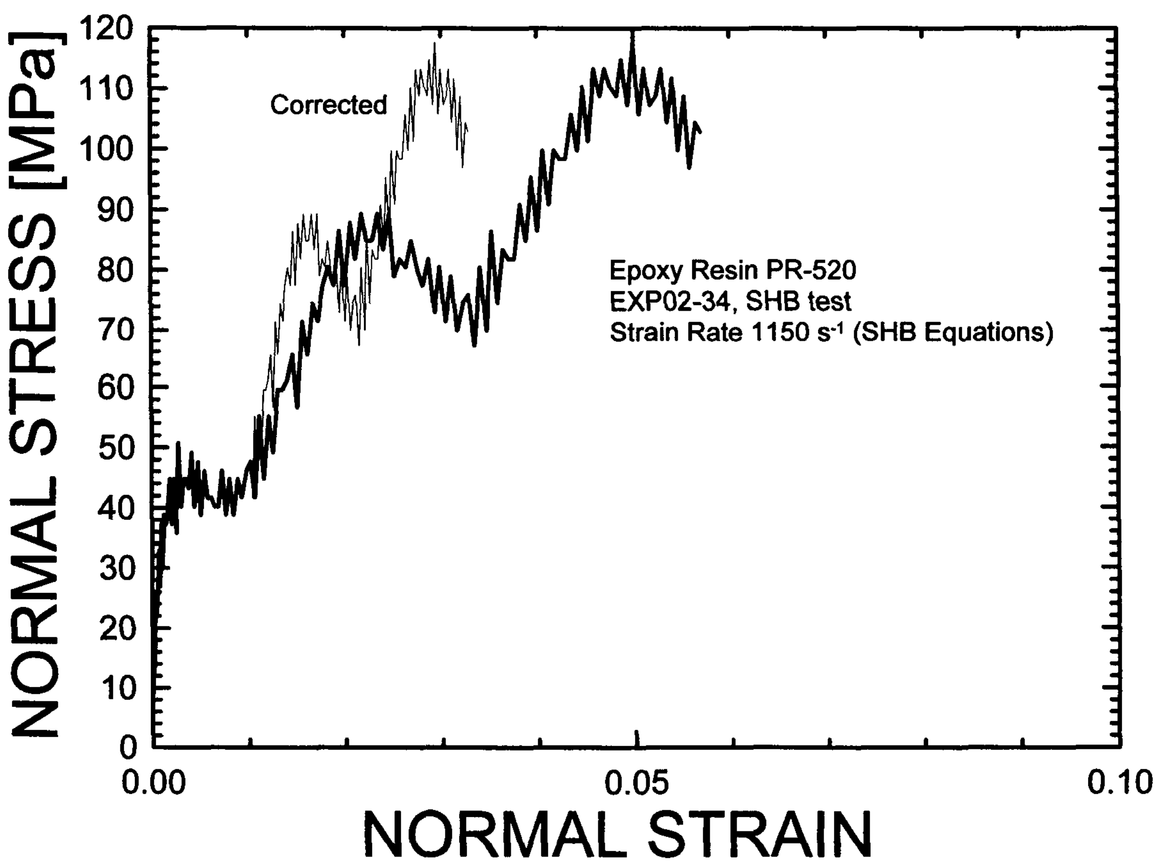


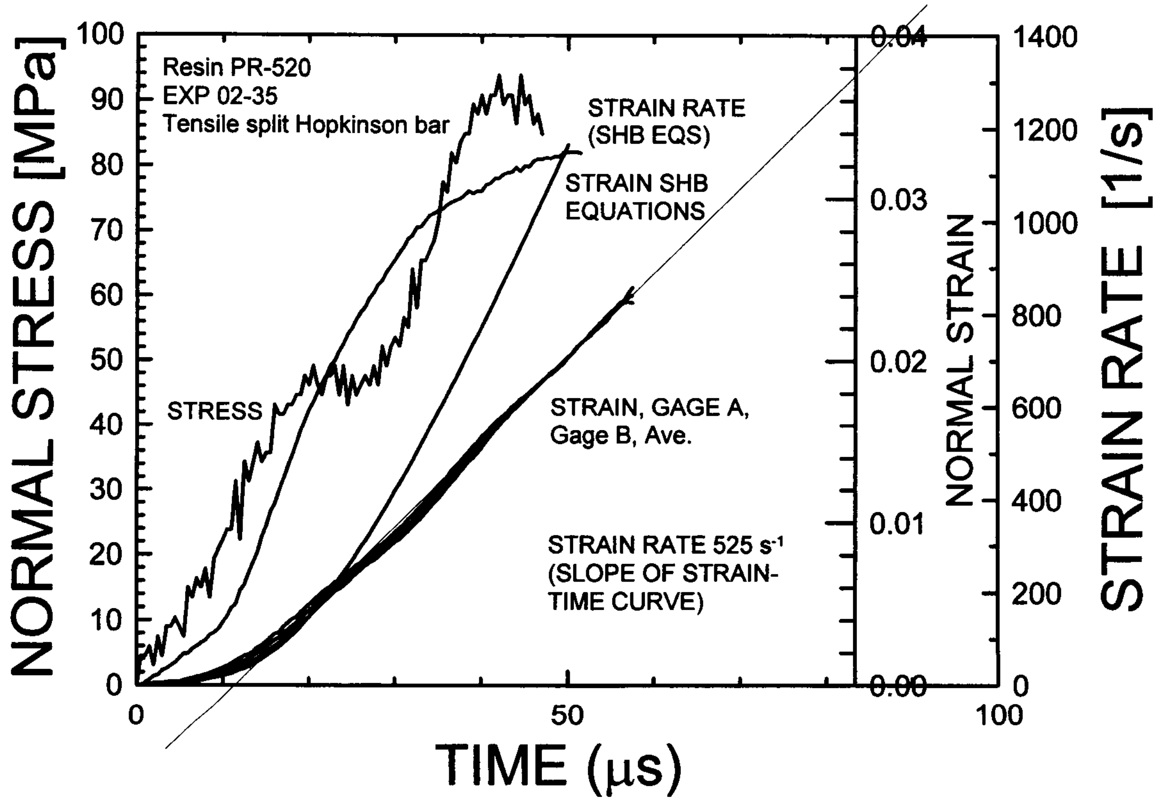
epoxy PR-520
EXP 02-33,
Instron (torsion)
strain rate 2.6 s^{-1}
STRESS
STRAIN
(head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0
10
20
30
40
50
60
70
80
90
0.00
0.10
0.20
0.30
0.40
0.50
0.00
0.05
0.10
0.15
0.20

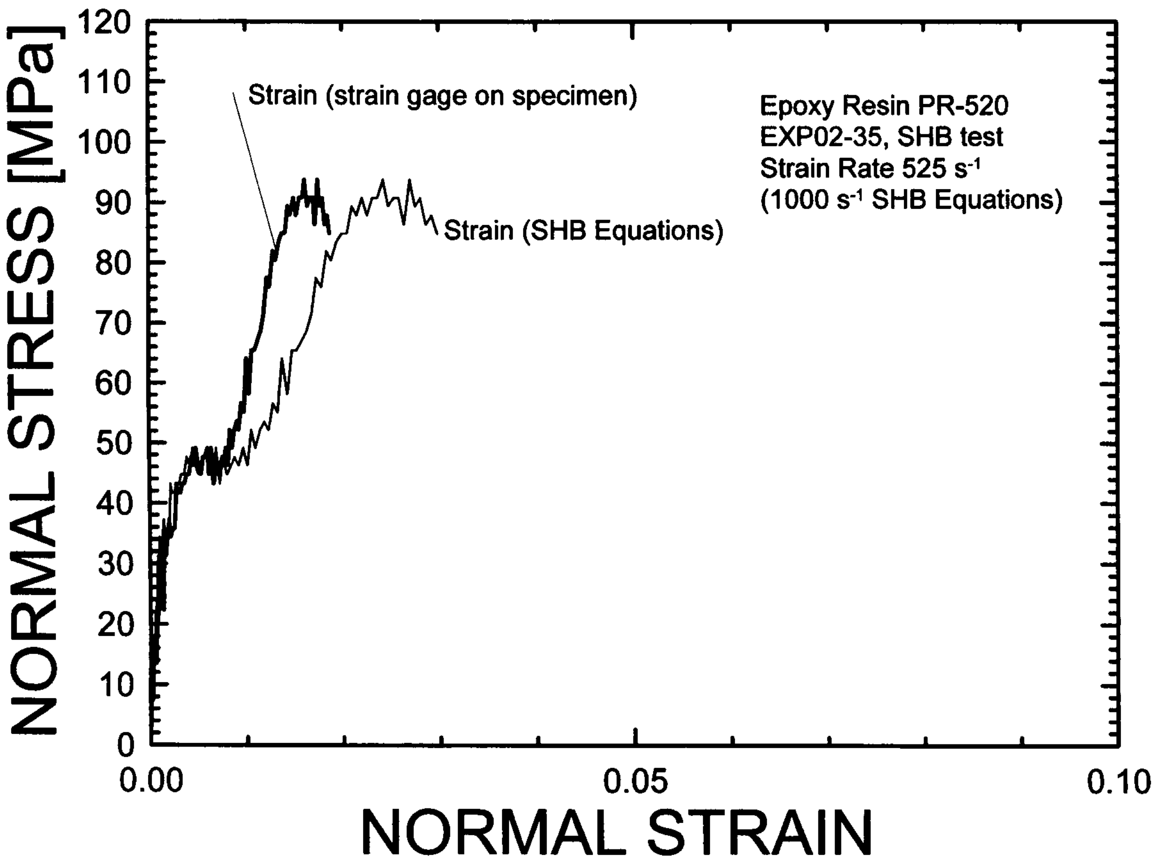


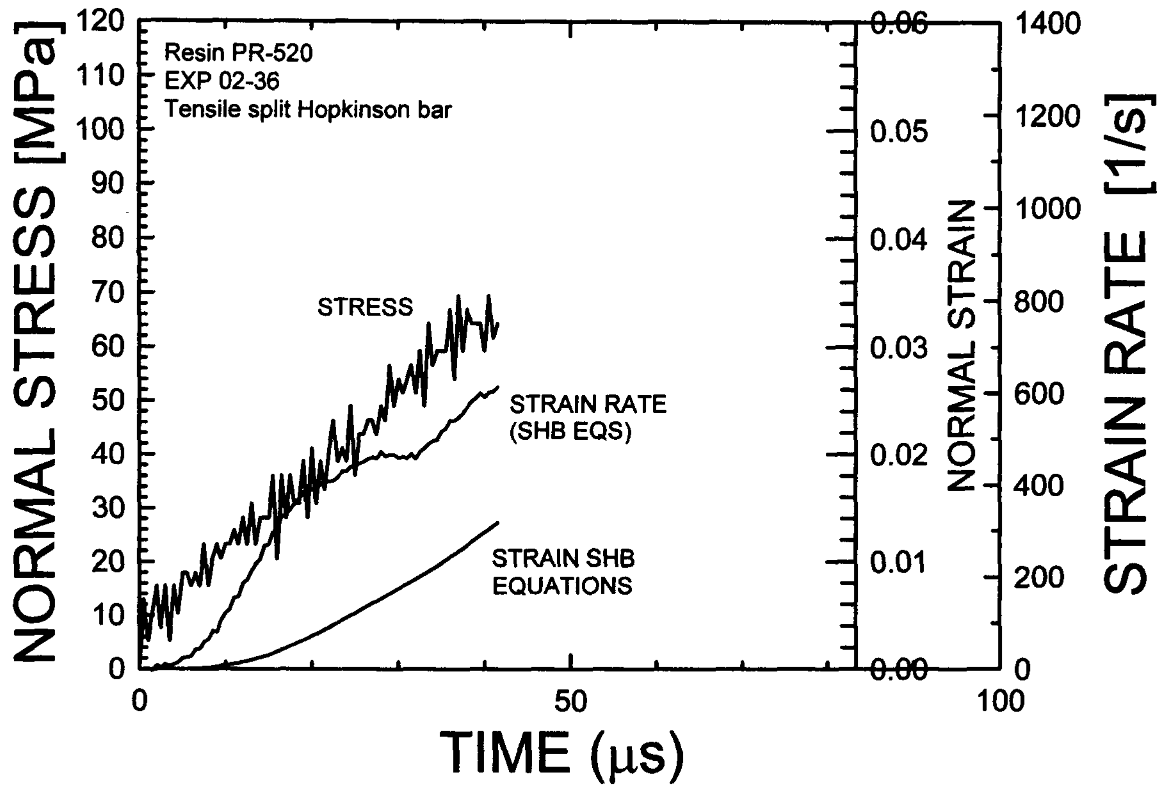
STRAIN
(LVDT)
STRAIN
(head rotation)
epoxy PR-520
EXP02-33, Instron torsion
Strain Rate 2.6 s^{-1}
Thick wall
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40

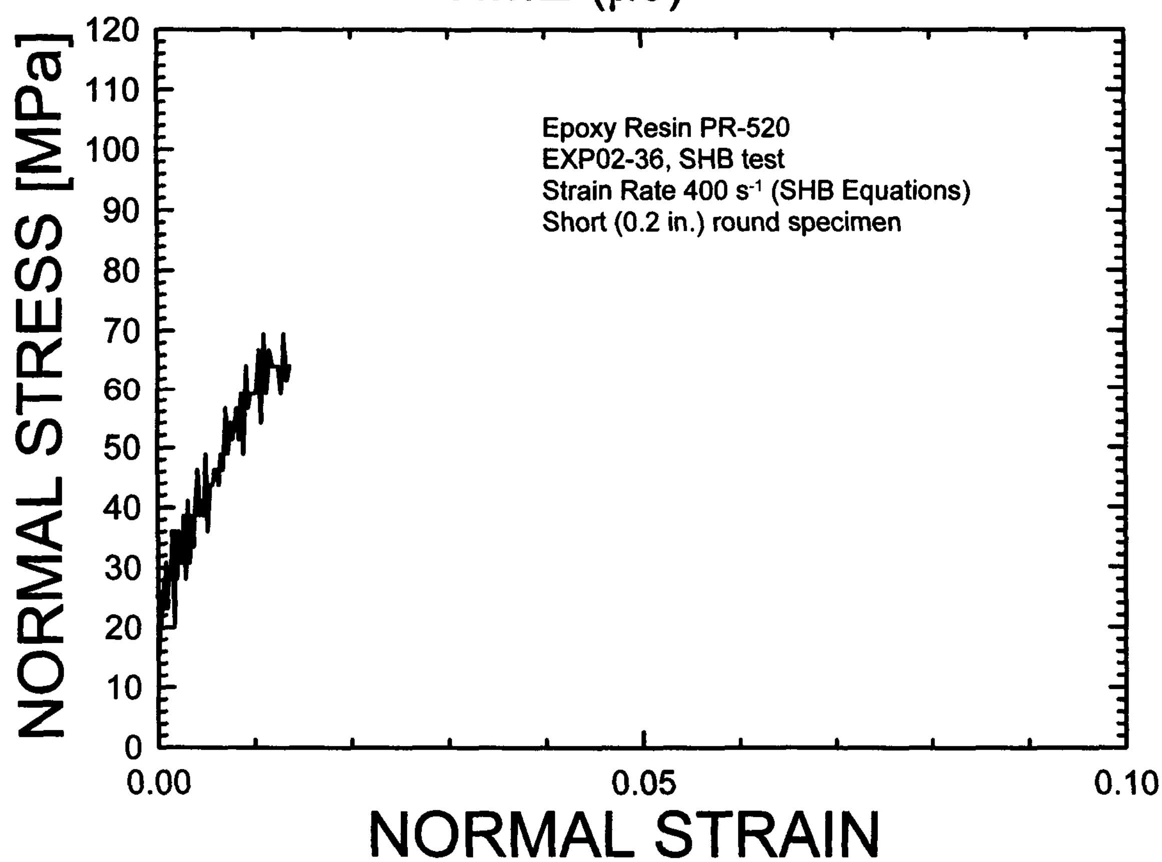

Resin PR-520
EXP 02-34
Tensile split Hopkinson bar
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
STRESS
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

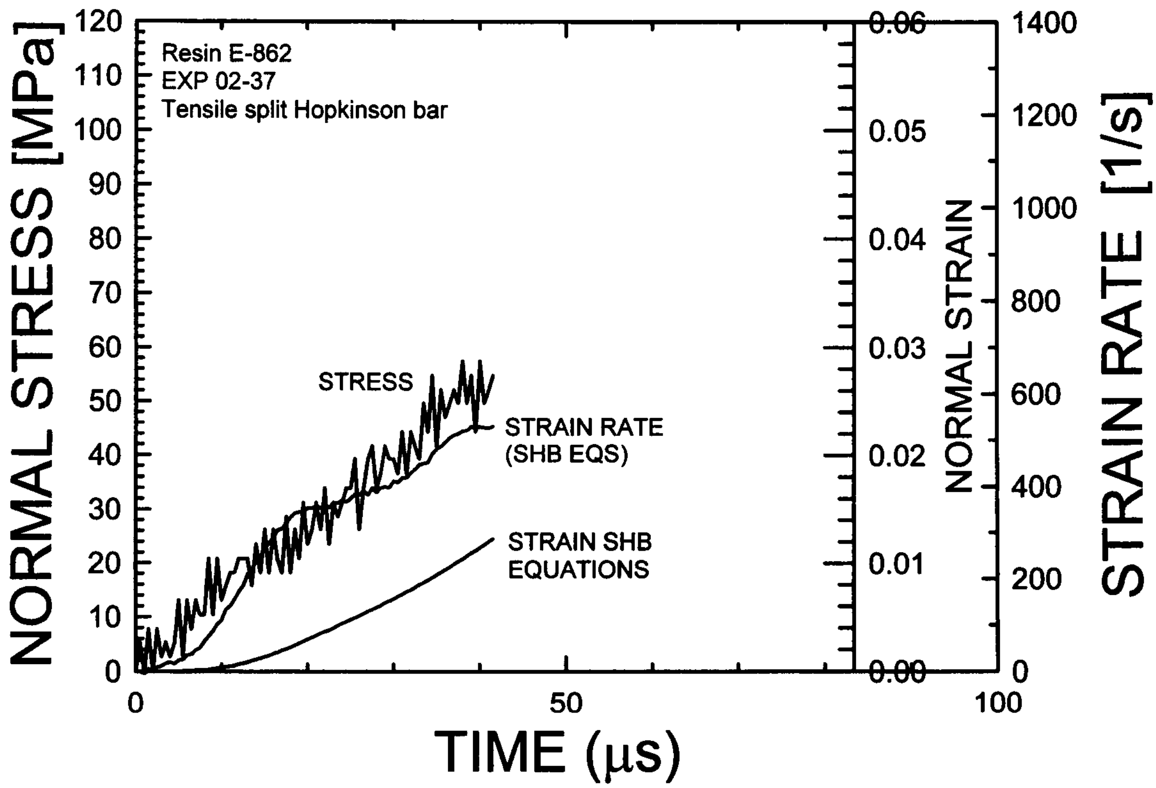

Corrected
Epoxy Resin PR-520
EXP02-34, SHB test
Strain Rate 1150 s-1 (SHB Equations)
NORMAL STRESS [MPa]
NORMAL STRAIN

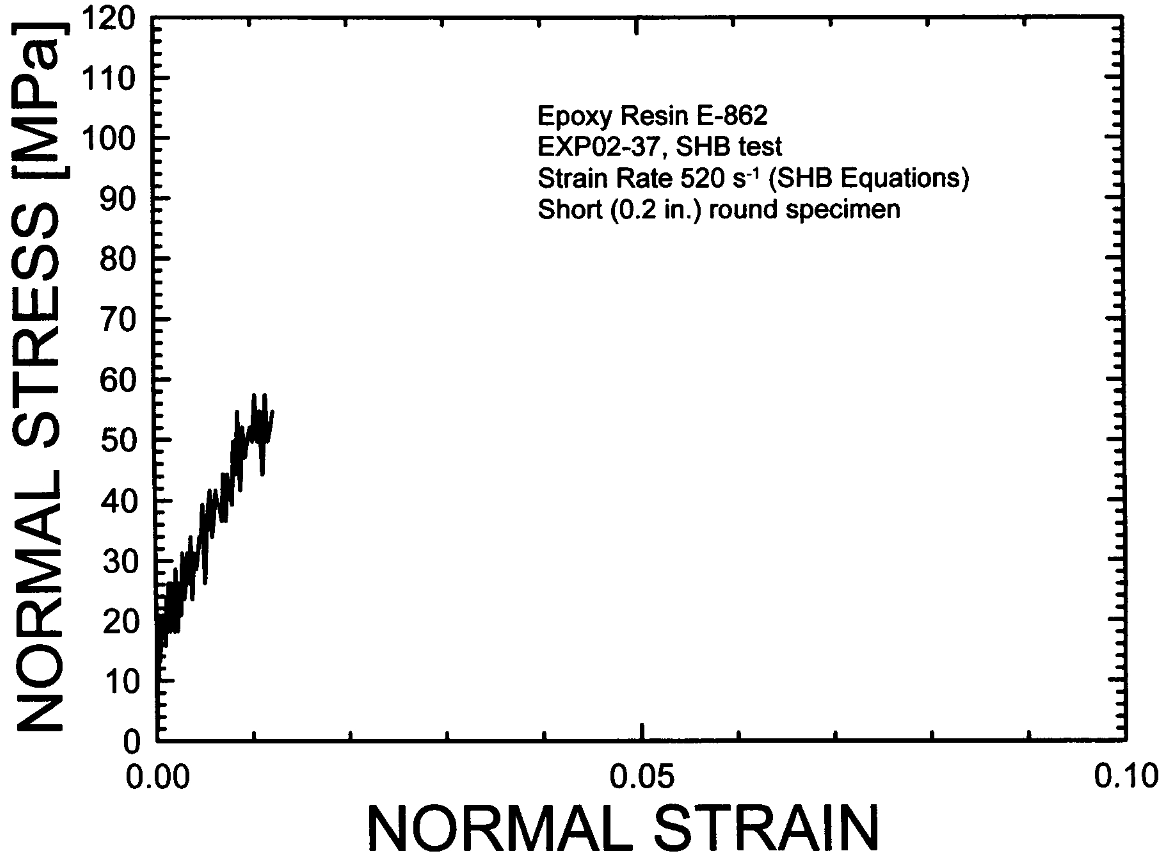

Resin PR-520
EXP 02-35
Tensile split Hopkinson bar
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
STRESS
STRAIN, GAGE A,
Gage B, Ave.
STRAIN RATE 525 s-1
(SLOPE OF STRAIN-
TIME CURVE)
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

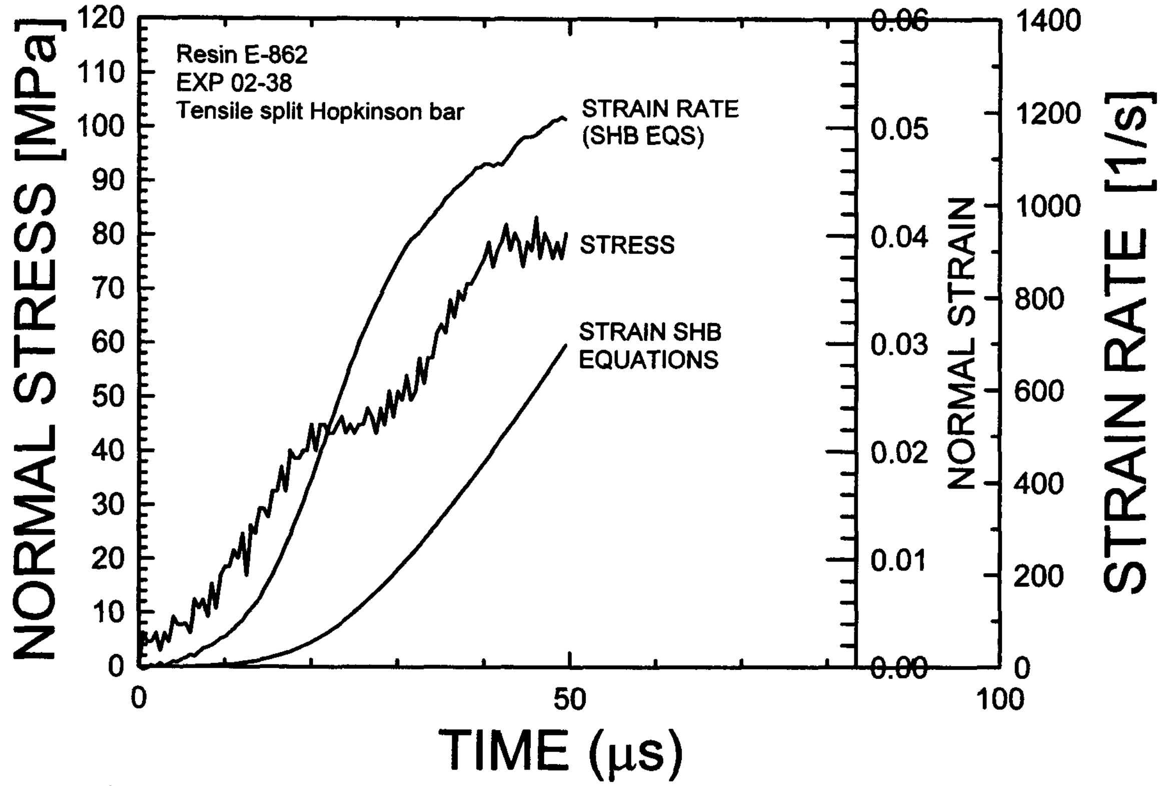

Strain (strain gage on specimen)
Strain (SHB Equations)
Epoxy Resin PR-520
EXP02-35, SHB test
Strain Rate 525 s-1
(1000 s-1 SHB Equations)
NORMAL STRESS [MPa]
NORMAL STRAIN

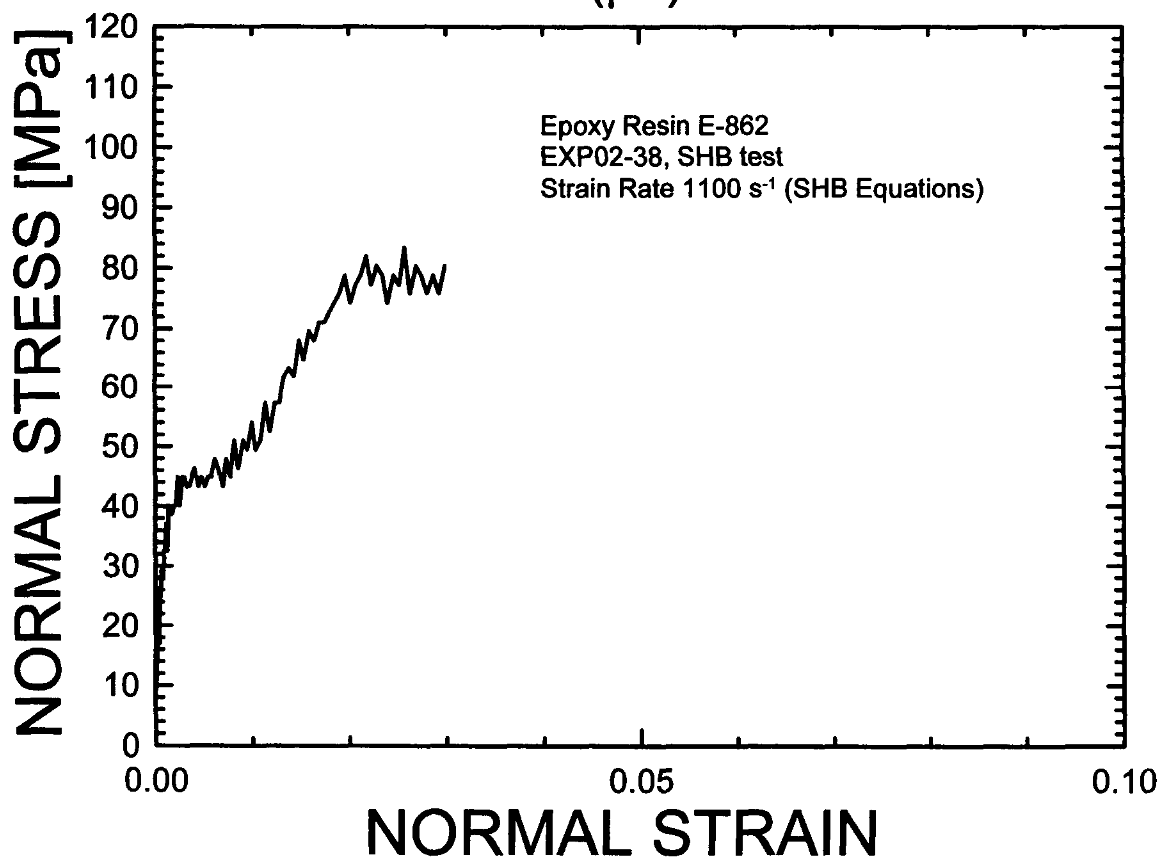

Resin PR-520
EXP 02-36
Tensile split Hopkinson bar
STRESS
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.01
0.02
0.03
0.04
0.05
0.06
200
400
600
800
1000
1200
1400
0
50
100

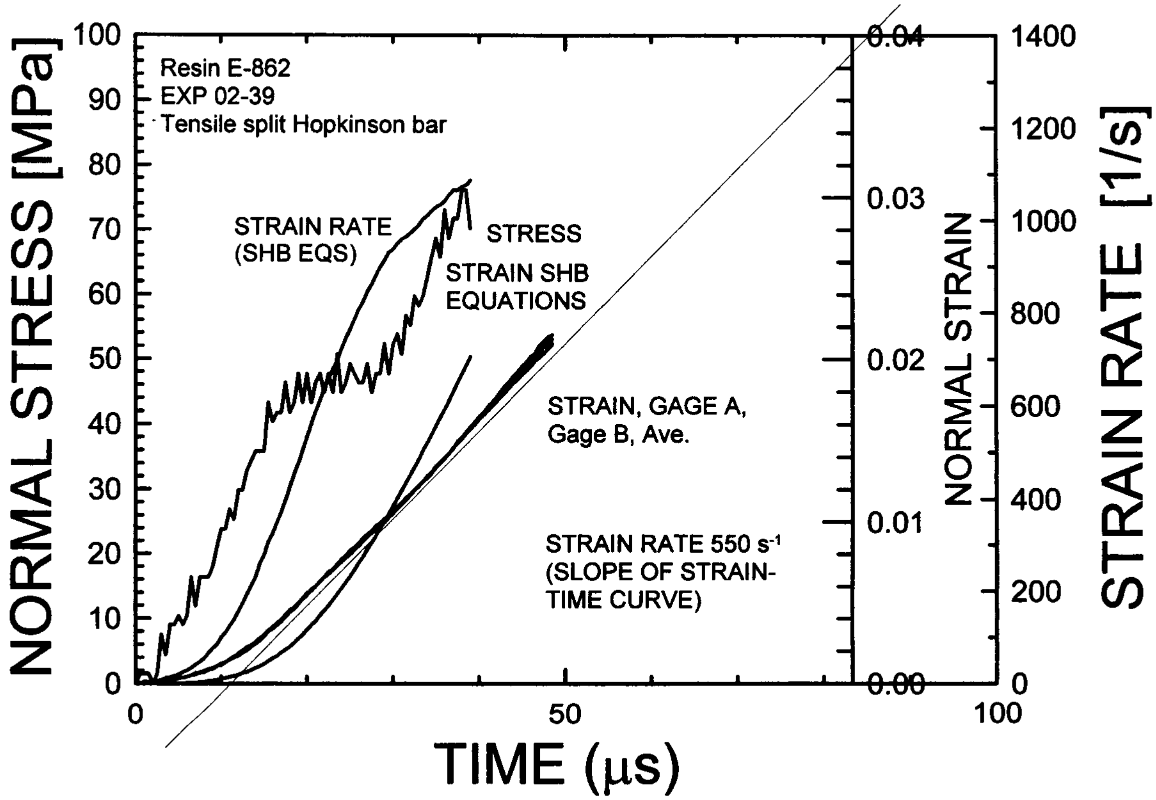

Epoxy Resin PR-520
EXP02-36, SHB test
Strain Rate 400 s-1 (SHB Equations)
Short (0.2 in.) round specimen
NORMAL STRESS [MPa]
NORMAL STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.05
0.10

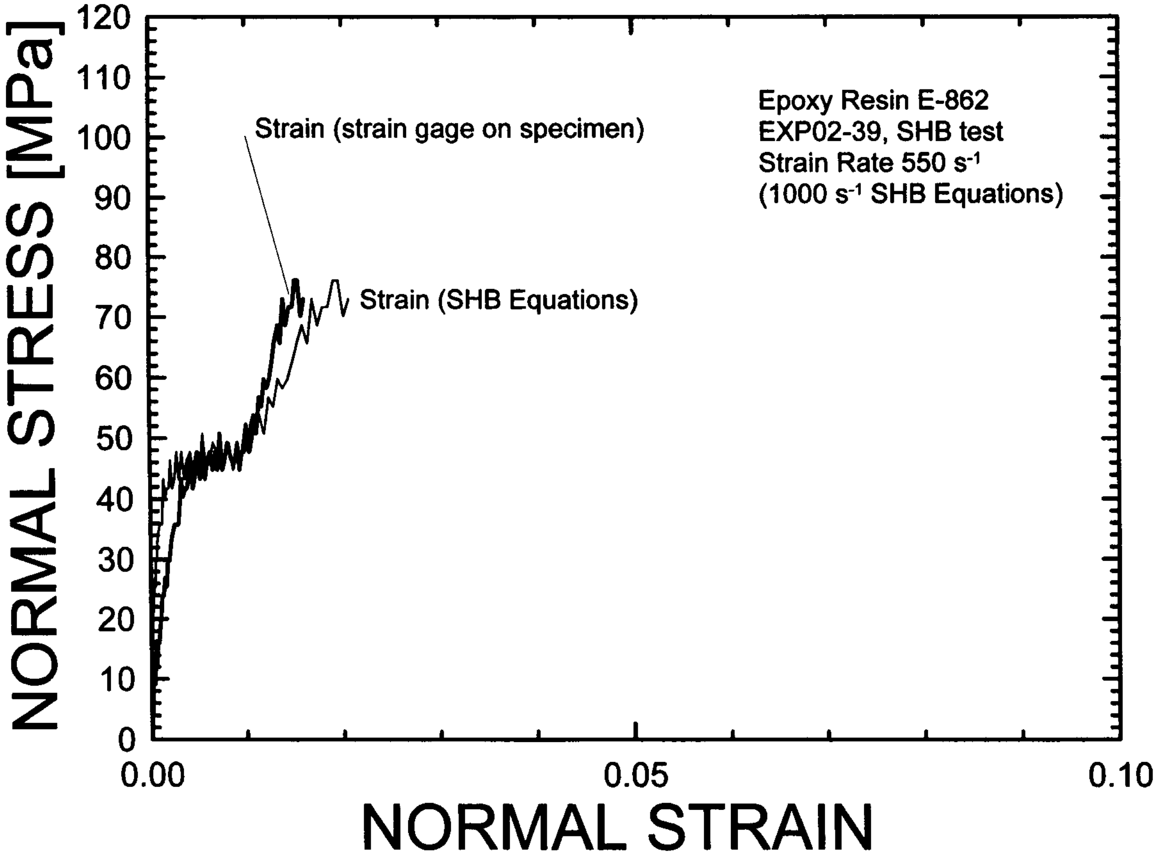

Resin E-862
EXP 02-37
Tensile split Hopkinson bar
STRESS
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

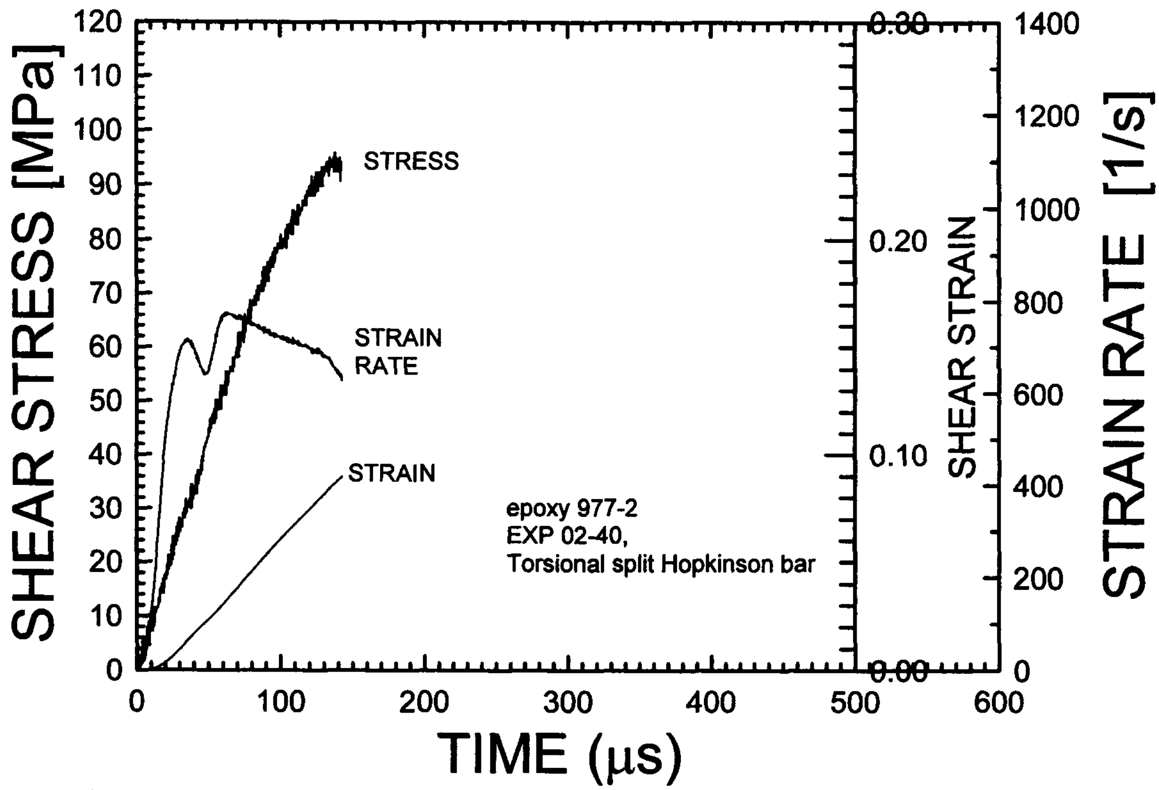

Epoxy Resin E-862
EXP02-37, SHB test
Strain Rate 520 s-1 (SHB Equations)
Short (0.2 in.) round specimen
NORMAL STRESS [MPa]
NORMAL STRAIN

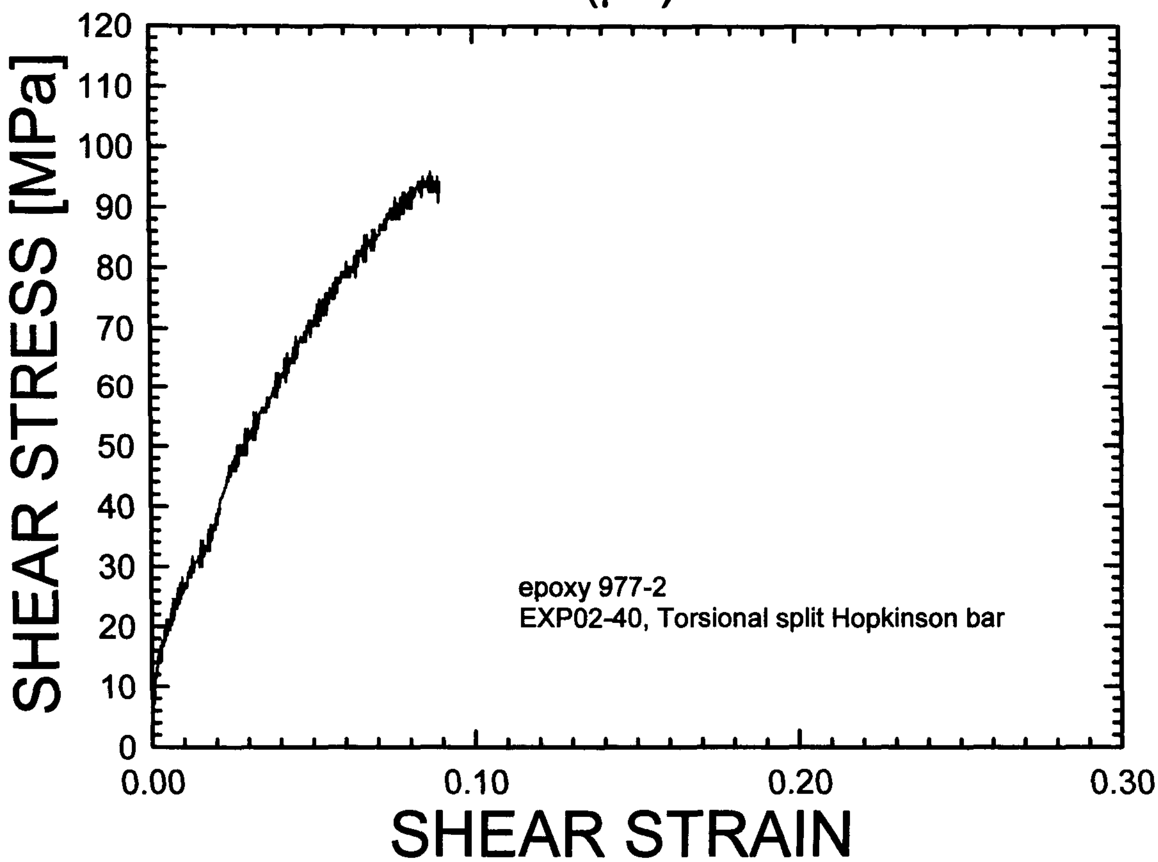

Resin E-862
EXP 02-38
Tensile split Hopkinson bar
STRAIN RATE (SHB EQS)
STRESS
STRAIN SHB EQUATIONS
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

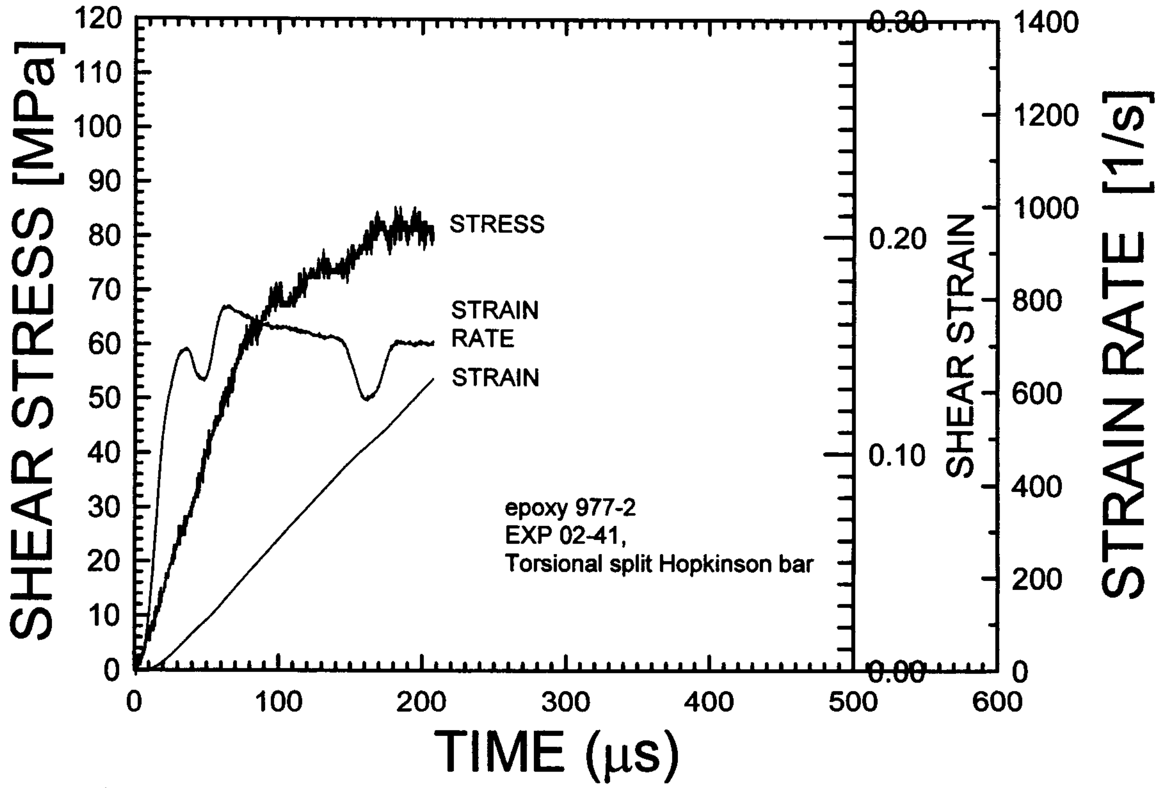

Epoxy Resin E-862
EXP02-38, SHB test
Strain Rate 1100 s-1 (SHB Equations)
NORMAL STRESS [MPa]
NORMAL STRAIN

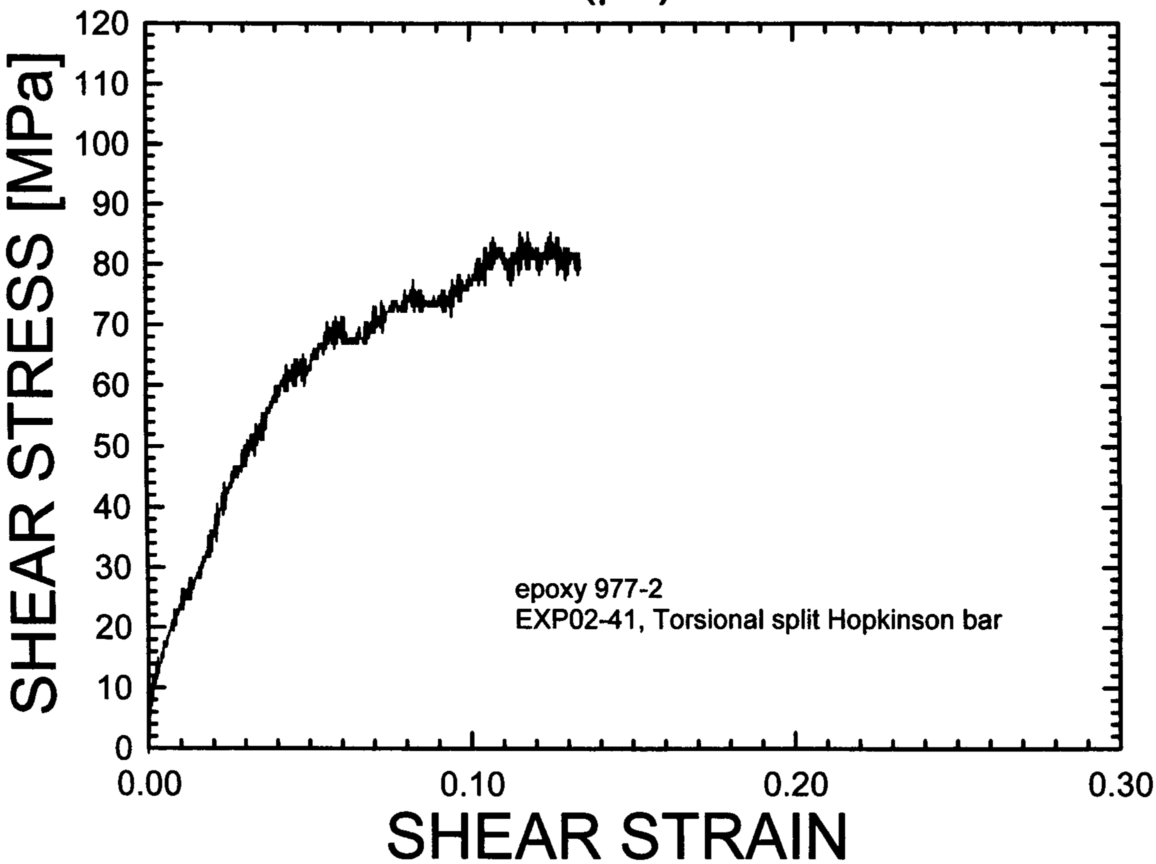

NORMAL STRESS [MPa]
Resin E-862
EXP 02-39
Tensile split Hopkinson bar
STRAIN RATE (SHB EQS)
STRESS
STRAIN SHB EQUATIONS
STRAIN, GAGE A, Gage B, Ave.
STRAIN RATE 550 s-1 (SLOPE OF STRAIN-TIME CURVE)
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

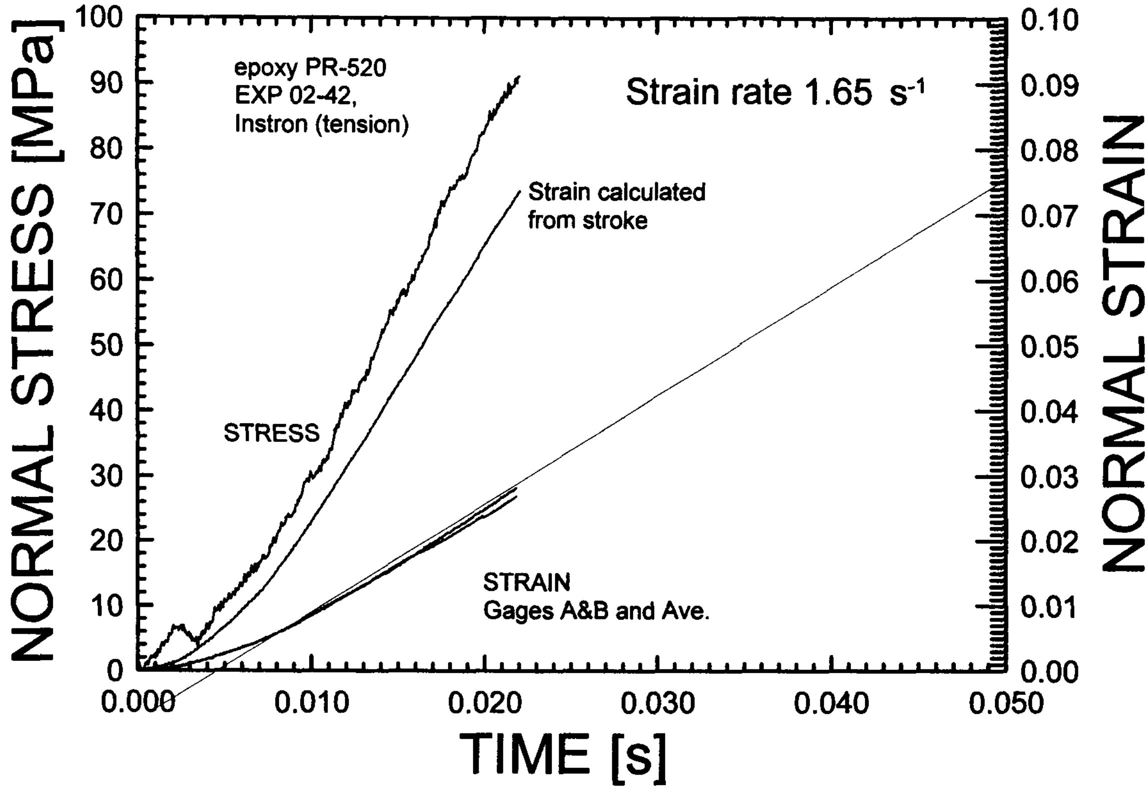

NORMAL STRESS [MPa]
Epoxy Resin E-862
EXP02-39, SHB test
Strain Rate 550 s-1
(1000 s-1 SHB Equations)
Strain (strain gage on specimen)
Strain (SHB Equations)
NORMAL STRAIN


SHEAR STRESS [MPa]
STRESS
STRAIN RATE
STRAIN
epoxy 977-2
EXP 02-40,
Torsional split Hopkinson bar
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

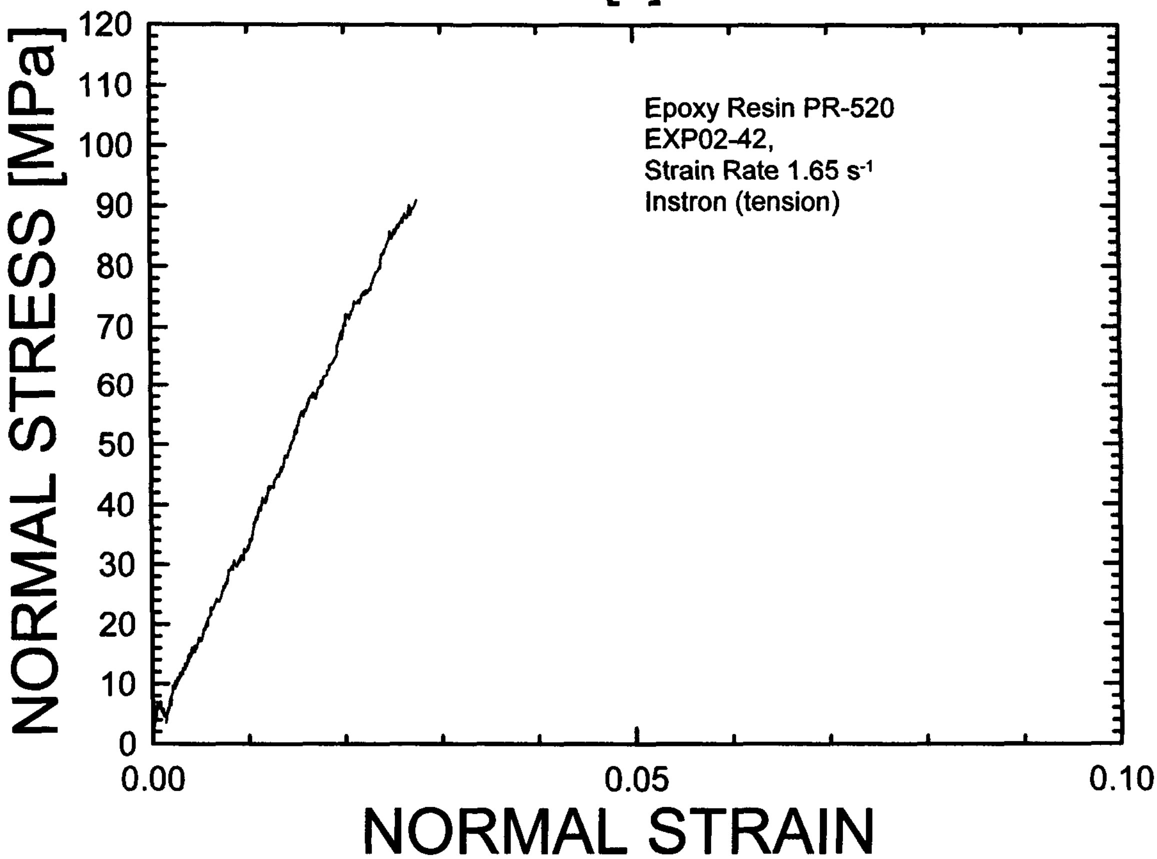

SHEAR STRESS [MPa]
epoxy 977-2
EXP02-40, Torsional split Hopkinson bar
SHEAR STRAIN


SHEAR STRESS [MPa]
STRESS
STRAIN
RATE
STRAIN
epoxy 977-2
EXP 02-41,
Torsional split Hopkinson bar
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

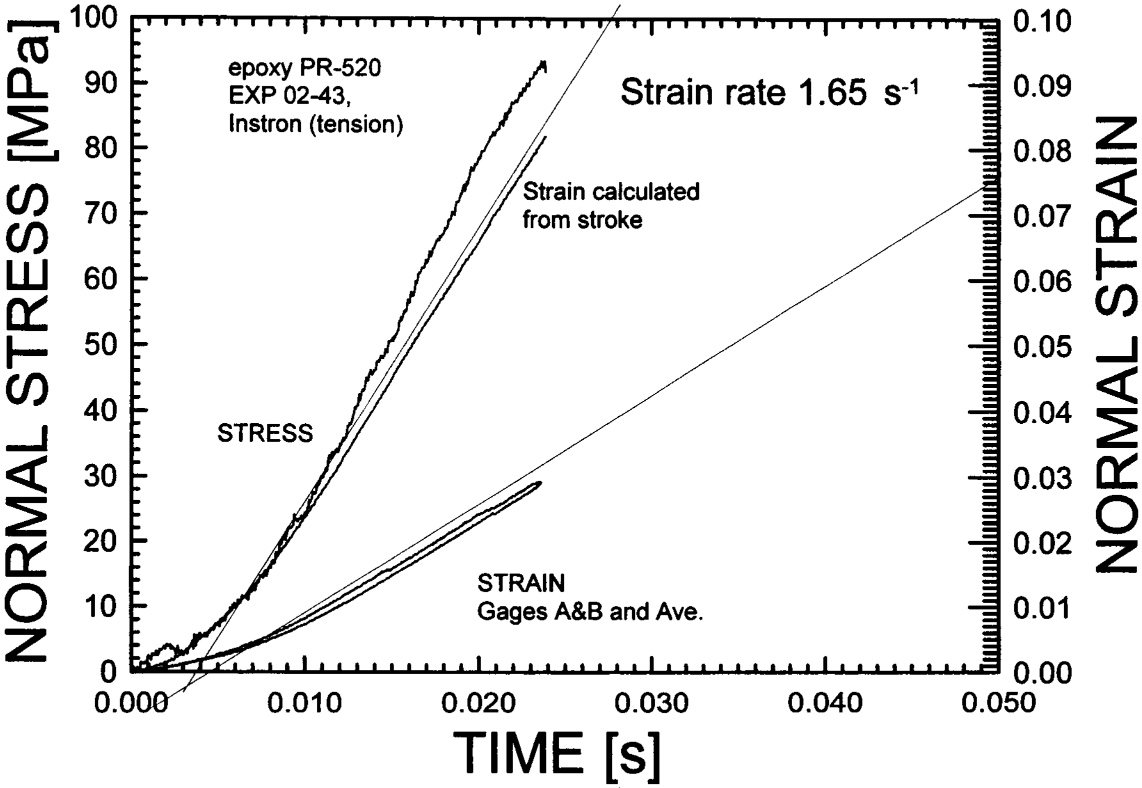

SHEAR STRESS [MPa]
epoxy 977-2
EXP02-41, Torsional split Hopkinson bar
SHEAR STRAIN

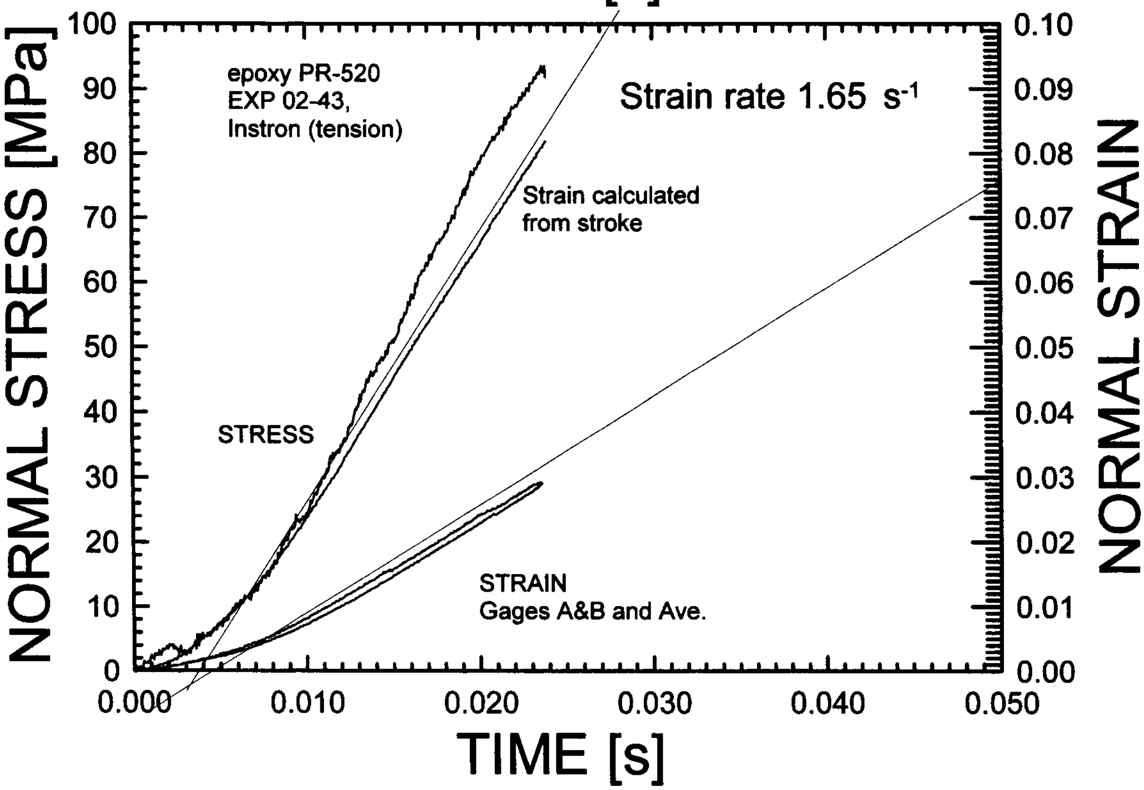


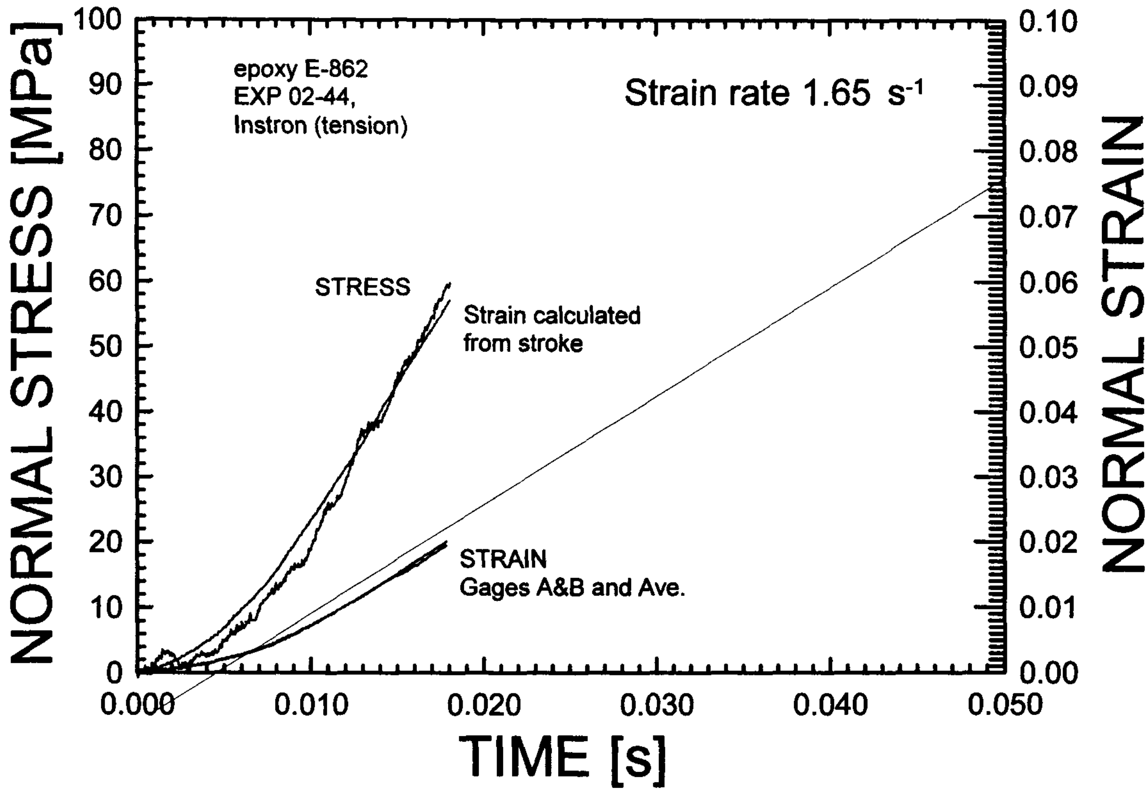
NORMAL STRESS [MPa]
100
90
80
70
60
50
40
30
20
10
0
epoxy PR-520
EXP 02-42,
Instron (tension)
Strain rate 1.65 s^{-1}
Strain calculated
from stroke
STRESS
STRAIN
Gages A&B and Ave.
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
NORMAL STRAIN
0.000
0.010
0.020
0.030
0.040
0.050
TIME [s]



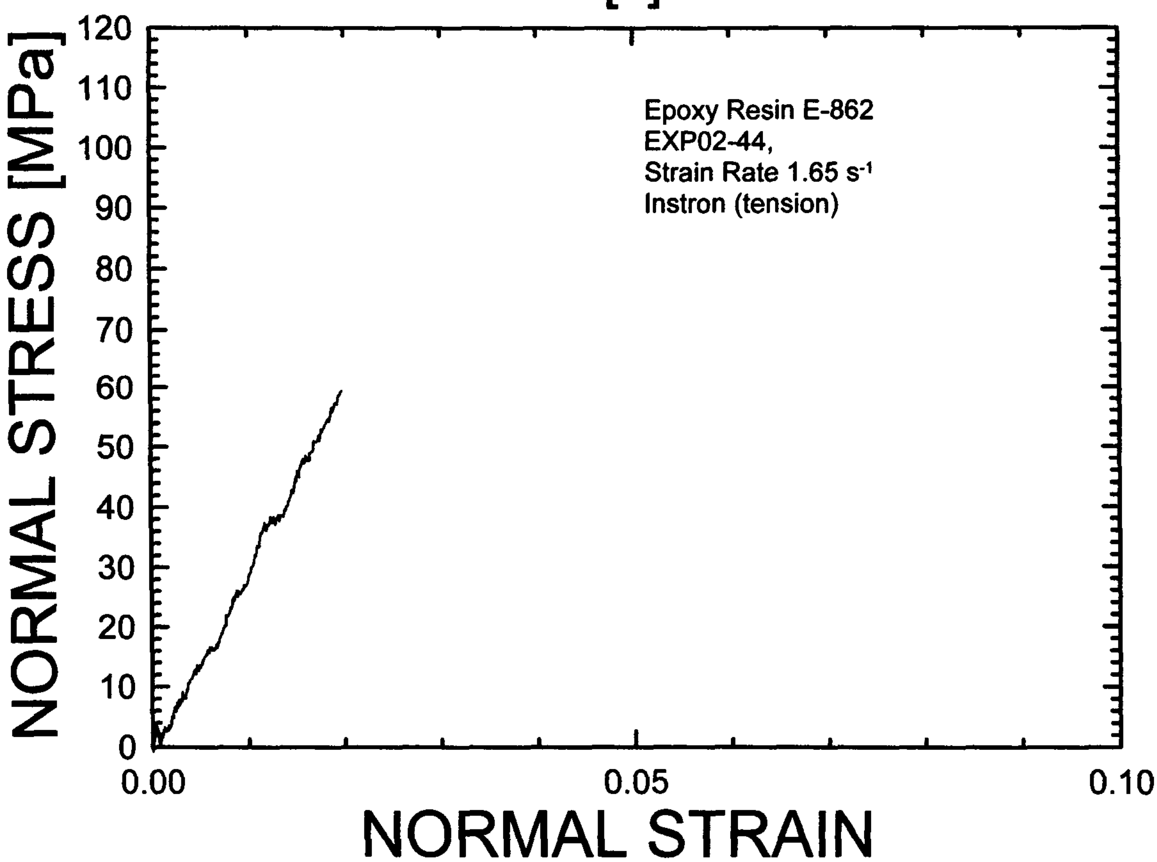
NORMAL STRESS [MPa]
120
110
100
90
80
70
60
50
40
30
20
10
0
Epoxy Resin PR-520
EXP02-42,
Strain Rate 1.65 s^{-1}
Instron (tension)
0.00
0.05
0.10
NORMAL STRAIN


NORMAL STRESS [MPa]
100
90
80
70
60
50
40
30
20
10
0
epoxy PR-520
EXP 02-43,
Instron (tension)
Strain rate 1.65 s^{-1}
Strain calculated
from stroke
STRESS
STRAIN
Gages A&B and Ave.
0.000
0.010
0.020
0.030
0.040
0.050
TIME [s]
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
NORMAL STRAIN

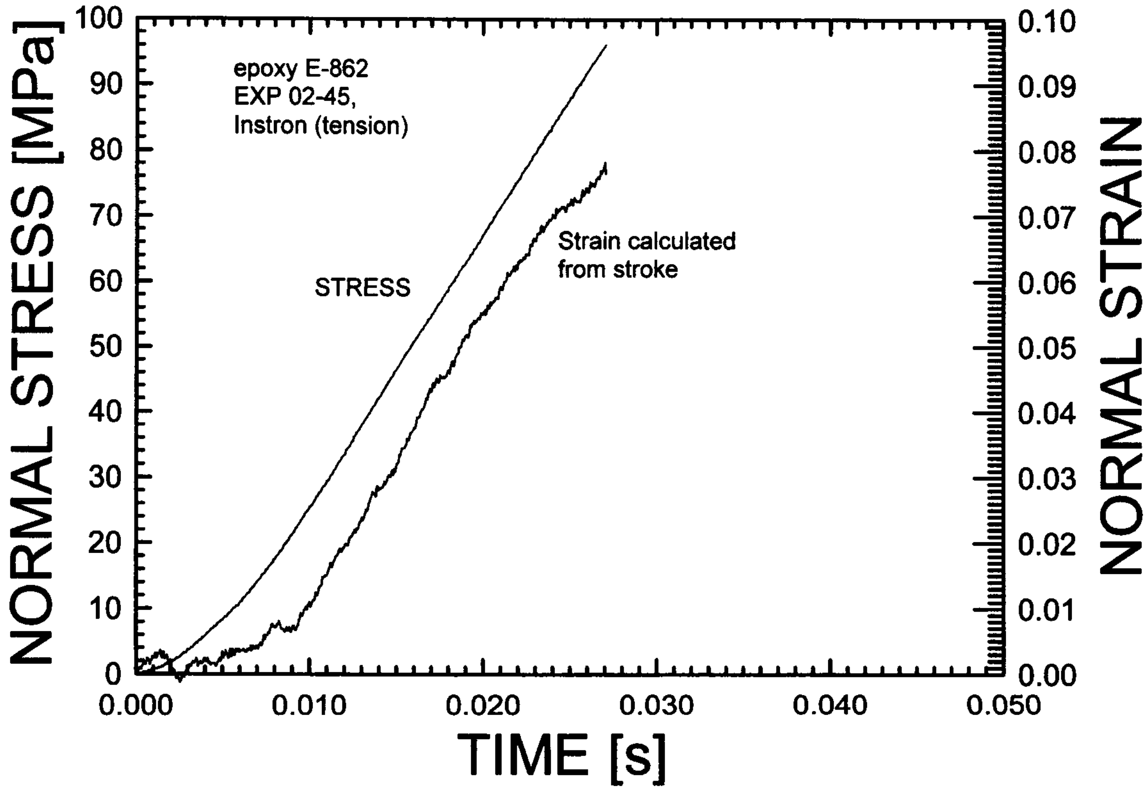

NORMAL STRESS [MPa]
100
90
80
70
60
50
40
30
20
10
0
epoxy PR-520
EXP 02-43,
Instron (tension)
Strain rate 1.65 s^{-1}
Strain calculated
from stroke
STRESS
STRAIN
Gages A&B and Ave.
0.000
0.010
0.020
0.030
0.040
0.050
TIME [s]
0.10
0.09
0.08
0.07
0.06
0.05
0.04
0.03
0.02
0.01
0.00
NORMAL STRAIN

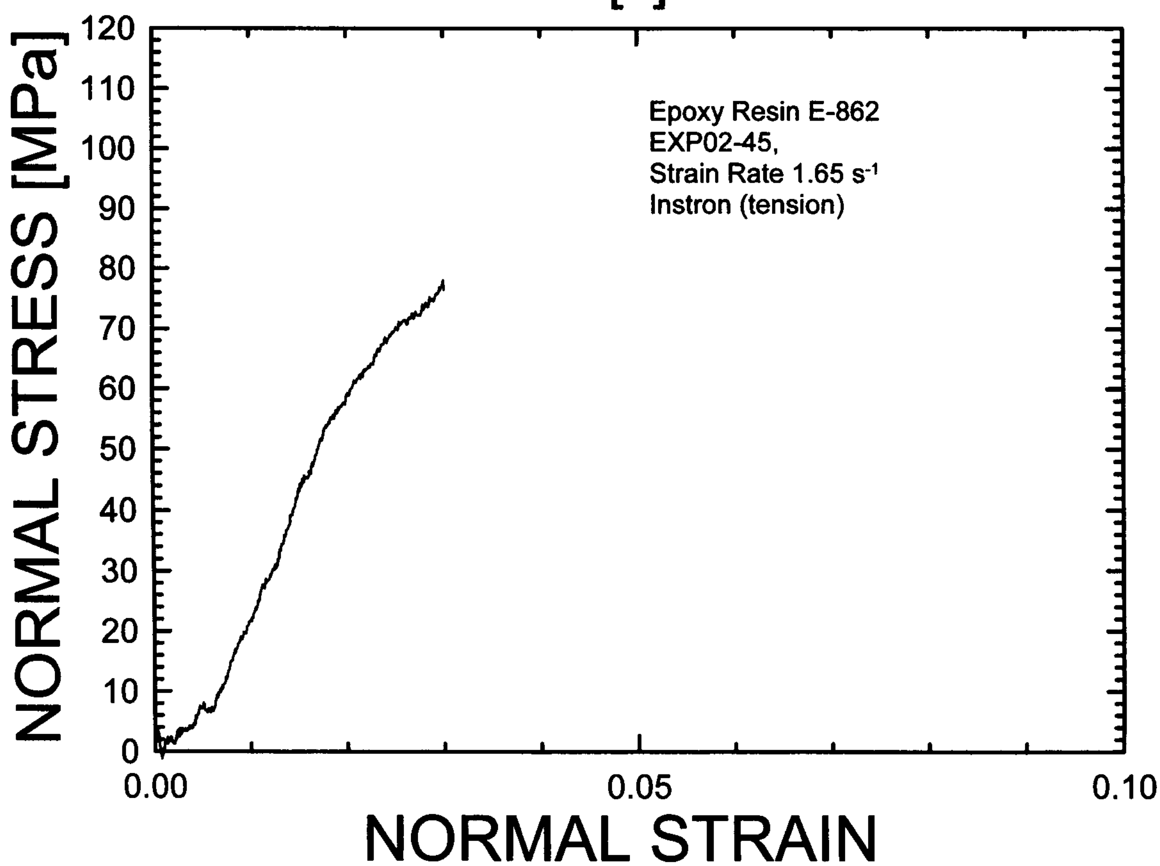


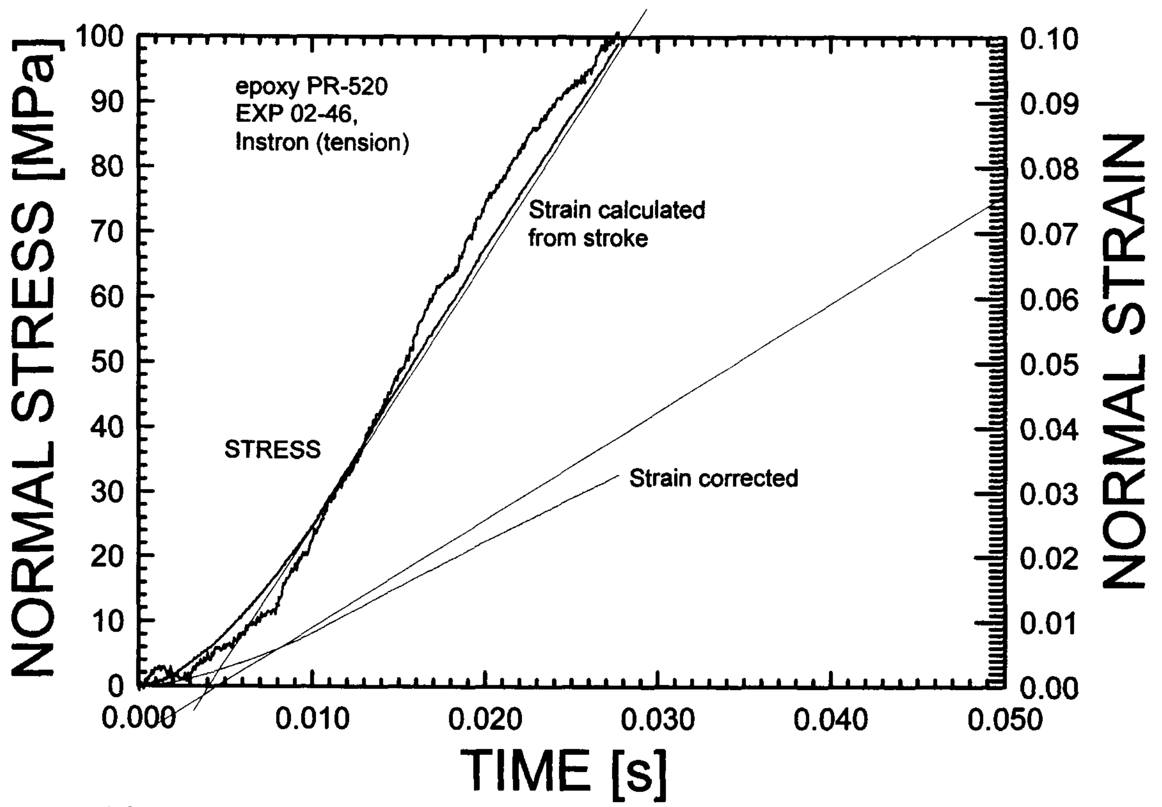
epoxy E-862
EXP 02-44,
Instron (tension)
Strain rate 1.65 s-1
STRESS
Strain calculated from stroke
STRAIN
Gages A&B and Ave.
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]



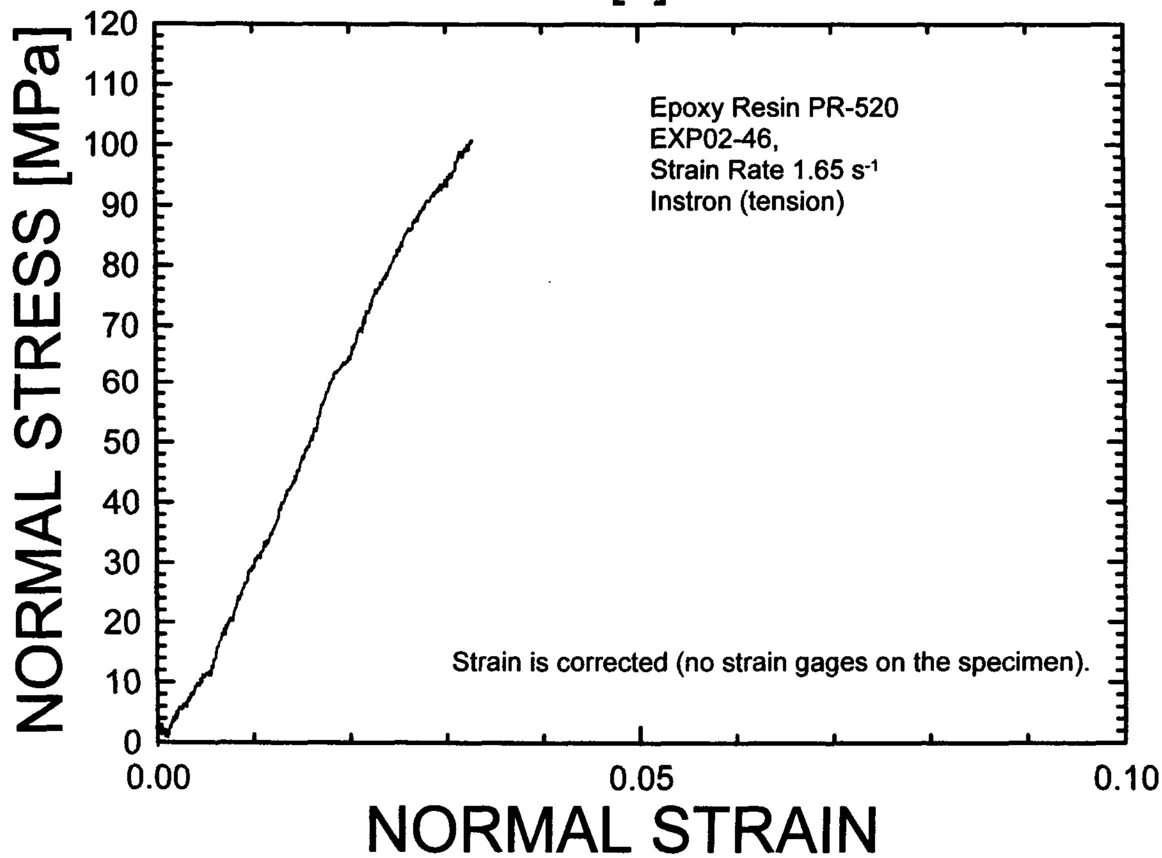
Epoxy Resin E-862
EXP02-44,
Strain Rate 1.65 s-1
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN


epoxy E-862
EXP 02-45,
Instron (tension)
STRESS
Strain calculated
from stroke
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

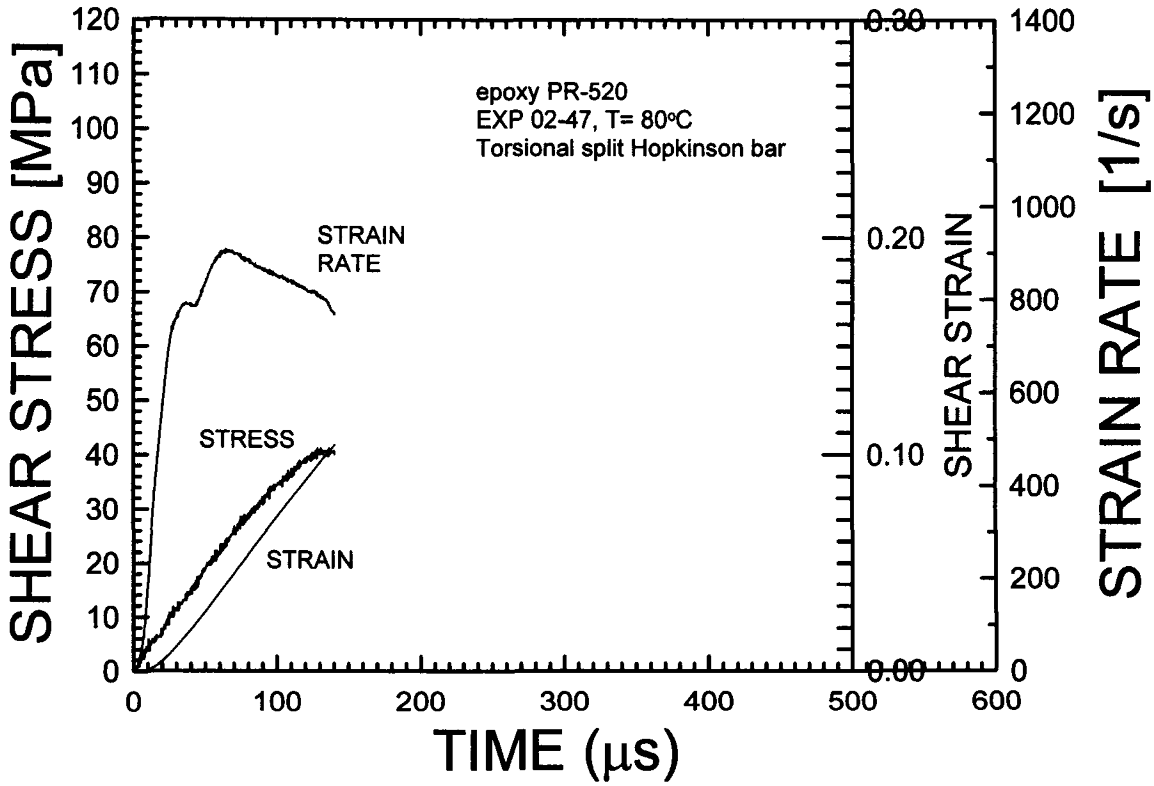

Epoxy Resin E-862
EXP02-45,
Strain Rate 1.65 s-1
Instron (tension)
NORMAL STRESS [MPa]
NORMAL STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.05
0.10



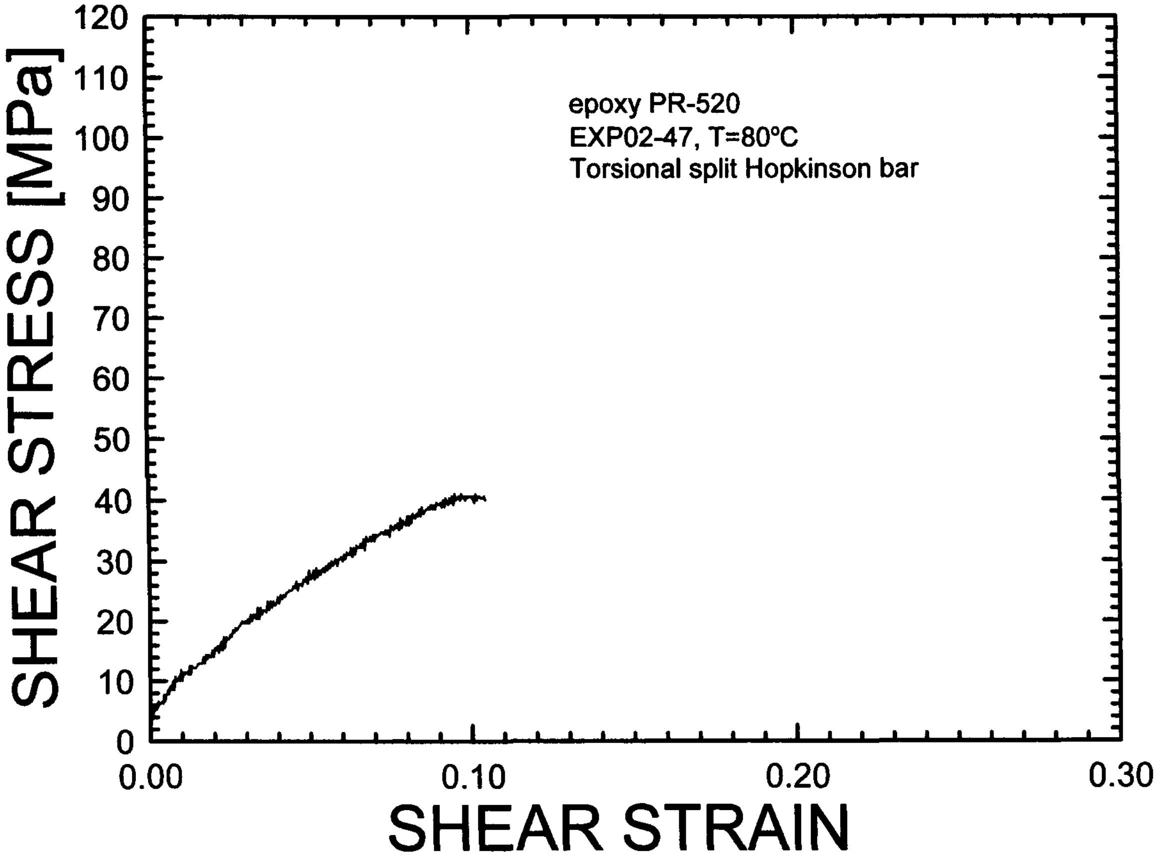
epoxy PR-520
EXP 02-46,
Instron (tension)
Strain calculated from stroke
STRESS
Strain corrected
NORMAL STRESS [MPa]
NORMAL STRAIN
TIME [s]



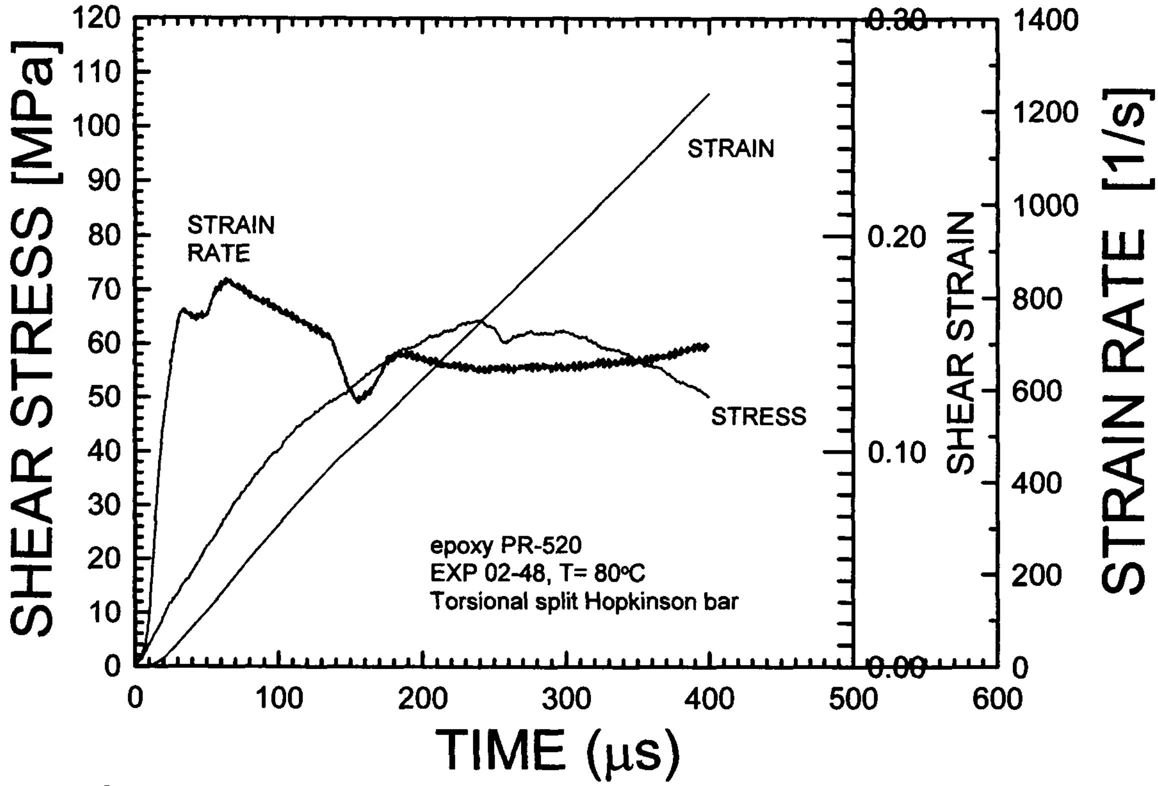
Epoxy Resin PR-520
EXP02-46,
Strain Rate 1.65 s-1
Instron (tension)
Strain is corrected (no strain gages on the specimen).
NORMAL STRESS [MPa]
NORMAL STRAIN

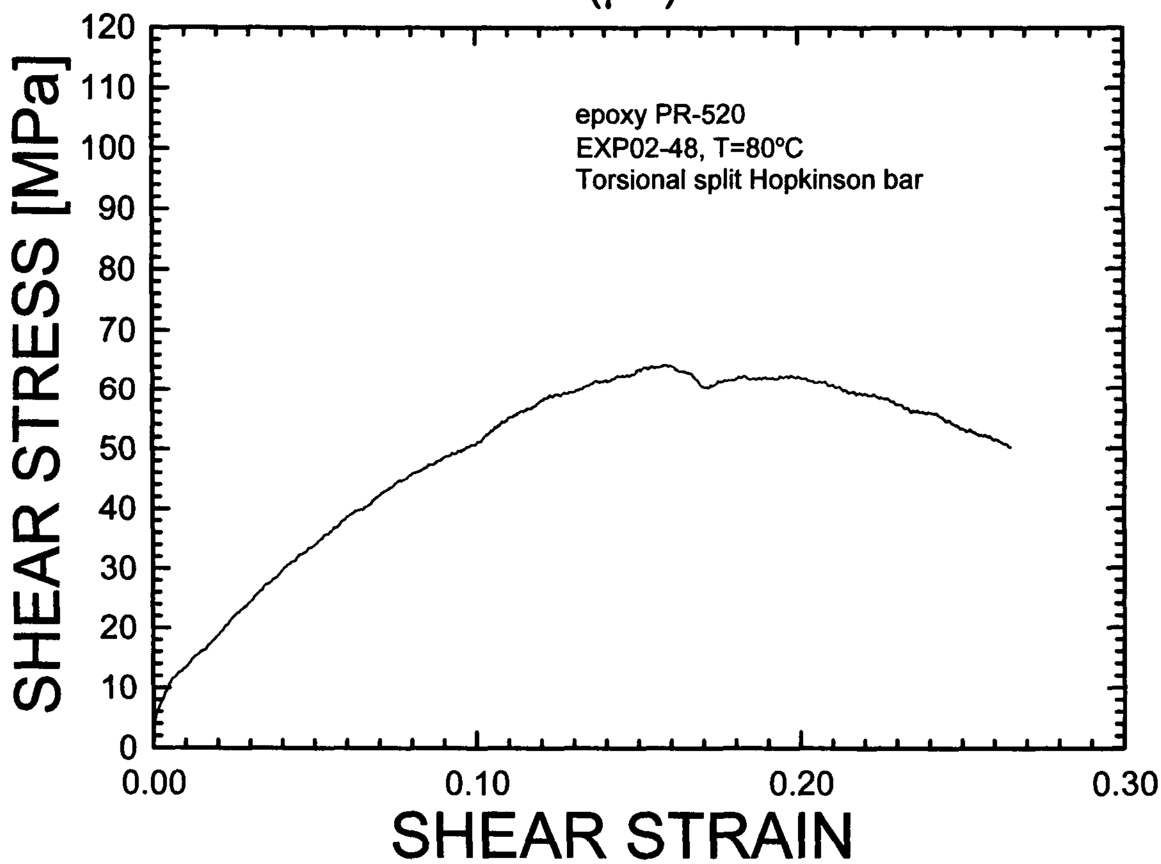


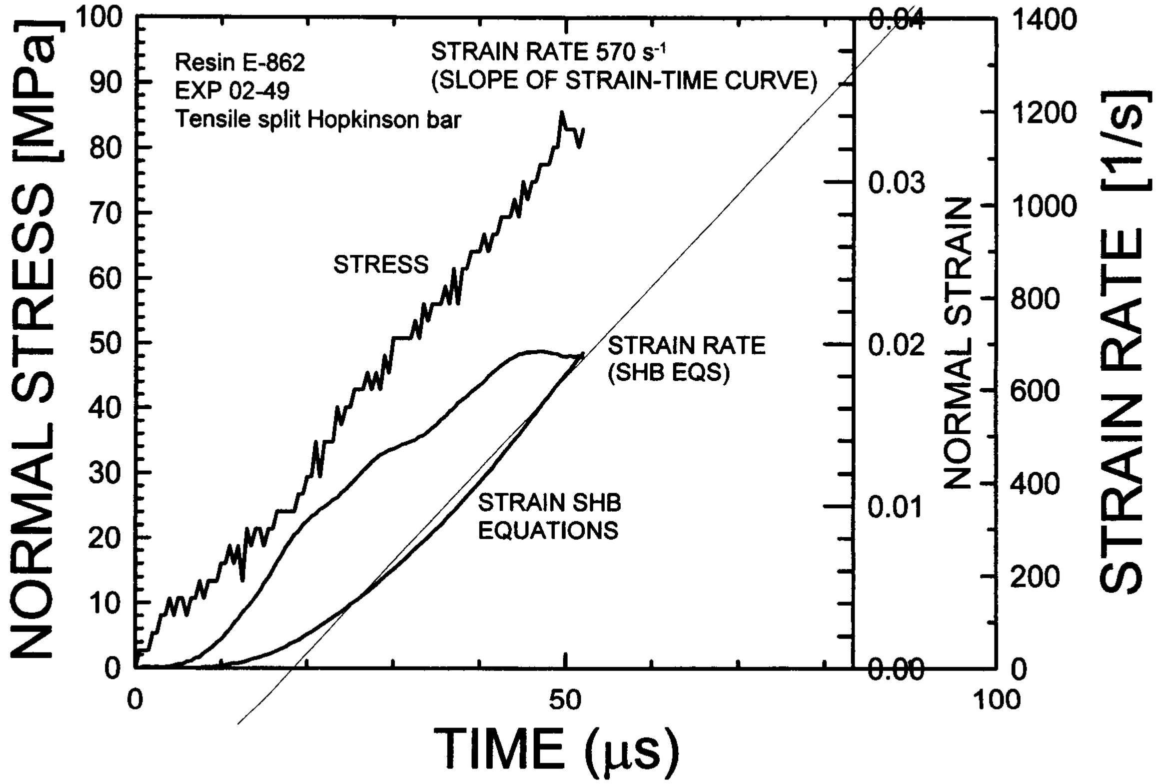
epoxy PR-520
EXP 02-47, T= 80°C
Torsional split Hopkinson bar
STRAIN RATE
STRESS
STRAIN
SHEAR STRESS [MPa]
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

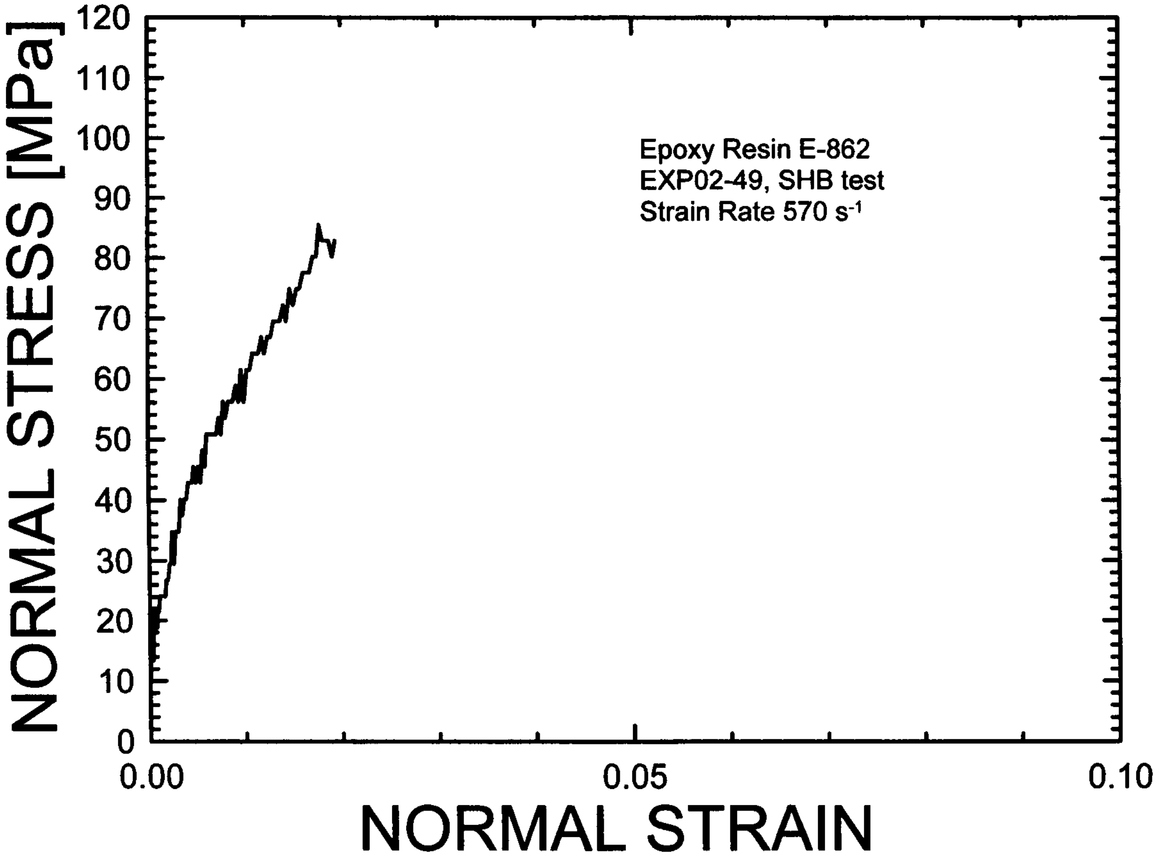


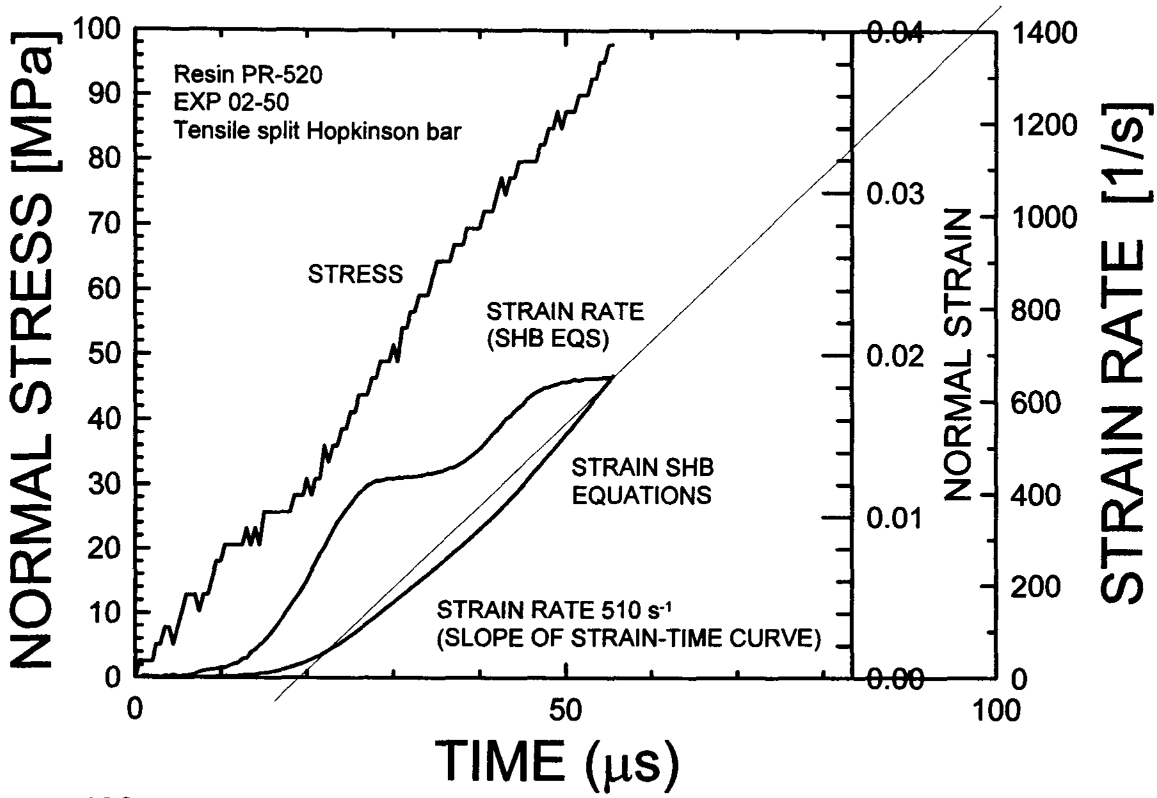
epoxy PR-520
EXP02-47, T=80°C
Torsional split Hopkinson bar
SHEAR STRESS [MPa]
SHEAR STRAIN


SHEAR STRESS [MPa]
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)
STRAIN
STRAIN RATE
STRESS
epoxy PR-520
EXP 02-48, T= 80°C
Torsional split Hopkinson bar

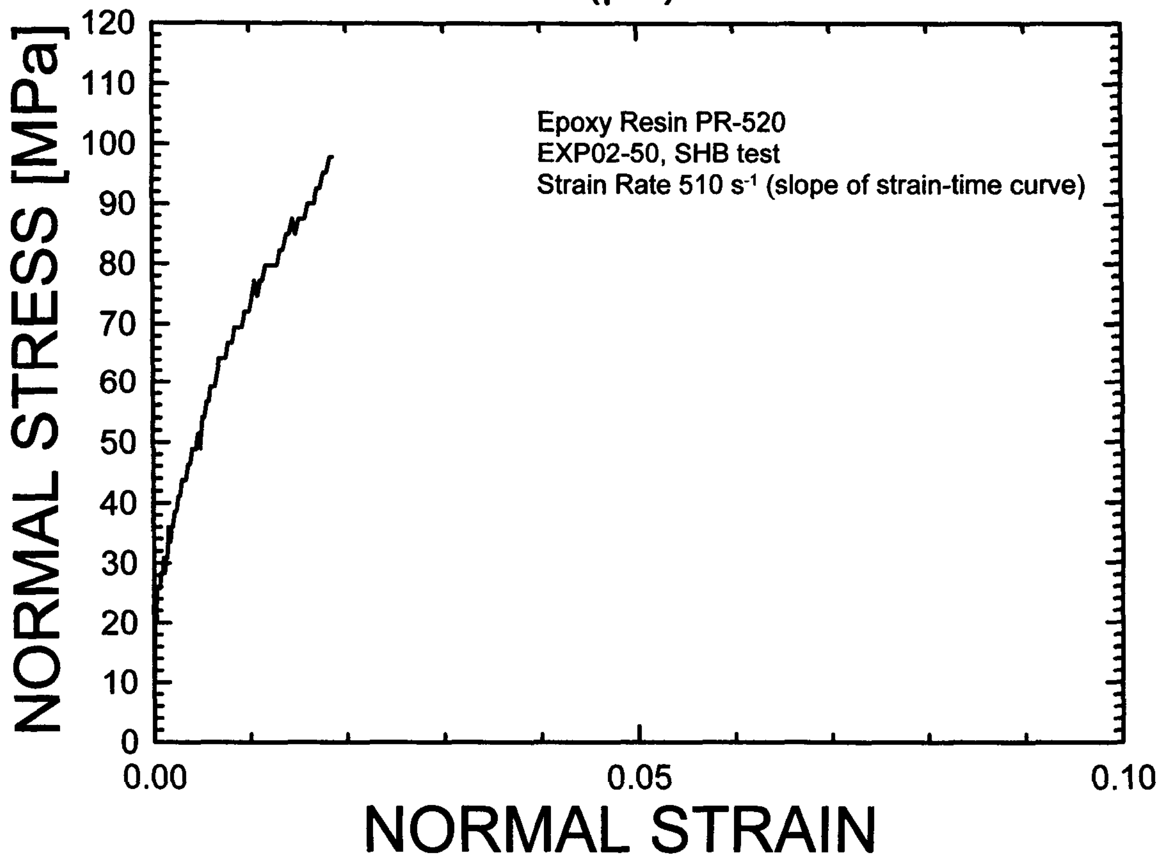

SHEAR STRESS [MPa]
SHEAR STRAIN
epoxy PR-520
EXP02-48, T=80°C
Torsional split Hopkinson bar


Resin E-862
EXP 02-49
Tensile split Hopkinson bar
STRAIN RATE 570 s-1
(SLOPE OF STRAIN-TIME CURVE)
STRESS
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

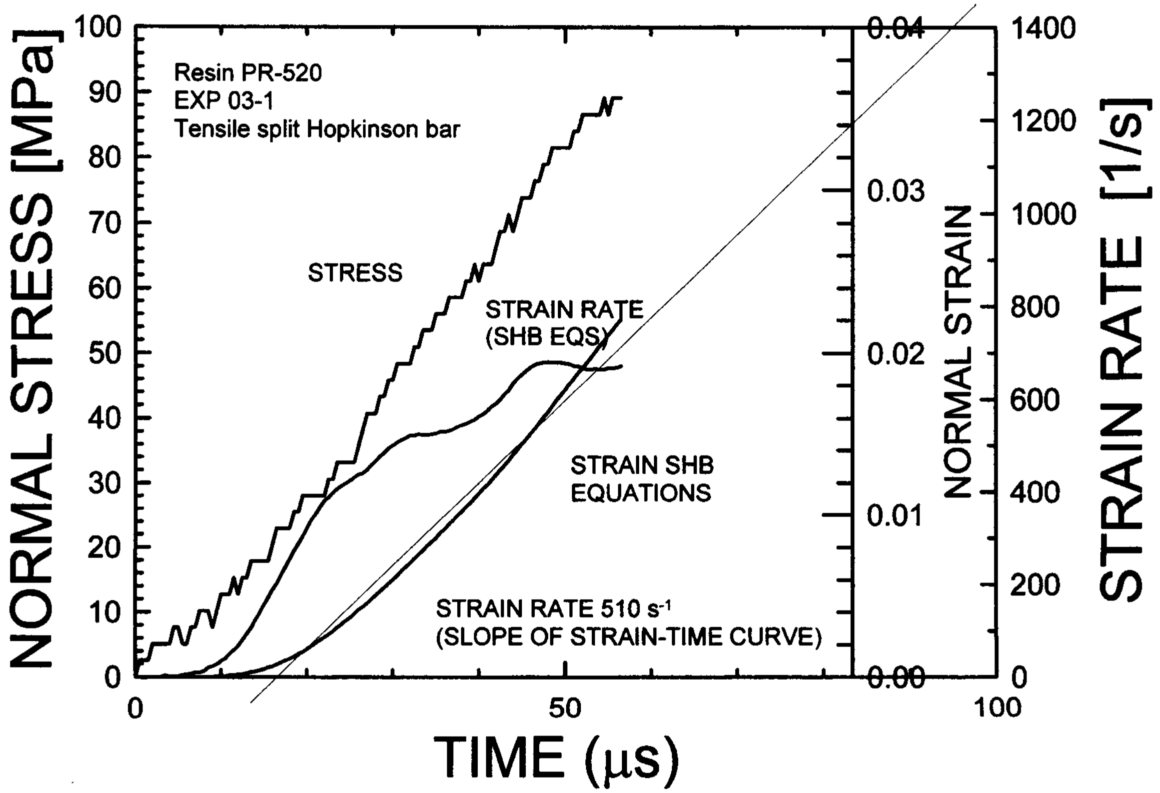

Epoxy Resin E-862
EXP02-49, SHB test
Strain Rate 570 s-1
NORMAL STRESS [MPa]
NORMAL STRAIN



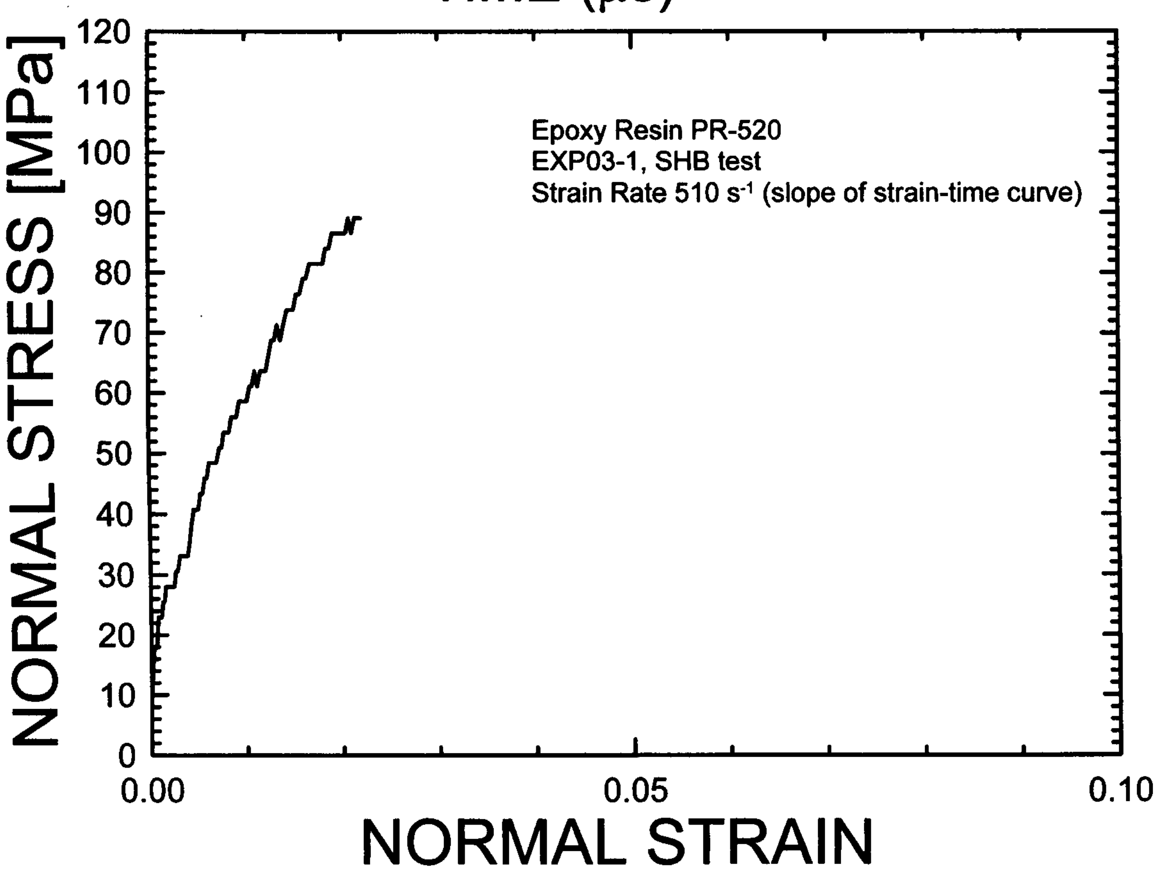
Resin PR-520
EXP 02-50
Tensile split Hopkinson bar
STRESS
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
STRAIN RATE 510 s-1
(SLOPE OF STRAIN-TIME CURVE)
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)



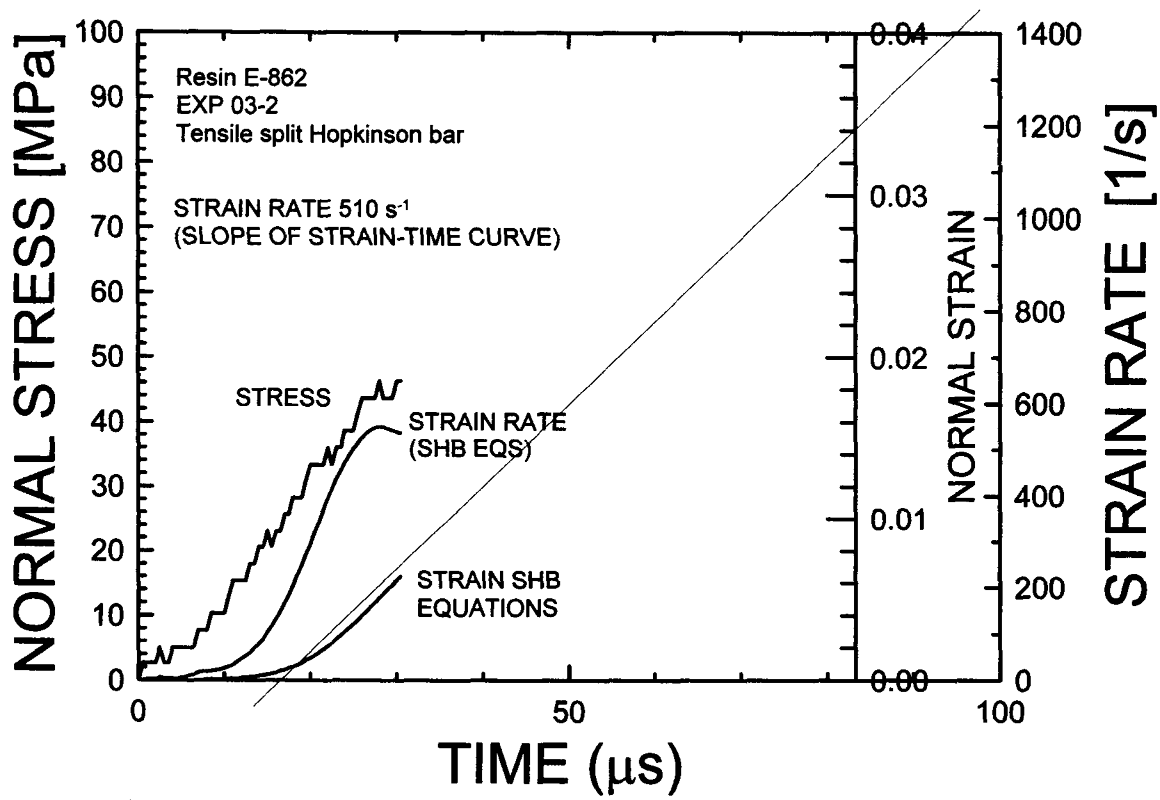
Epoxy Resin PR-520
EXP02-50, SHB test
Strain Rate 510 s-1 (slope of strain-time curve)
NORMAL STRESS [MPa]
NORMAL STRAIN

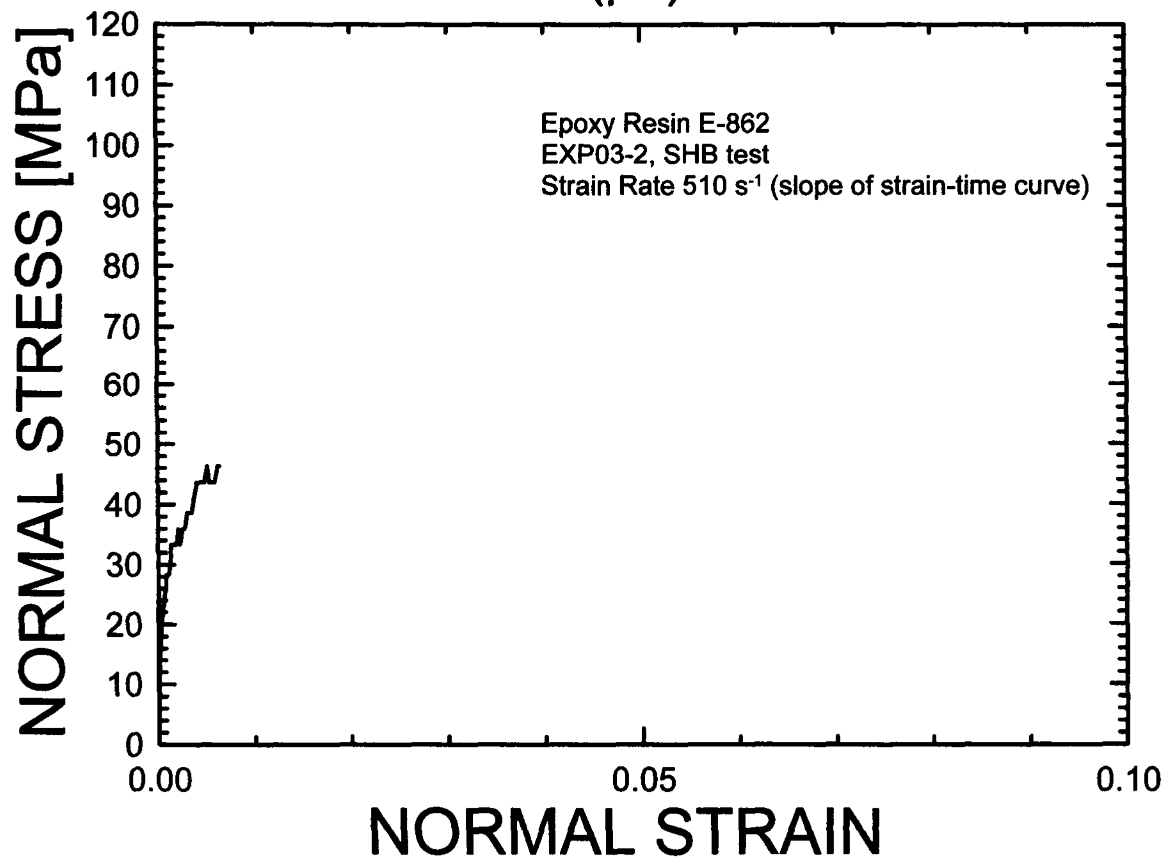


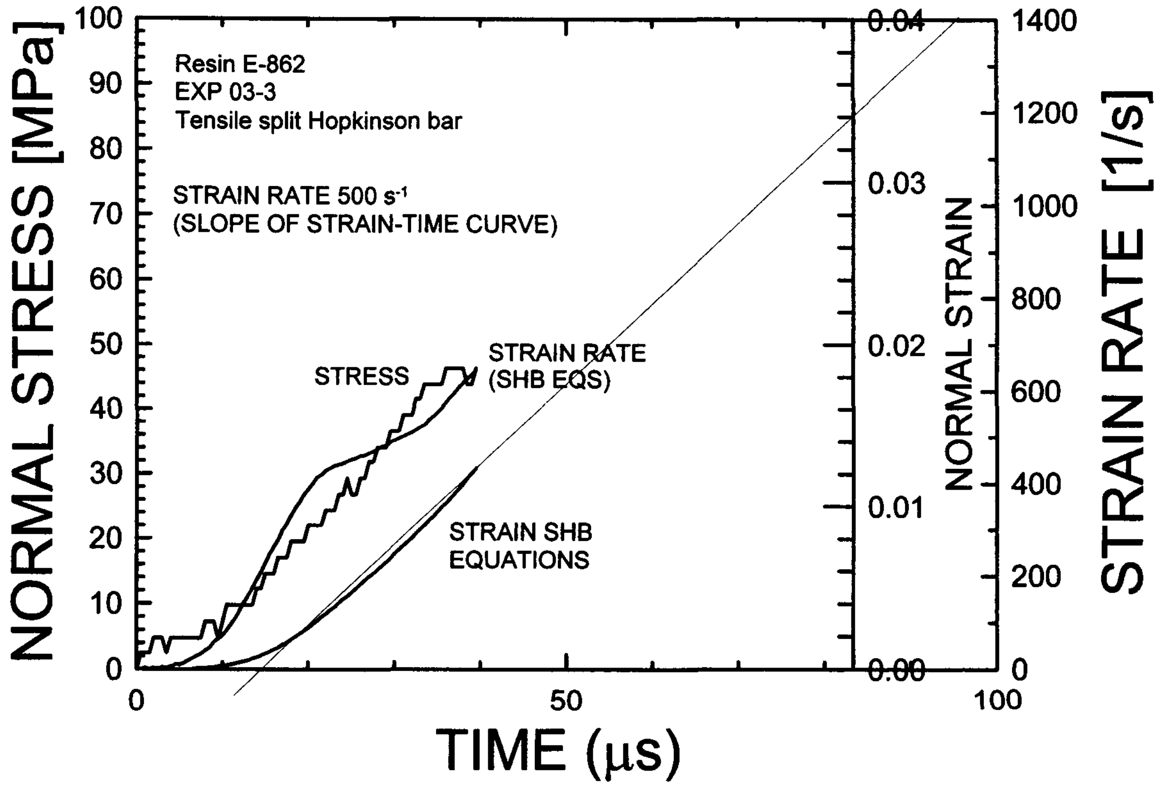
Resin PR-520
EXP 03-1
Tensile split Hopkinson bar
STRESS
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
STRAIN RATE 510 s-1
(SLOPE OF STRAIN-TIME CURVE)
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

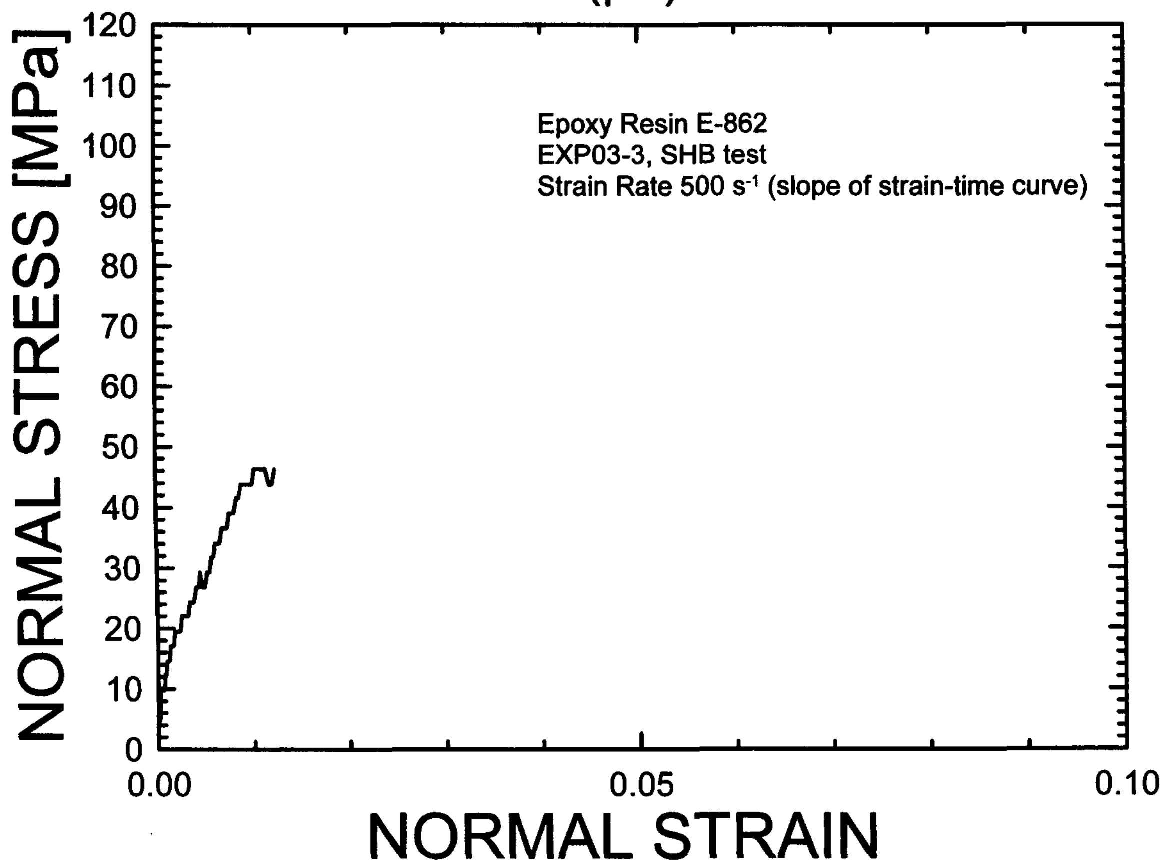


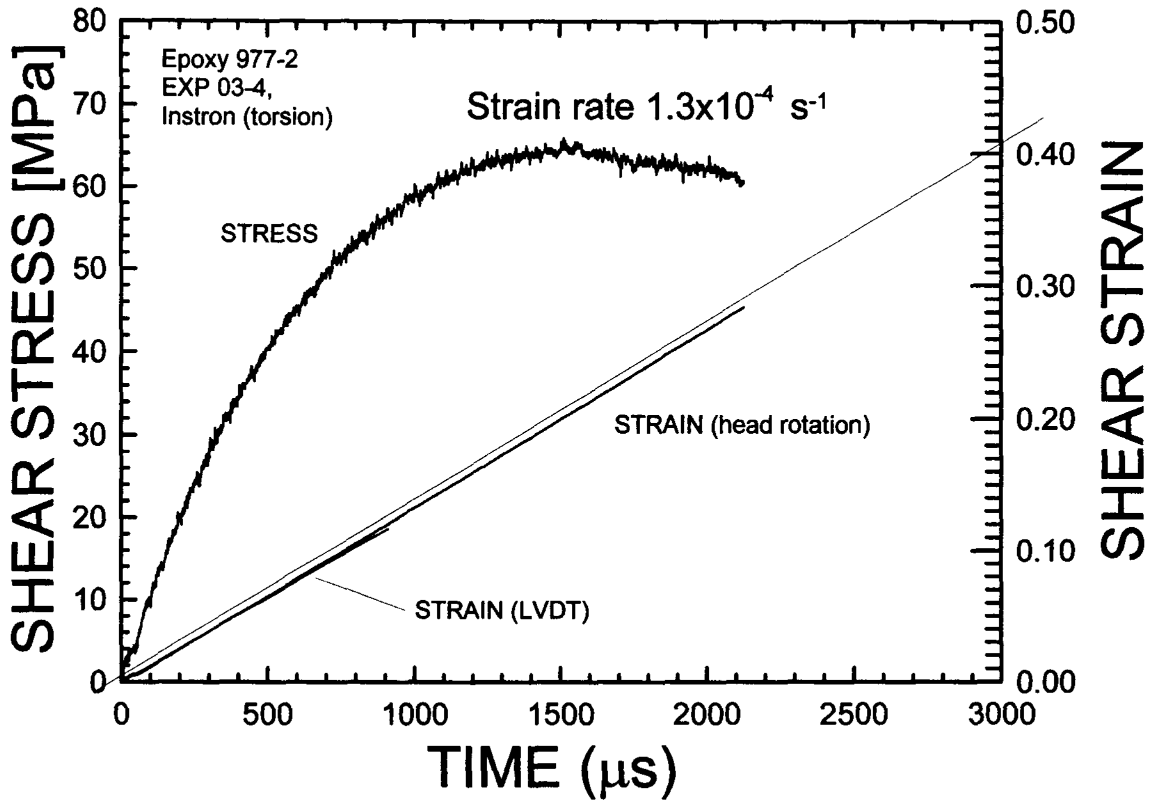
Epoxy Resin PR-520
EXP03-1, SHB test
Strain Rate 510 s-1 (slope of strain-time curve)
NORMAL STRESS [MPa]
NORMAL STRAIN

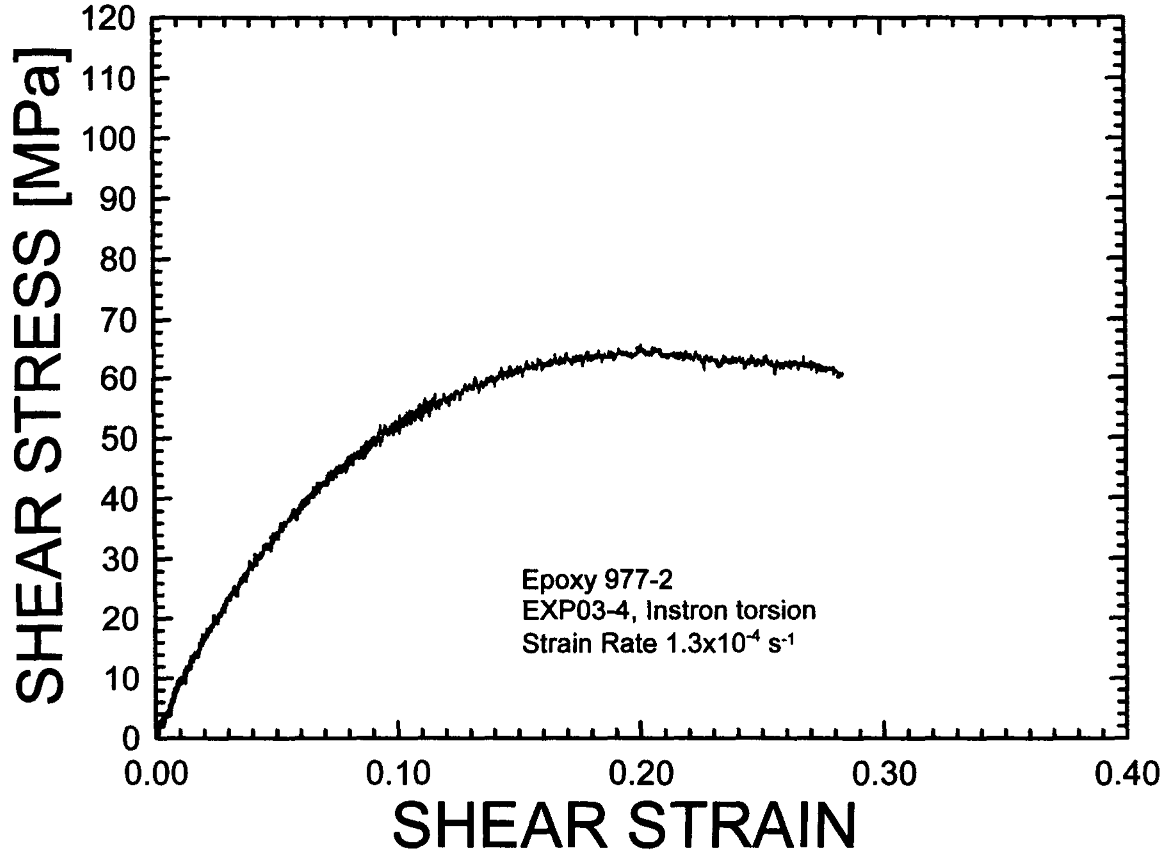

Resin E-862
EXP 03-2
Tensile split Hopkinson bar
STRAIN RATE 510 s-1
(SLOPE OF STRAIN-TIME CURVE)
STRESS
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
NORMAL STRESS [MPa]
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

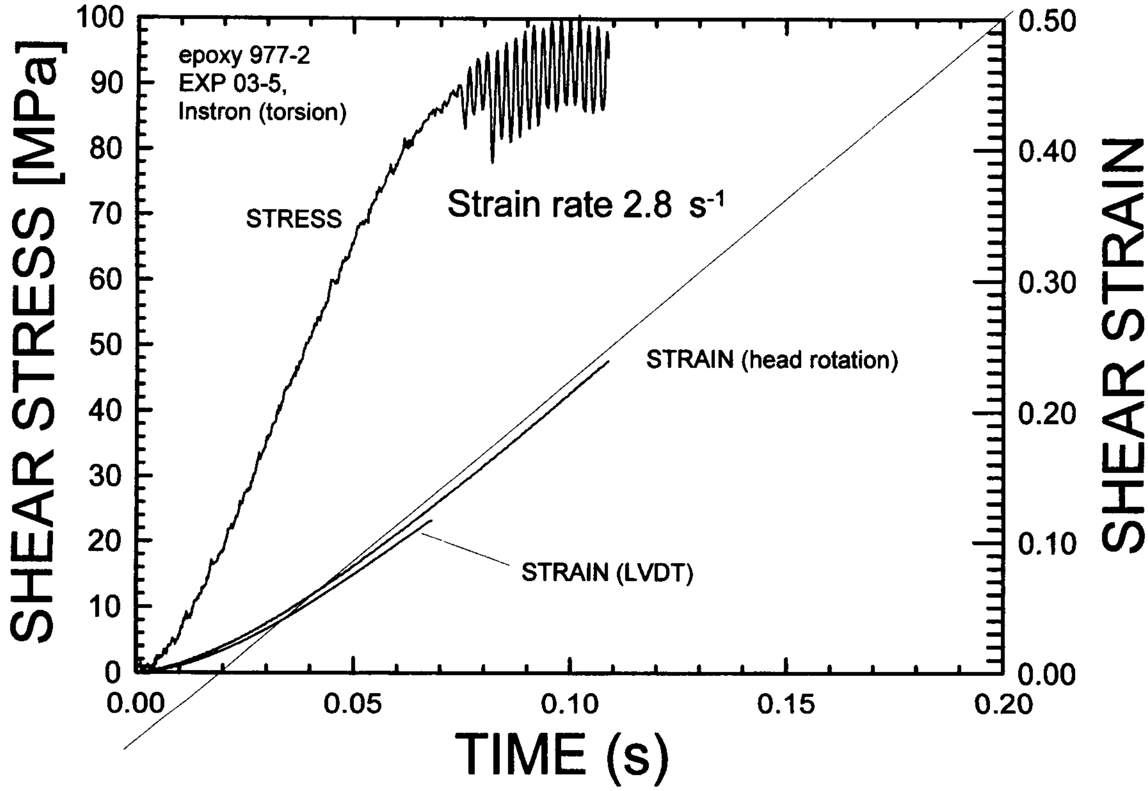

Epoxy Resin E-862
EXP03-2, SHB test
Strain Rate 510 s-1 (slope of strain-time curve)
NORMAL STRESS [MPa]
NORMAL STRAIN

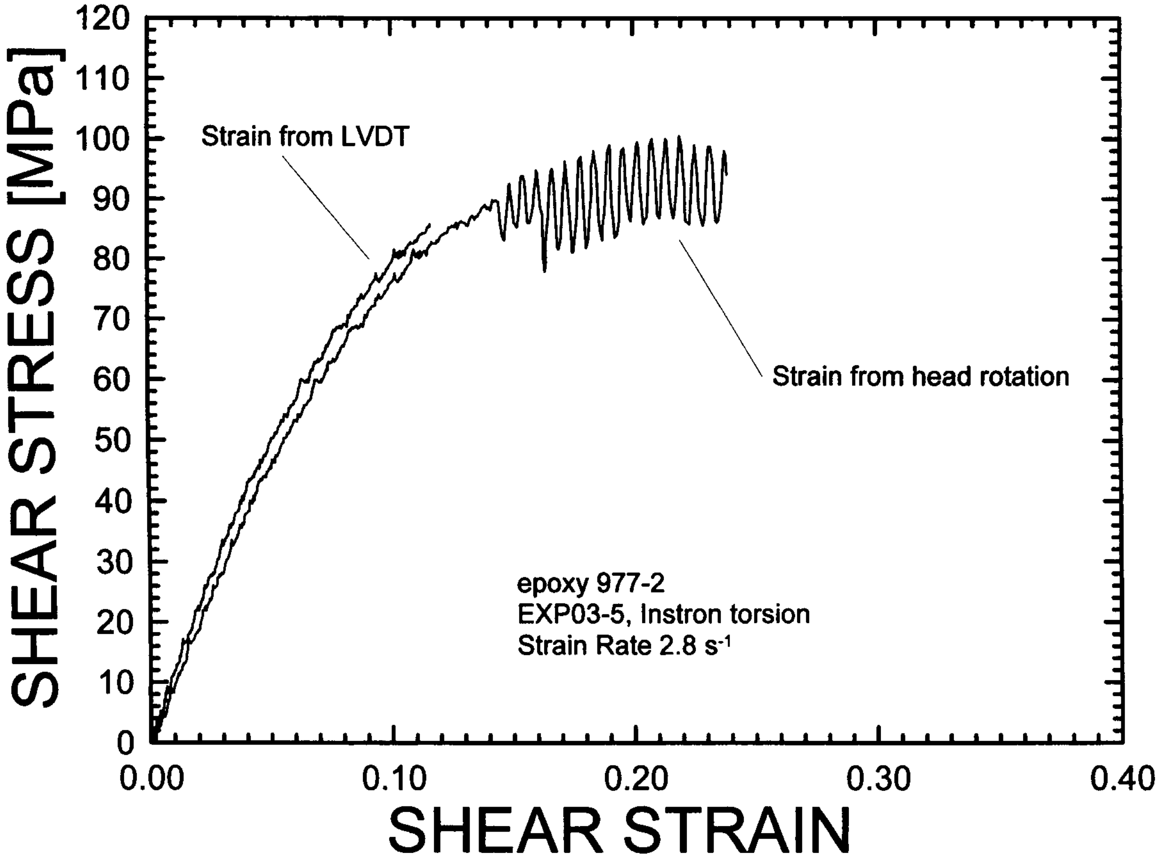

NORMAL STRESS [MPa]
Resin E-862
EXP 03-3
Tensile split Hopkinson bar
STRAIN RATE 500 s-1
(SLOPE OF STRAIN-TIME CURVE)
STRESS
STRAIN RATE
(SHB EQS)
STRAIN SHB
EQUATIONS
NORMAL STRAIN
STRAIN RATE [1/s]
TIME (μs)

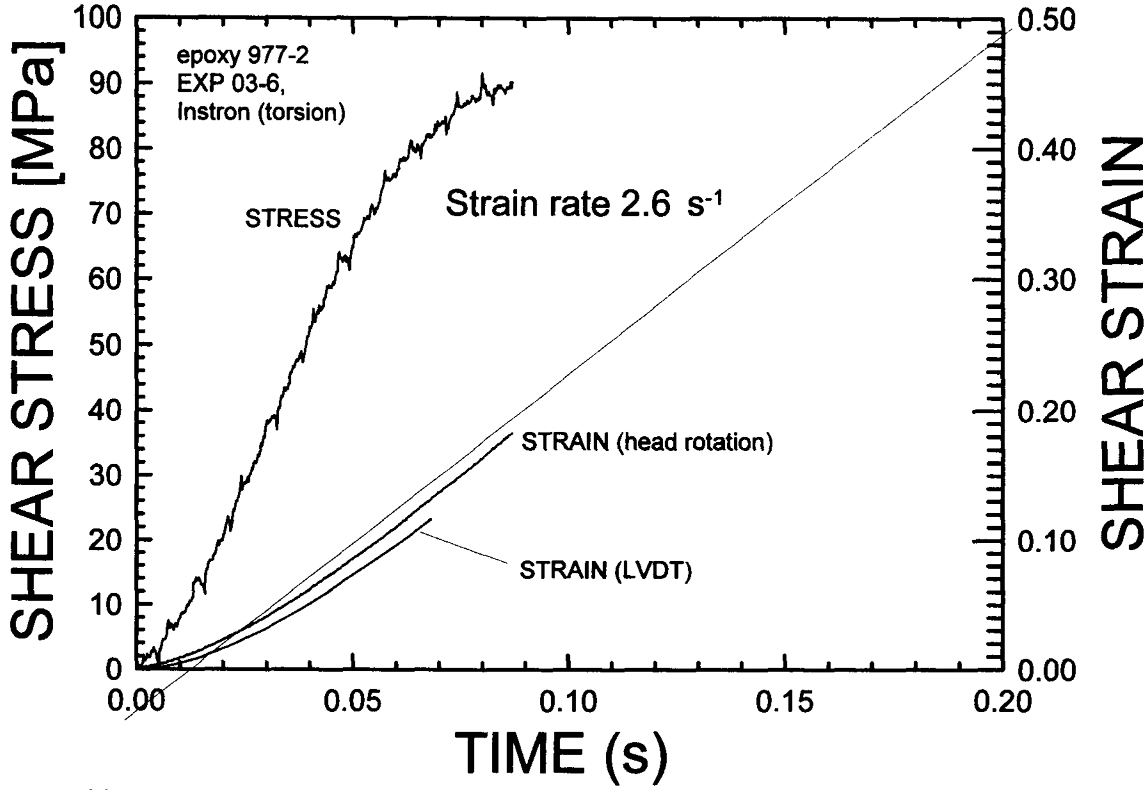

NORMAL STRESS [MPa]
Epoxy Resin E-862
EXP03-3, SHB test
Strain Rate 500 s-1 (slope of strain-time curve)
NORMAL STRAIN


Epoxy 977-2
EXP 03-4,
Instron (torsion)
Strain rate 1.3x10^{-4} s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)
0
10
20
30
40
50
60
70
80
0
500
1000
1500
2000
2500
3000
0.00
0.10
0.20
0.30
0.40
0.50

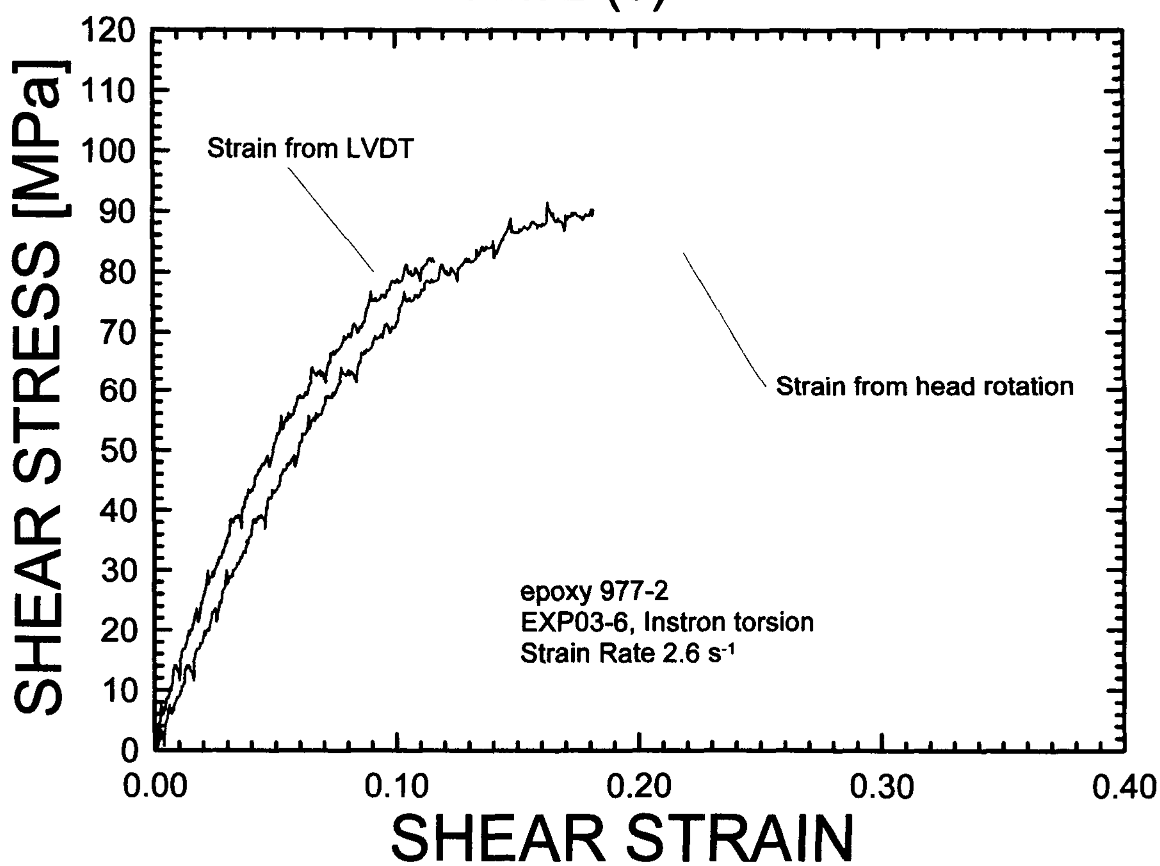

Epoxy 977-2
EXP03-4, Instron torsion
Strain Rate 1.3x10^{-4} s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40


epoxy 977-2
EXP 03-5,
Instron (torsion)
STRESS
Strain rate 2.8 s-1
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)

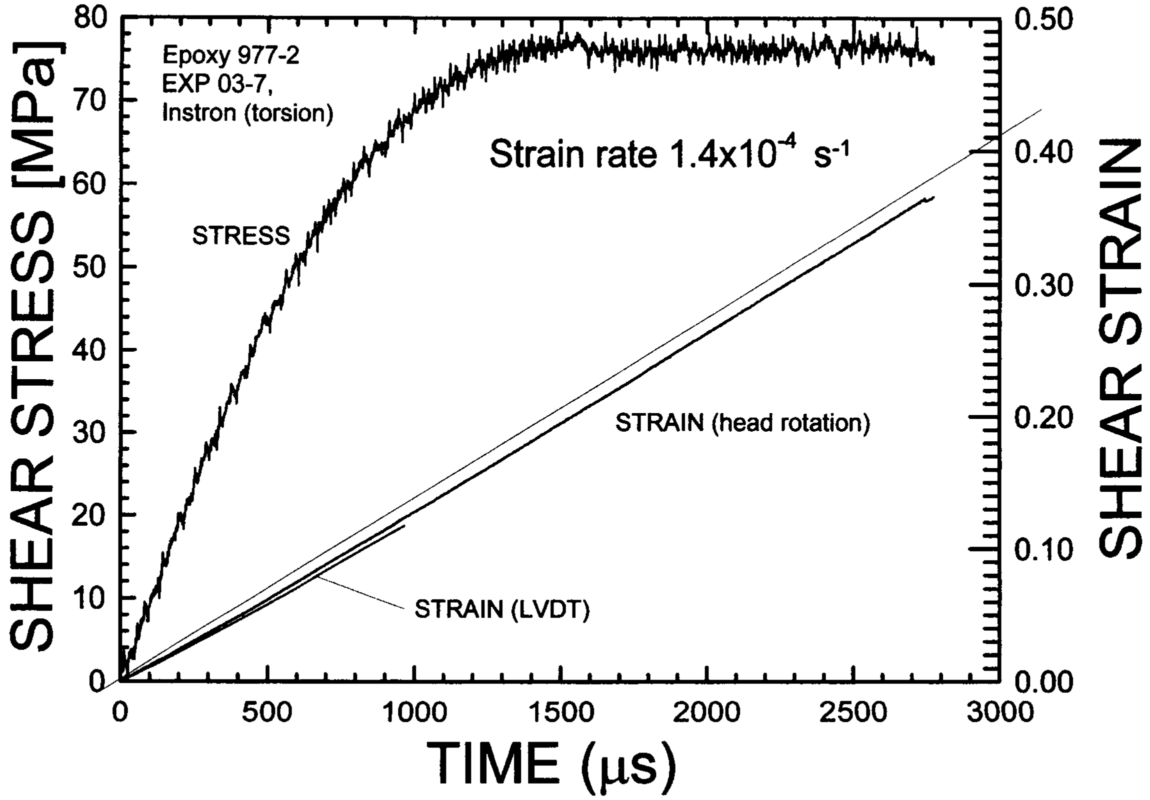

Strain from LVDT
Strain from head rotation
epoxy 977-2
EXP03-5, Instron torsion
Strain Rate 2.8 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN

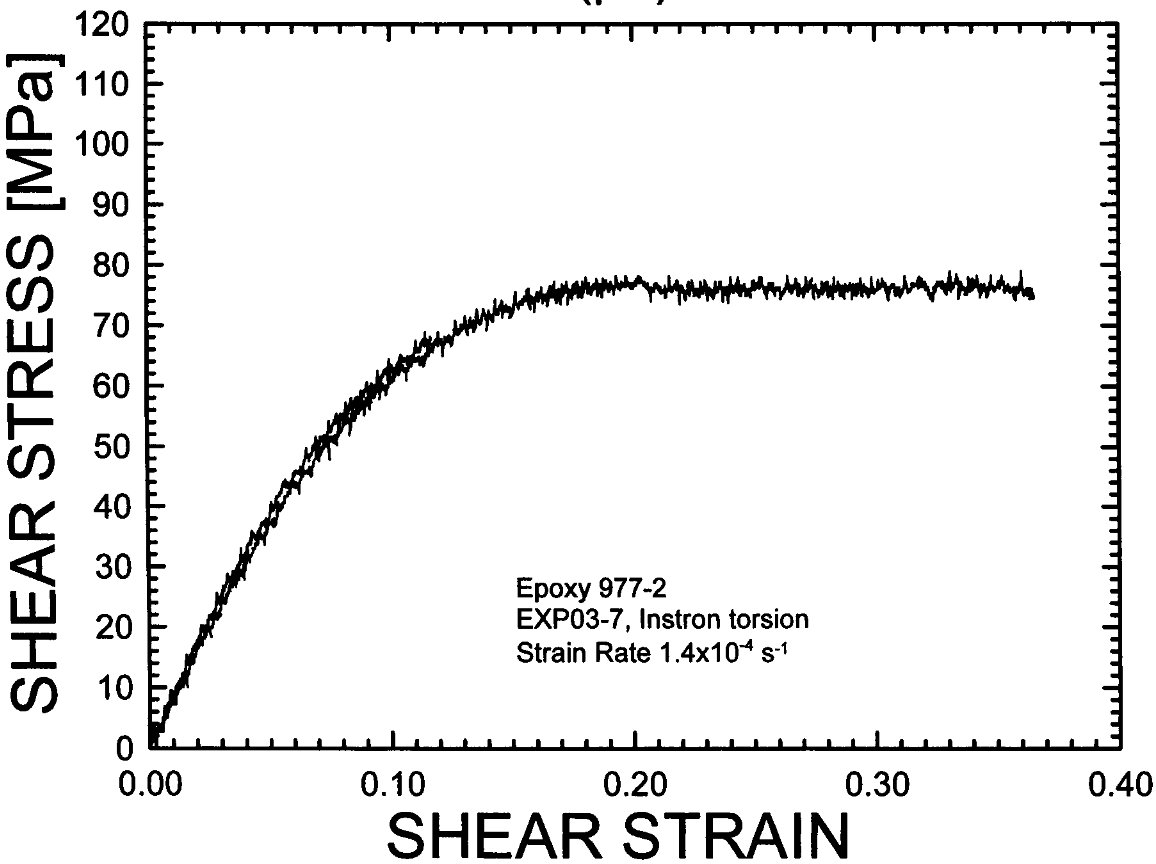


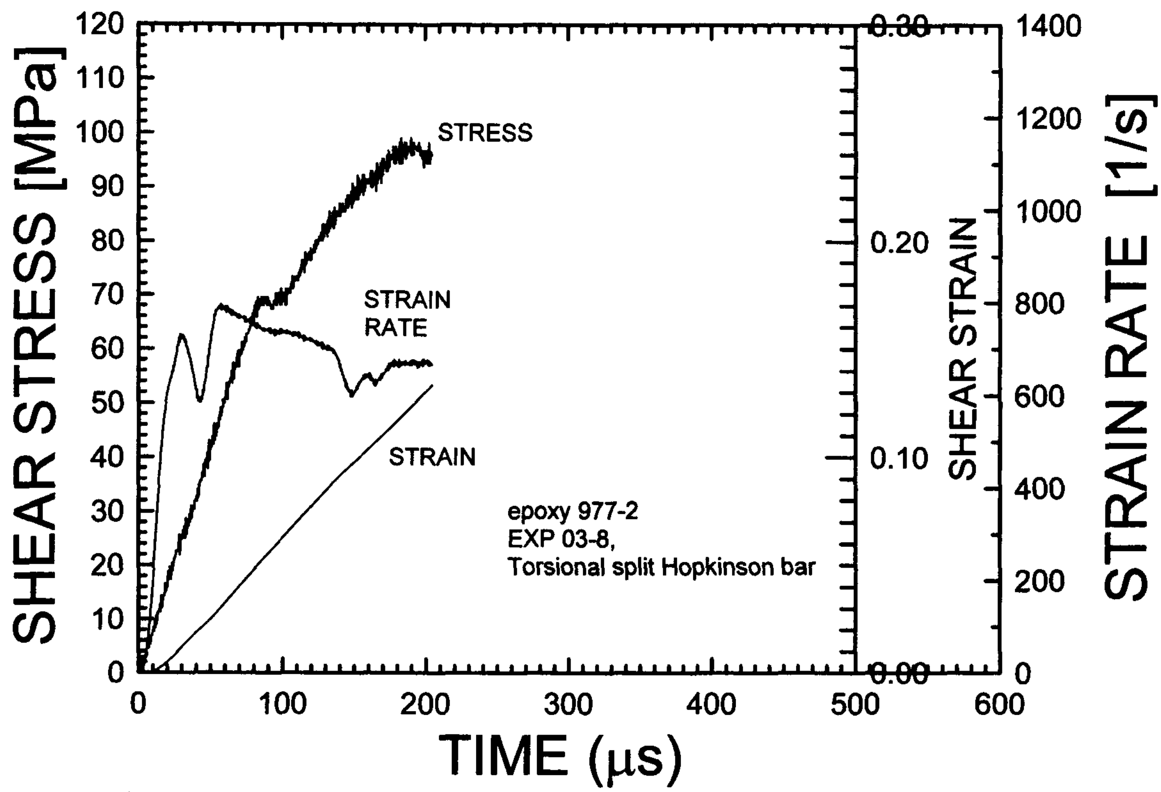
epoxy 977-2
EXP 03-6,
Instron (torsion)
STRESS
Strain rate 2.6 s-1
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)
0.00
0.05
0.10
0.15
0.20
0
10
20
30
40
50
60
70
80
90
100
0.00
0.10
0.20
0.30
0.40
0.50

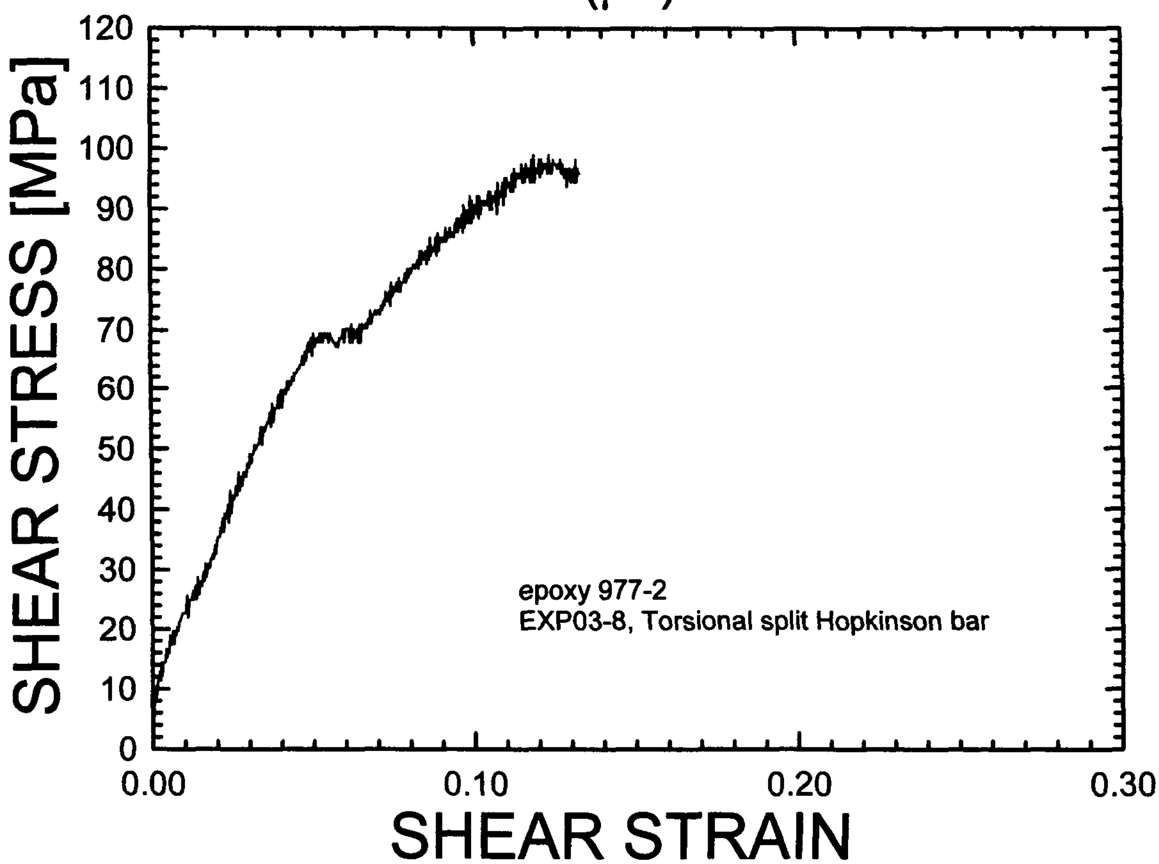


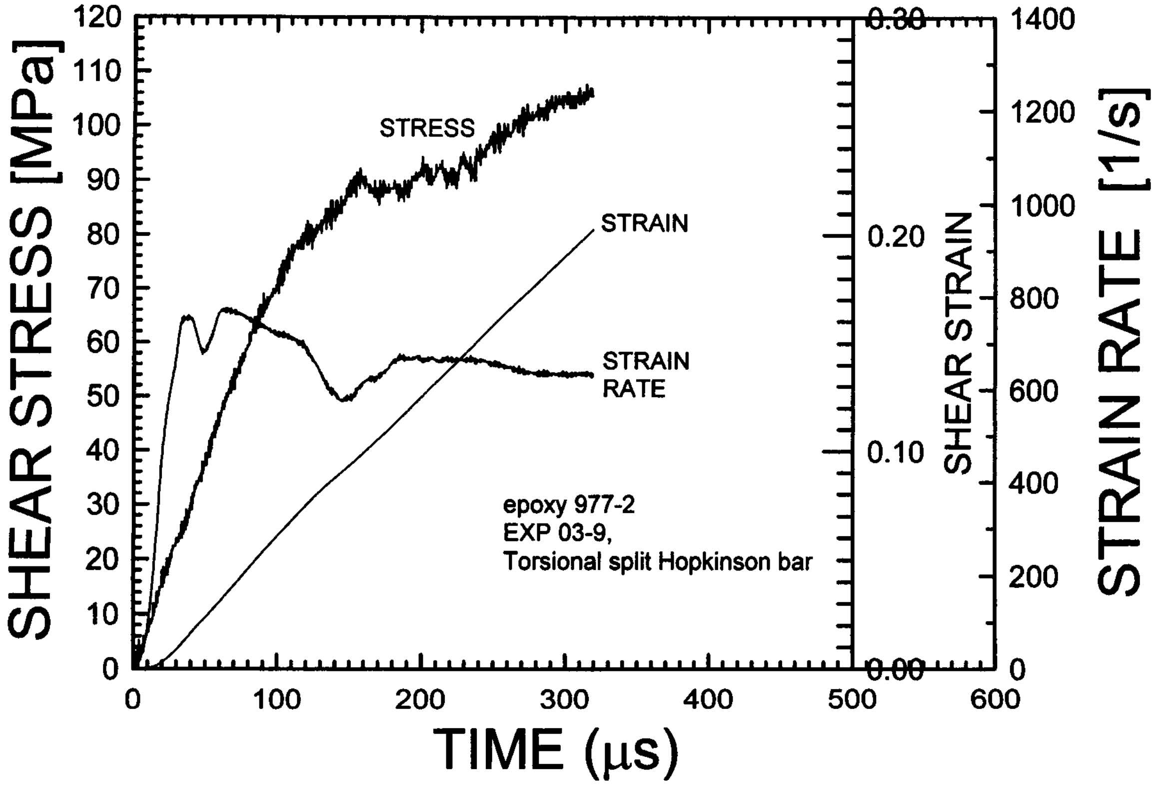
Strain from LVDT
Strain from head rotation
epoxy 977-2
EXP03-6, Instron torsion
Strain Rate 2.6 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN
0.00
0.10
0.20
0.30
0.40
0
10
20
30
40
50
60
70
80
90
100
110
120

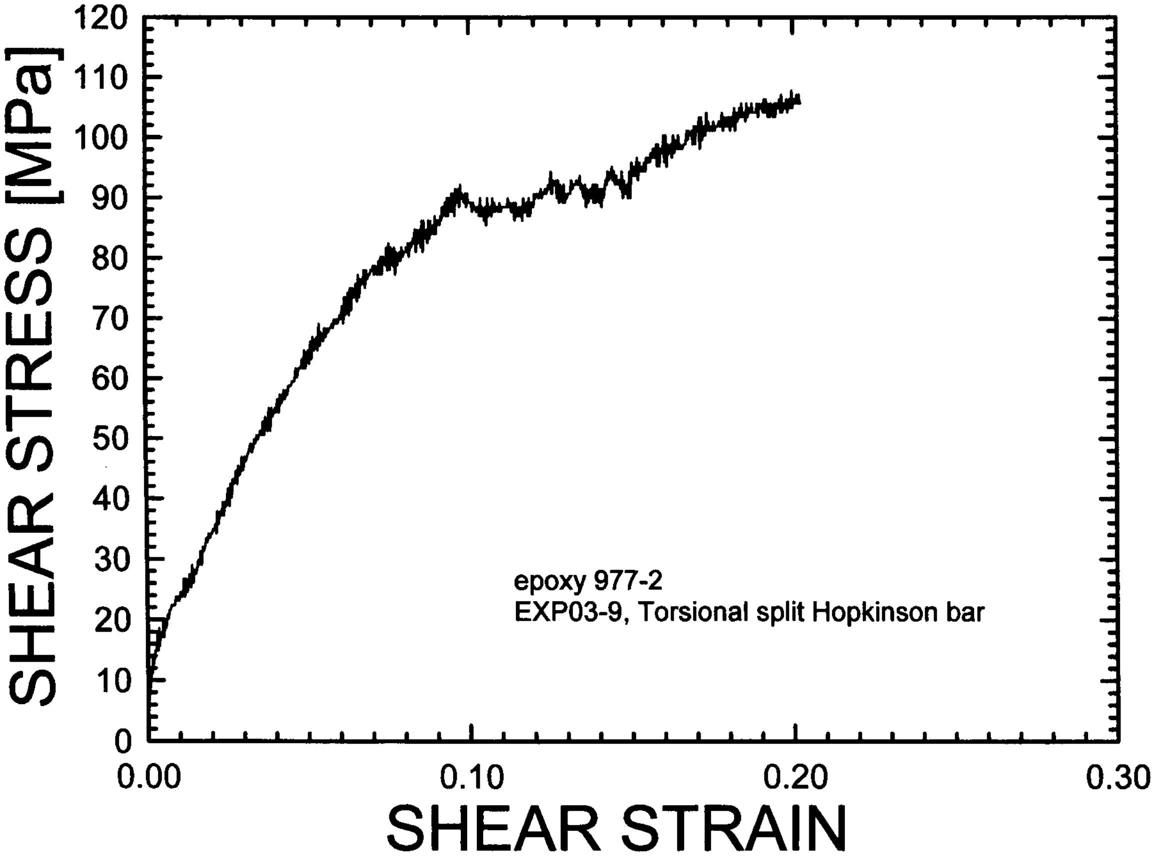

Epoxy 977-2
EXP 03-7,
Instron (torsion)
Strain rate 1.4x10⁻⁴ s⁻¹
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)

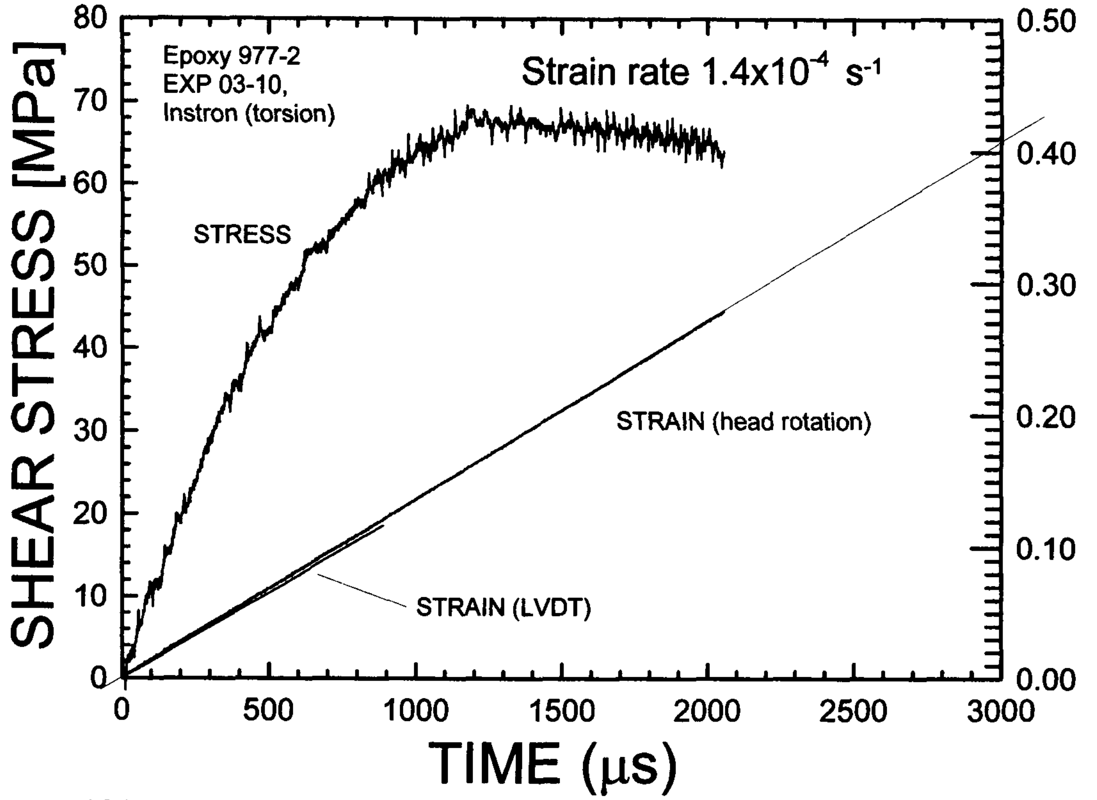

Epoxy 977-2
EXP03-7, Instron torsion
Strain Rate 1.4x10⁻⁴ s⁻¹
SHEAR STRESS [MPa]
SHEAR STRAIN


SHEAR STRESS [MPa]
STRESS
STRAIN RATE
STRAIN
epoxy 977-2
EXP 03-8,
Torsional split Hopkinson bar
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

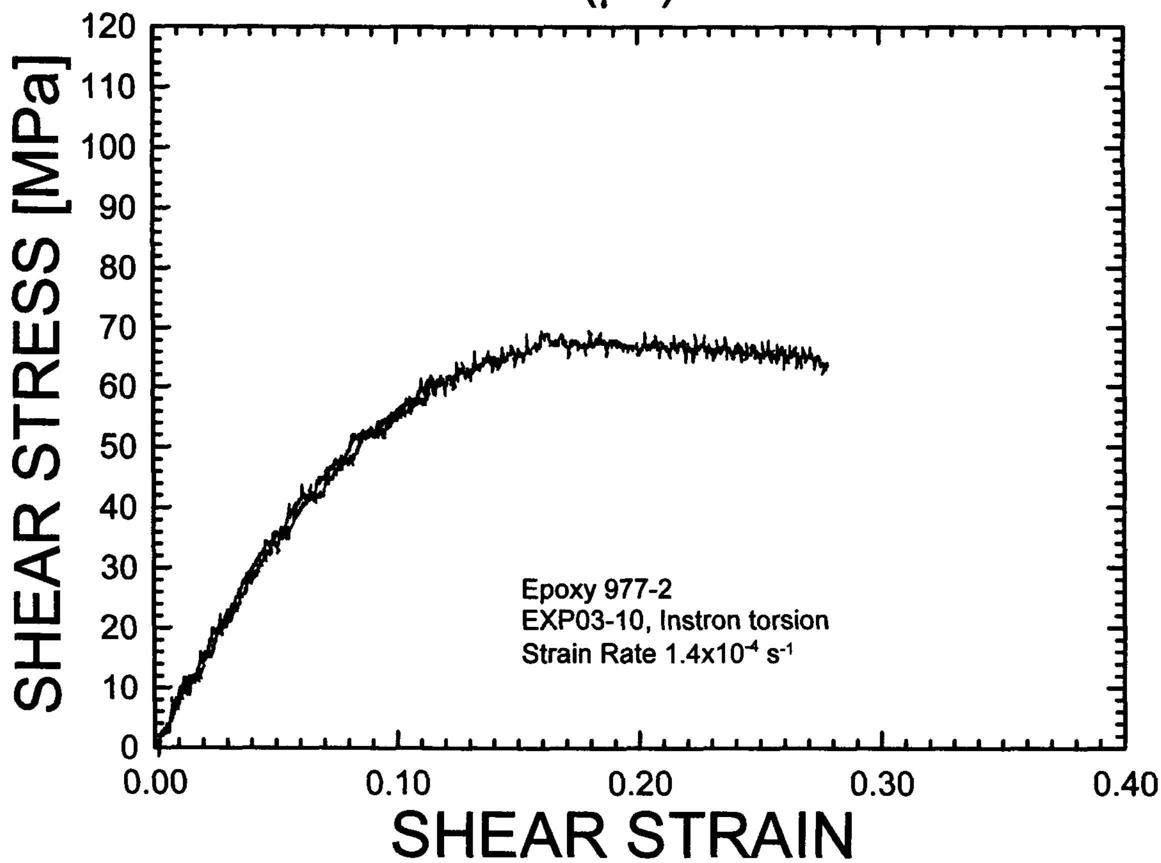

SHEAR STRESS [MPa]
epoxy 977-2
EXP03-8, Torsional split Hopkinson bar
SHEAR STRAIN


SHEAR STRESS [MPa]
STRESS
STRAIN
STRAIN
RATE
epoxy 977-2
EXP 03-9,
Torsional split Hopkinson bar
SHEAR STRAIN
STRAIN RATE [1/s]
TIME (μs)

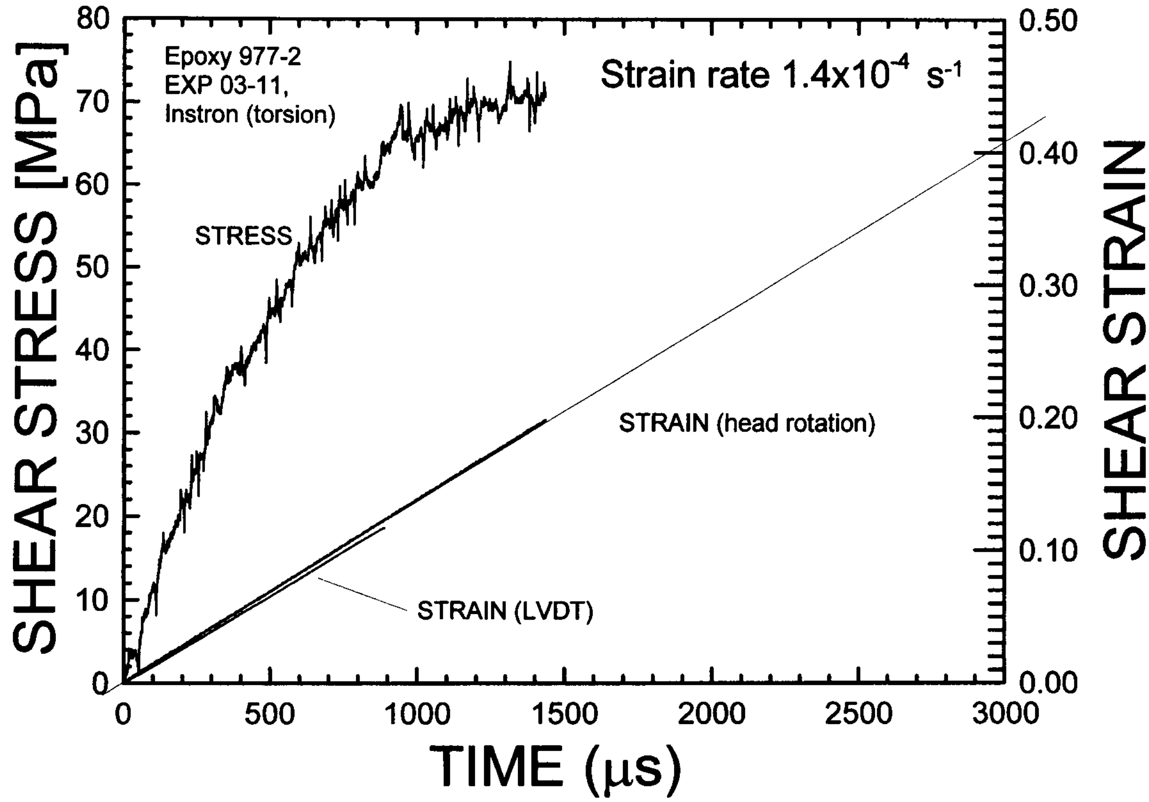

SHEAR STRESS [MPa]
epoxy 977-2
EXP03-9, Torsional split Hopkinson bar
SHEAR STRAIN

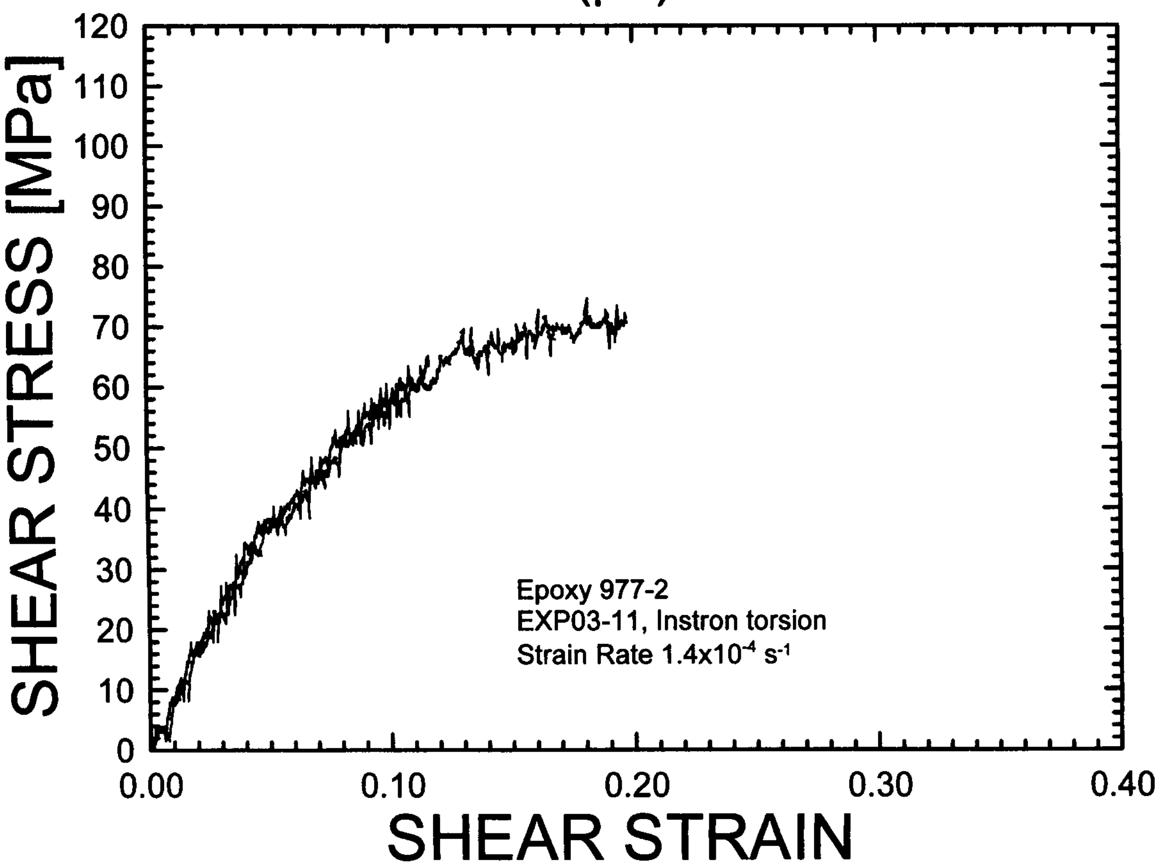


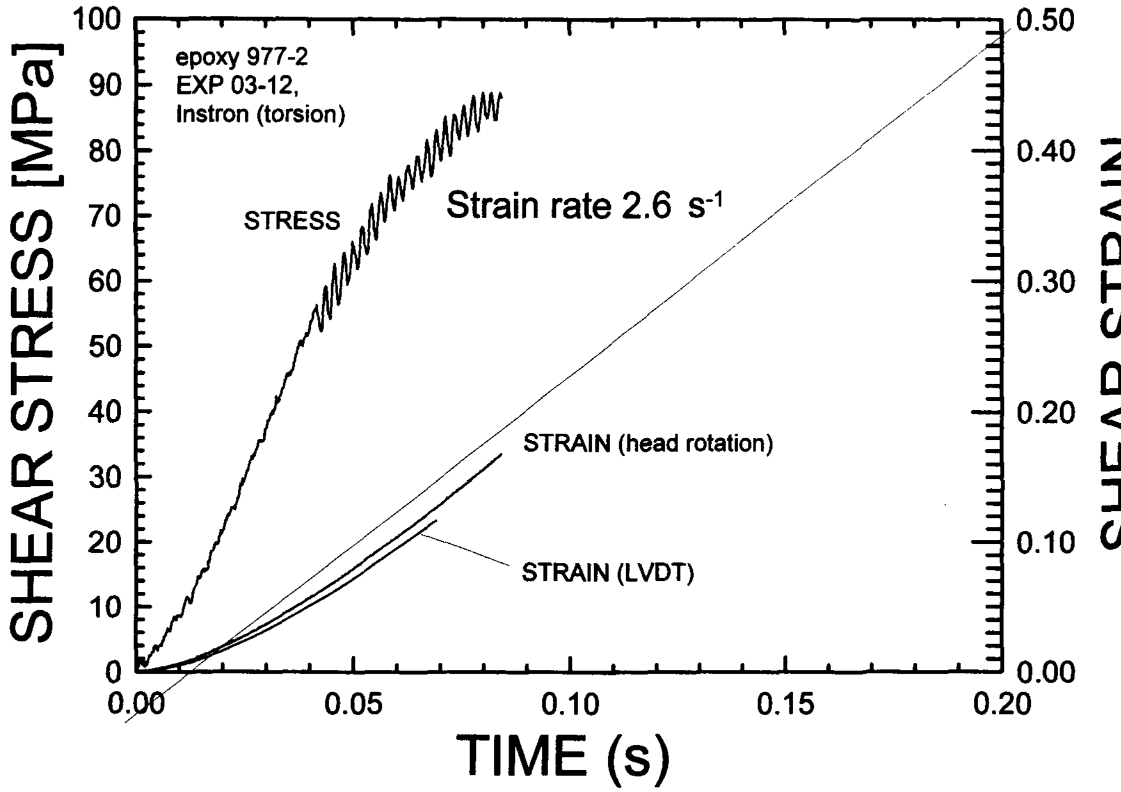
Epoxy 977-2
EXP 03-10,
Instron (torsion)
Strain rate 1.4x10^{-4} s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (μs)
0
500
1000
1500
2000
2500
3000
0
10
20
30
40
50
60
70
80
0.00
0.10
0.20
0.30
0.40
0.50

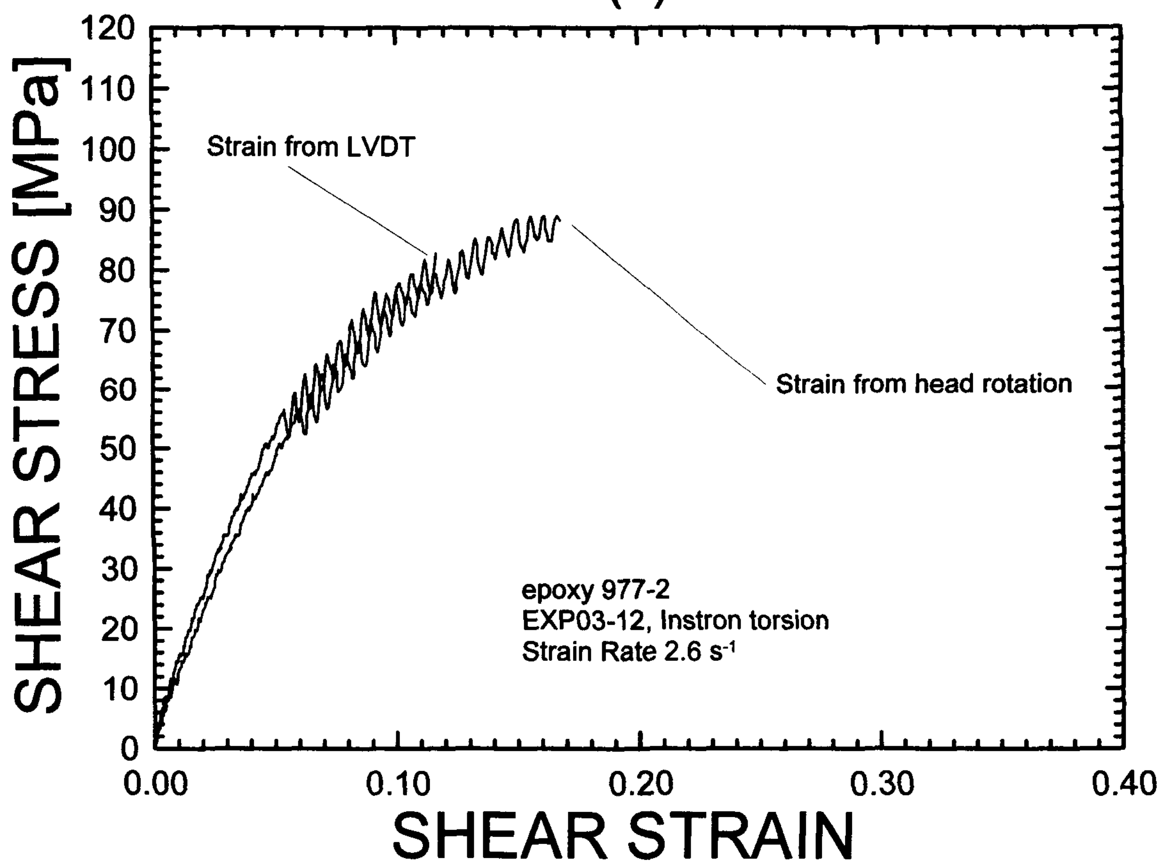


Epoxy 977-2
EXP03-10, Instron torsion
Strain Rate 1.4x10^{-4} s^{-1}
SHEAR STRESS [MPa]
SHEAR STRAIN
0
10
20
30
40
50
60
70
80
90
100
110
120
0.00
0.10
0.20
0.30
0.40


SHEAR STRESS [MPa]
80
70
60
50
40
30
20
10
0
Epoxy 977-2
EXP 03-11,
Instron (torsion)
Strain rate 1.4x10^{-4} s^{-1}
STRESS
STRAIN (head rotation)
STRAIN (LVDT)
0.50
0.40
0.30
0.20
0.10
0.00
SHEAR STRAIN
0
500
1000
1500
2000
2500
3000
TIME (μs)


SHEAR STRESS [MPa]
120
110
100
90
80
70
60
50
40
30
20
10
0
Epoxy 977-2
EXP03-11, Instron torsion
Strain Rate 1.4x10^{-4} s^{-1}
0.00
0.10
0.20
0.30
0.40
SHEAR STRAIN


epoxy 977-2
EXP 03-12,
Instron (torsion)
STRESS
Strain rate 2.6 s-1
STRAIN (head rotation)
STRAIN (LVDT)
SHEAR STRESS [MPa]
SHEAR STRAIN
TIME (s)


Strain from LVDT
Strain from head rotation
epoxy 977-2
EXP03-12, Instron torsion
Strain Rate 2.6 s-1
SHEAR STRESS [MPa]
SHEAR STRAIN