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IISI-AutoCo Round-Robin Dynamic Tensile Testing Project

By

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1.0 Summary

A round robin study was performed to compare the results from the participating testing laboratories. High strain rate test results from different labs have been difficult to compare due to differences in testing systems, test specimen geometry and data processing methods. The purpose of this study is to examine the impact of the testing approaches used by participating labs on high strain rate results when common material is used.

The participants in this study were: Arcelor, Colorado School of Mines, JFE Steel, Kobe Steel, Nippon Steel Corporation, POSCO, Sumitomo Metals, Technical University of Aachen, Thyssen-Krupp-Stahl and University of Dayton Research Institute. The material for this study (mild steel and DP590) was provided by Nippon Steel Corporation. The high strain rate results from the participating laboratories were compared for data quality, agreement of data and influence of testing procedure.

The results showed reasonable agreement among the testing labs though there were some results that showed considerable variation. Differences in testing results were attributed to differences in high strain rate specimen geometry, testing procedures and raw data processing methods. The results showed that some labs were able to overcome the difficulties in providing quality high strain rate data through the use of good testing procedures and other practices. These practices should be identified and shared so that the quality of high strain rate data from all testing labs can be improved.

2.0 Procedure

Nippon Steel provided the labs with samples of mild steel and DP590 with a thickness of 1.4 mm. Each lab used their own high strain rate specimen geometry. The high strain rate specimen geometries that were used by each lab are presented in Appendix A. The labs were requested to perform the following tests:

Quasi-static tests:
- conventional tests with three specimen orientations (L, T, 45^{0}D)
- quasi-static test with the high strain rate specimen for three specimen orientations (L, T, 45^{0}D)

High strain rate tests:
- Each lab run three duplicate tests for each steel grade and each strain rate in the transverse direction (T)
- Recommended strain rate increments are 1, 10, 100, 250, 500 and 1000 s^{-1}

Testing labs were also asked to provide unsmoothed engineering stress-strain data, strain rate for each high strain rate test, a description of the procedure to calculate the strain rate, a description of the testing system used and the fracture elongation measured from the sample. Table 1 summarizes the testing system and high strain rate specimen geometries that the labs used.

Lab	Testing system	Strain measurement device	Stress measurement device	System Resonant Freq. (kHz)	Max. Speed (m/s)	Gage width (mm)	Gage length (mm)	Strain Rate (s^{-1})
A	Servo-hydraulic	Opto-electronic extensometer	Piezoelectric load cell	7.8	12	6	20	< 100
			Strain gage	15-20				> 100
B	Servo-hydraulic	LVDT	Piezo		20	4	10	< 100
	SHB	Strain gage	Strain gage		10	4	10	> 100
C	Servo-hydraulic	Strain gage	Strain gage/ Piezoelectric Load Washer		13.5	6.4	25.4	
D	Servo-hydraulic	Strain gage	Load cell		1	5	10	< 100
	SHB	Strain gage	Elastic bar		14	5	10	> 100
E	Servo-hydraulic	High speed camera	Strain gage	not observed	12	4.3	12	
	SHB	Strain gage	Strain gage		12	3	10	
F	Servo-hydraulic	Optical extensometer	Strain gauge instrumented load cell	4.8	12	5	10	< 100
	Bar system (one bar method)	Electro-optical extensometer	Strain gauge attached to output bar		20	5	10	> 200
G	Servo-hydraulic	Cross head displacement	Strain gage		22	6	30	
H	Servo-hydraulic	Magnetic reluctance sensor	Sensing Block type load cell	46	5	2	6	
I	Servo-hydraulic	Laser-Doppler Extensometer	Piezoelectric Load Cell		20	12	20	< 100
			Strain gage		20	12	20	> 100
J	Servo-hyrdraulic	Electo-optical extensometer Strain Gage	Piezo Electric Load Washer	7-9	22	3.175	9.5	< 650
	SHB	-	-		-	3.175	9.5	>700

Table 1: High Strain Rate Test Conditions for labs

3.0 Results

The results from the round robin testing are presented in the following five sections: 1) the comparison of the high strain rate specimen tested at a quasi-static strain rate with a conventional quasi-static test, 2) the total elongation measured from the sample at the end of the high strain rate test, 3) the high strain rate results by testing lab, 4) a comparison of high strain rate results from the testing labs by strain rate and 5) a comparison of the flow stress at 1%, 2%, 4%, 6% and 10% for the strain rates tested.

3.1 Comparison of Quasi-static Results for High Strain Rate Specimens

The following two tables show the average Yield Stress, Ultimate Tensile Stress, Uniform Elongation and Total Elongation for the three directions (L, T and 45) from the quasi-static tests from each testing lab. The averaged results for the labs that performed the quasi-static test with their high strain rate specimen are also shown. Many labs used a smaller gage length for their high strain rate specimen compared to the conventional quasi-static specimen. A consequence of the smaller gage length is that higher total elongations will be measured due to the change in measurement area.

Table 2 shows the results for mild steel. In general, the yield stress and ultimate tensile stress of the high strain rate specimen were very close to the values for the quasi-static specimen. The Lab E results show lower uniform and total elongations of about 5% strain than their quasi-static specimen. The Lab G results show a lower total elongation of about 5% strain lower than their quasi-static specimen. The Lab H results show a higher total elongation of about 13-15% strain higher than their quasi-static specimen. The Lab I results show a higher uniform elongation by about 3% strain and a higher total elongation by about 12% strain than their quasi-static specimen.

Table 3 shows the results for DP590. The Lab D results show a lower yield stress of about 70 MPa lower than their quasi-static sample. The results for Lab E show a lower yield stress by about 30 MPa than their quasi-static specimen. The Lab H results show a higher uniform elongation of about 3% strain and a higher total elongation of about 10% than their quasi-static specimen. The Lab I results show a higher total elongation by about 4 to 10% strain than their quasi-static specimen. In general, the other results showed acceptable agreement with the quasi-static specimen.

These results show the high strain rate specimen geometry for most labs is acceptable for direct comparison to quasi-static results. The differences in stress between the high strain rate samples and the quasi-static samples is greater in the yield stress than in the ultimate tensile stress. However, the combination of large gage length (24 mm) and large gage width (12 mm) of the Lab I sample produces total elongations that are higher than the conventional quasi-static test for both mild steel and DP590. The mild steel results from Lab A, who used a gage length of 20 mm did not show major differences in total elongation. The results from Lab H also show notable differences in total elongation when compared to a quasi-static test. This may be a consequence of their use of high strain rate specimens that have the smallest gage width (2 mm) and gage length (6 mm). The high elongation in the results from Lab J may also be caused by a small gage width (3.175 mm).

Lab	Direction	Quasi-Static Specimen				High Strain Rate Specimen			
		YS (MPa)	UTS (MPa)	UE (%)	TE (%)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)
A	T	147.15	285.81	26.15	47.76	155.13	288.40	25.29	49.30
	L	146.29	290.38	26.94	49.87	151.13	291.65	25.64	50.89
	45	153.93	301.00	25.29	44.50	157.23	300.82	24.39	48.57
B	T	155.33	292.33	23.23	43.43				
	L	145.67	293.33	24.07	44.53				
	45	160.33	304.00	22.17	41.17				
C	T	157.50	288.50	28.40	50.15	150.00	286.50	25.65	50.20
	L	152.50	291.50	28.35	50.55	147.00	293.00	26.70	50.45
	45	153.00	298.50	26.40	48.30	155.00	301.00	25.35	48.00
D	T	157.20	290.08	26.00		143.00	293.00	21.40	
	L	148.35	291.20	27.30					
	45	158.85	300.85	25.30					
E	T	149.80	287.40	27.27	49.00	154.90	288.97	22.27	45.50
	L	149.00	291.87	27.83	51.53	146.93	291.80	23.30	45.43
	45	159.00	301.13	26.17	52.53	159.30	300.83	22.73	44.83
F	T	158.45	287.07	26.09	53.13	166.50	281.00	20.90	49.35
	L	148.03	289.41	27.09	53.46				
	45	163.71	299.43	25.09	49.51				
G	T	151.99	287.45	24.52	50.75	159.76	290.65	24.92	44.09
	L	148.75	290.76	25.28	50.54	152.40	293.66	25.56	44.97
	45	157.39	299.61	23.50	47.34	164.95	304.64	23.83	42.32
H	T	155.50	291.00	27.50	52.60	163.00	299.50	27.00	65.90
	L	150.00	295.50	27.50	53.20	159.00	298.00	28.60	67.15
	45	160.50	304.00	25.60	49.20	168.00	308.50	28.10	66.85
I	T	155.00	293.50	23.80	47.00	154.00	294.50	26.95	59.15
	L	147.50	299.00	23.75	46.55	150.50	296.50	27.80	59.65
	45	160.00	305.50	22.70	43.95	163.50	308.00	25.70	55.65
J	T					166.00	291.00		70.08
	L					157.00	294.00		69.90
	45					164.00	303.00		69.40

Table 2: Quasi-Static properties for Mild Steel

3.2 Total Elongation of Specimen After High Strain Rate Testing

Table 4 shows the total elongation for mild steel and DP590 measured from the high strain rate specimens after each high strain rate test. Four testing labs provided this information. The results show variation between labs in total elongation reported due to differences in specimen geometry and test setup. The results for each lab are consistent as the strain rate increases.

Lab	Direction	Quasi-Static Specimen				High Strain Rate Specimen			
		YS (MPa)	UTS (MPa)	UE (%)	TE (%)	YS (MPa)	UTS (MPa)	UE (%)	TE (%)
A	T	402.60	635.26	16.46	23.97				
	L	379.43	621.35	17.28	26.16				
	45	395.94	627.09	17.35	26.98				
B	T	395.67	629.33	15.13	22.40				
	L	377.67	633.33	15.23	23.63				
	45	390.33	621.00	15.60	25.03				
C	T	376.50	641.50	19.10	30.10	373.50	630.50	17.05	31.10
	L	369.50	620.00	18.90	28.45	366.50	621.00	18.10	29.22
	45	401.50	646.00	16.95	27.75	388.50	626.50	17.30	28.55
D	T	400.80	622.20	16.40		336.00	635.40	16.60	
	L	383.10	616.70	17.00					
	45	399.00	618.10	17.40					
E	T	387.93	627.50	17.63	30.40	355.23	632.43	15.43	29.17
	L	369.77	617.97	18.20	30.00	346.67	619.60	16.57	28.90
	45	387.93	627.50	17.63	30.40	350.57	621.03	16.23	29.00
F	T	369.31	619.32	17.37	30.07	378.50	629.50	14.30	29.57
	L	394.19	641.99	16.75	29.04				
	45	396.09	627.88	16.60	28.09				
G	T	394.39	636.44	15.08	24.95	395.96	629.06	15.94	
	L	376.66	631.98	15.51	25.05	376.24	620.19	16.30	
	45	401.78	638.94	15.31	26.07	393.75	623.51	16.60	
H	T	396.00	650.00	15.70	29.00	366.00	643.00	18.35	41.40
	L	371.00	634.00	16.50	31.20	374.50	645.00	19.25	41.45
	45	394.50	648.00	16.55	28.10	372.50	642.50	18.30	41.80
I	T	399.50	632.00	13.90	21.50	396.50	645.00	16.90	30.85
	L	383.50	607.00	16.05	26.85	379.00	626.50	17.35	31.10
	45	394.50	629.00	15.45	24.05	390.00	625.50	17.15	30.75
J	T					402.00	644.00		38.90
	L					380.00	632.00		43.70
	45					404.00	634.00		41.20

Table 3: Quasi-static properties for DP590

Lab	Mild Steel – Strain Rates s^{-1} Total Elongation from Specimen						DP590 – Strain Rates s^{-1} Total Elongation from Specimen					
	1	10	100	250	500	1000	1	10	100	250	500	1000
E	47	48.9	49.3	46.9	48.8	47.4	29.2	30.5	30.7	32.7	34.7	34.3
G	53.3	57.4	54.8	53.8	49.1	-	31.6	32.6	34.3	35.8	36.7	-
H	69	65	60	60	56	56	40	38	40	44	44	44
I	61.3	63.2	61.5	61.5	61.3	-	33.5	34.8	38	38	38.3	-

Table 4: Total Elongation measured from specimen for mild steel and DP590

3.3 High Strain Rate Results by Testing Lab

The following is a qualitative discussion of the high strain rate data quality by lab. Tests performed using a Split Hopkinson Bar (SHB) system are labeled with SHB in the legend while tests performed with a Single Bar system are labeled SB. Note: all strain rate values are quoted directly from the testing lab reports.

Lab A

This lab provided three data sets per steel grade. A representative result was selected from the three data sets for data analysis. All tests were performed with a servo-hydraulic system. Tests performed with a strain rate below 100 s^{-1} used a piezo-electric load measurement system while tests with a strain rate 100 s^{-1} and above used a calibrated strain gage on the sample for load measurement. The bending oscillation frequency was 2-3 kHz. Figure 1 shows the results for mild steel and Figure 2 shows the results for DP590. Figure 3 shows the true stress-true plastic strain results for DP590. The mild steel samples were tested at strain rates of: 0.9829, 11.4989, 111.5632, 280.8127 and 543.2411 s^{-1}. The DP590 samples were tested at strain rates of: 0.9, 10.47, 89.2293, 248.881 and 531.1105 s^{-1}. The strain rate was calculated by averaging the strain rate from yield stress to ultimate tensile stress.

The results for mild steel showed oscillations were present for strain rates of 11.4989, 111.5632, 280.8127 and 543.2411 s^{-1}. The results for the tests performed at 111.5632, 280.8127 s^{-1} showed very similar flow stresses.

The results for DP590 showed minor oscillations were present for strain rates of 89.2293, 248.881 and 531.1105 s^{-1}. The results for the tests performed at 89.2293 and 248.881 s^{-1} showed very similar flow stresses.

Lab B

This lab provided one data set per steel grade. Tests with a strain rate below 100 s^{-1} were performed with a servo-hydraulic system while tests with a strain rate above 100 s^{-1} were performed with a Split-Hopkinson Bar (SHB) system. Figure 4 shows the results for mild steel and Figure 5 shows the results for DP590. Figure 6 shows the true stress-true plastic strain results for DP590. The mild steel samples were tested at strain rates of: 0.986, 8.249, 127.69, 253.9, 508.9 and 1060.1 s^{-1}. The DP590 samples were tested at strain rates of: 0.748, 6.24, 129.15, 250.3, 505.8 and 1031.6 s^{-1}. The strain rate appears to have been calculated by averaging the strain rate over the entire strain range. The test data provided included only the plastic response of the material.

The results for mild steel show that the tests performed with the servo-hydraulic system are smooth. The tests performed with the SHB system show indications of an initial stress peak at the start of the test. The SHB results showed no signs of oscillation.

The results for DP590 show that the tests performed with the servo-hydraulic and SHB systems are smooth. The SHB results showed no signs of oscillation or an initial stress peak.

Lab C

This lab provided one data set per steel grade. All tests were performed with a servo-hydraulic system. Figure 7 shows the results for mild steel and Figure 8 shows the results for DP590. Figure 9 shows the true stress-true plastic strain results for DP590. The mild steel samples were tested at strain rates of: 0.95, 7.71, 125, 384 and 509 s^{-1}. The DP590 samples were tested at strain rates of: 0.97, 9.4, 90, 311 and 417 s^{-1}. The strain rate was calculated by taking the slope of the plastic strain gage output versus time in the uniform deformation region.

The results for mild steel show that oscillations begin at a strain rate of 7.71 s^{-1}. The results for higher strain rates show oscillations that become larger and extend further in the strain range as the strain rate increases. The results for the tests performed at 384 and 509 s^{-1} showed overlapping flow stresses during much of the tests.

The results for DP590 show relatively small oscillations and very similar flow stresses at strain rates of 311 and 417 s^{-1}. The results for both mild steel and DP590 at the higher strain rates show a larger total elongation compared to results from lower strain rates.

Lab D

This lab provided one data set per steel grade. Tests with a strain rate below 100 s^{-1} were performed with a servo-hydraulic system while tests with a strain rate above 100 s^{-1} were performed with a Split-Hopkinson Bar (SHB) system. Figure 10 shows the results for mild steel and Figure 11 shows the results for DP590. Figure 12 shows the true stress-true plastic strain results for DP590. The mild steel samples were tested at strain rates of: 1.009, 7.2, 26.3, 214.5, 910.3 and 1226 s^{-1}. The DP590 samples were tested at strain rates of: 0.9165, 7.019, 112.4, 593 and 694.6 s^{-1}. The strain rate was calculated by averaging the strain rate from 1 to 10% strain.

The results for mild steel show that oscillation develops at the strain rate of 26.3 s^{-1}. Tests using the SHB system (strain rates 214.5, 910.3 and 1226 s^{-1}) show an initial stress peak and oscillation that increases as the strain rate increases. The results for strain rates of 910.3 and 1226 s^{-1} showed very similar flow stresses for the first half of the test.

The results for DP590 show that tests performed with the servo-hydraulic system show no signs of oscillation. The tests performed with the SHB system (strain rates 112.4, 593 and 694.6 s^{-1}) show an initial stress peak and oscillations that increase as the strain rate increases. These SHB tests also showed similar flow stresses for much of the test.

Lab E

This lab provided three data sets per steel grade. A representative result was selected from the three data sets for data analysis. Tests were performed with a servo-hydraulic system for the requested strain rates and one test was performed with a Split-Hopkinson Bar system for one strain rate. Figure 13 shows the results for mild steel and Figure 14 shows the results for DP590. Figure 15 shows the true stress-true plastic strain results for DP590. The mild steel samples were tested using the servo-hydraulic system at strain rates of: 0.77, 7.19, 58.8, 174, 350 and 626 s^{-1}. The DP590 samples were tested using the servo-hydraulic system at strain rates of: 0.7, 6.47, 57.1, 158, 335 and 481 s^{-1}. The SHB system was also used to test a mild steel sample at a strain rate of: 361 s^{-1} and a DP590 sample at a strain rate of 486 s^{-1}. The procedure for strain rate calculation was not provided.

The results for mild steel and DP590 show that the tests performed with the servo-hydraulic system showed no oscillations. The results for the two tests that used the SHB system did show an initial stress peak, but no oscillations. The SHB test for mild steel showed a higher flow stress compared to the rest of the servo-hydraulic results. The SHB test for DP590 showed a lower flow stress compared to the rest of the servo-hydraulic results.

Lab F

This lab provided one data set per steel grade. Tests with a strain rate below 100 s^{-1} were performed with a servo-hydraulic system while tests with a strain rate above 200 s^{-1} were performed with a Single Bar (SB) system. Figure 16 shows the results for mild steel and Figure 17 shows the results for DP590. Figure 18 shows the true stress-true plastic strain results for DP590. The mild steel samples were tested at strain rates of: 0.83, 10.8, 710 and 1077 s^{-1}. The DP590 samples were tested at strain rates of: 0.83, 10.1, 93.9, 551 and 1124 s^{-1}. The strain rate was calculated by averaging the measured strain rate from yield point to maximum engineering strain (necking) for the one bar method and the servo-hydraulic system. The test data provided included only the plastic response of the material.

The results for mild steel show that the tests performed with the servo-hydraulic system (strain rates 0.83 and 10.8 s^{-1}) showed no oscillations. The tests that used the SB system (strain rates 710 and 1077 s^{-1}) showed an initial stress peak, but showed no oscillations as the test progressed. The SB tests showed very little difference in flow stress.

The results for DP590 show that the tests performed with the servo-hydraulic system (strain rates 0.83, 10.1 and 93.9 s^{-1}) showed no oscillations. The tests that used the SB system (strain rates 551 and 1124 s^{-1}) showed no oscillations or an initial stress peak. The SB tests showed overlapping flow stress after 8% strain.

Lab G

This lab provided one data set per steel grade. All tests were performed with a servo-hydraulic system. Figure 19 shows the results for mild steel and Figure 20 shows the results for DP590. Figure 21 shows the true stress-true plastic strain results for DP590. The mild steel samples were tested at strain rates of: 1, 10.3, 99.3, 241.3 and 468.6 s^{-1}. The DP590 samples were tested at strain rates of: 1, 10.4, 94.6, 239.5 and 459.7 s^{-1}. The strain rate appears to have been calculated by averaging the strain rate over the entire strain range.

The results for mild steel show that oscillations are present at strain rates of 241.3 and 468.6 s^{-1} with the magnitude of the oscillations increasing at the higher strain rate.

The results for DP590 show that oscillations are present at strain rates of 239.5 and 459.7 s^{-1} with the magnitude of the oscillations increasing at the higher strain rate. The results of tests performed at strain rates of 239.5 and 459.7 s^{-1} show overlapping flow stresses.

Lab H

This lab provided one data set per steel grade. All tests were performed with a servo-hydraulic system using a sensing block measurement system. Figure 22 shows the results for mild steel and Figure 23 shows the results for DP590. Figure 24 shows the true stress-true plastic strain results for DP590. The mild steel samples were tested at strain rates of: 0.93, 8.2, 86, 246, 465 and 1008 s^{-1}. The DP590 samples were tested at strain rates of: 0.84, 7.9, 75, 233, 491 and 1040 s^{-1}. The strain rate was calculated by averaging the strain rate from the yield point to 15% strain.

The results for mild steel show that all of the tests indicated an elastic modulus less than expected. An initial stress peak was present for strain rates 86, 246, 465 and 1008 s^{-1}. Oscillations were present at strain rates of 465 and 1008 s^{-1}.

The results for DP590 show that all of the tests indicated an elastic modulus less than expected. Oscillations were present at strain rates of 491 and 1040 s^{-1}.

Lab I

This lab provided three data sets per steel grade. A representative result was selected from the three data sets for data analysis. All tests were performed with a servo-hydraulic system. Figure 25 shows the results for mild steel and Figure 26 shows the results for DP590. Figure 27 shows the true stress-true plastic strain results for DP590. The mild steel samples were tested at strain rates of: 1, 9.1, 131.4, 240 and 509.4 s^{-1}. The DP590 samples were tested at strain rates of: 0.9, 9.2, 90.8, 218.5 and 478.5 s^{-1}. The strain rate was calculated from the beginning of plastic deformation to uniform elongation.

The results for mild steel show oscillations develop at a strain rate of 9.1 s^{-1}. Oscillations in stress response become more severe in magnitude as well as further in the strain range over which they appear as the strain rate increases. The mild steel results show higher total elongation compared to the results from other testing labs.

The results for DP590 show oscillations develop at strain rates of 218.5 and 478.5 s^{-1}. The results of tests performed at strain rates of 9.2, 90.8, 218.5 and 478.5 s^{-1} show overlapping flow stresses.

Lab J

This lab provided three data sets per steel grade. A representative result was selected from the three data sets for data analysis. Tests were performed with a servo-hydraulic system and a Split Hopkinson Bar system was used for strain rates higher than 650 s^{-1}. Figure 28 shows the results for mild steel and Figure 29 shows the results for DP590. Figure 30 shows the true stress-true plastic strain results for DP590. The mild steel samples were tested at strain rates of: 0.8685, 8.8, 100.93, 187.5, 450.8 and 800 s^{-1}. The DP590 samples were tested at strain rates of: 1.024, 9.246, 90.8, 196, 441 and 700 s^{-1}. The strain rate was measured over a region before ultimate and up until the start of necking. An average strain rate was calculated from the region by taking the slope of the strain versus time curve. An electro-optical extensometer was used to capture strain for the servo-hydraulic system. The resolution was optimized to capture failure and so the data in the initial part of the stress-strain curves are estimates of the elastic response. The elastic response was measured with separate tests using strain gages.

The results for mild steel showed oscillations were present at a strain rate of 187.5 s^{-1}. The test that used the SHB system, 800 s^{-1}, also showed oscillations and a lower than expected flow stress compared to the results with lower strain rates.

The results for DP590 showed oscillations were present for the test that used the SHB system, 700 s^{-1}, and a lower flow stress compared to the results with lower strain rates. The results for tests performed with the servo-hydraulic system had some overlapping flow stresses at strains below 5%.

3.4 Comparison of High Strain Rate Results by Strain Rate

The following is a qualitative discussion of the high strain rate data quality by strain rate. Tests performed using a Split Hopkinson Bar (SHB) system are labeled with SHB in the legend while tests performed with a Single Bar system are labeled SB.

Mild Steel

The results for the nominal strain rate of 1 s^{-1} are shown in Figure 31. The strain rates of the tests ranged from 0.77 to 1.009 s^{-1}. The engineering stress at 10% strain ranged from 292 to 319 MPa for a variation of approximately 27 MPa. The result for Lab E showed the lowest engineering stress and total elongation. The result from Lab I showed the highest total elongation.

The results for the nominal strain rate of 10 s^{-1} are shown in Figure 32. The strain rates of the tests ranged from 7.19 to 11.4989 s^{-1}. The engineering stress at 10% strain ranged from 327 to 357 MPa for a variation of approximately 30 MPa. The result for Lab D showed the lowest total elongation. The result from Lab J showed the highest total elongation.

The results for the nominal strain rate of 100 s^{-1} are shown in Figure 33. The strain rates of the tests ranged from 26.3 to 131.4 s^{-1}. The engineering stress at 10% strain ranged from 369 to 414 MPa for a variation of approximately 45 MPa. The results from Lab D and Lab E had the lowest engineering stress due to their tests being performed at the lowest strain rates 26.3 and 58.8 s^{-1}. The results from Lab C, Lab I and Lab J showed higher total elongations.

The results for the nominal strain rate of 250 s^{-1} are shown in Figure 34. The strain rates of the tests ranged from 174 to 384 s^{-1}. The engineering stress at 10% strain ranged from 397 to 441 MPa for a variation of approximately 44 MPa. The results for Lab E had the lowest engineering stress due to their test being performed at the lowest strain rate of 174 s^{-1}. The results from Lab C, Lab I and Lab J showed higher total elongations.

The results for the nominal strain rate of 500 s^{-1} are shown in Figure 35. The strain rates of the tests ranged from 350 to 910.3 s^{-1}. The engineering stress at 10% strain ranged from 422 to 463 MPa for a variation of approximately 41 MPa. The results from Lab F (using the Single Bar system) had one of the lower engineering stresses despite having one of the higher reported strain rates. The results from Lab C, Lab I and Lab J showed higher total elongations.

The results for the nominal strain rate of 1000 s^{-1} are shown in Figure 36. The strain rates of the tests ranged from 626 to 1226 s^{-1}. The engineering stress at 10% strain ranged from 424 to 476 MPa for a variation of approximately 52 MPa ignoring oscillations from the Lab J results. The results from Lab F (using the Single Bar system) had one of the lower engineering stresses despite having one of the higher reported strain rates.

DP590

The results for the nominal strain rate of 1 s^{-1} are shown in Figure 37. The strain rates of the tests ranged from 0.7 to 1.024 s^{-1}. The engineering stress at 10% strain ranged from 636 to 681 MPa for a variation of approximately 45 MPa. The results from Lab H and Lab J showed higher total elongations.

The results for the nominal strain rate of 10 s^{-1} are shown in Figure 38. The strain rates of the tests ranged from 6.24 to 10.47 s^{-1}. The engineering stress at 10% strain ranged from 671 to 702 MPa for a variation of approximately 31 MPa. The results from Lab H show a lower elastic response than expected. The results from Lab D show a lower total elongation compared to other testing labs. The results from Lab H and Lab J showed higher total elongations.

The results for the nominal strain rate of 100 s^{-1} are shown in Figure 39. The strain rates of the tests ranged from 57.1 to 129.15 s^{-1}. The engineering stress at 10% strain ranged from 666 to 725 MPa for a variation of approximately 59 MPa. The results from Lab H show a lower elastic modulus than expected. The results from Lab G, Lab H, Lab I and Lab J showed higher total elongations.

The results for the nominal strain rate of 250 s^{-1} are shown in Figure 40. The strain rates of the tests ranged from 158 to 311 s^{-1}. The engineering stress at 10% strain ranged from 700 to 744 MPa for a variation of approximately 44 MPa. The results from Lab H show a lower elastic modulus than expected. The results from Lab H, Lab I and Lab J showed higher total elongations.

The results for the nominal strain rate of 500 s^{-1} are shown in Figure 41. The strain rates of the tests ranged from 335 to 593 s^{-1}. The engineering stress at 10% strain ranged from 675 to 781 MPa for a variation of approximately 106 MPa. The results from Lab H show a lower elastic modulus than expected. The results from Lab G, Lab H, Lab I and Lab J showed higher total elongations.

The results for the nominal strain rate of 1000 s^{-1} are shown in Figure 42. The strain rates of the tests ranged from 481 to 1124 s^{-1}. The engineering stress at 10% strain ranged from 691 to 778 MPa for a variation of approximately 87 MPa. The results from Lab H showed higher total elongations.

The true stress-true plastic strain results for the nominal strain rate of 1 s^{-1} are shown in Figure 43. There is reasonable close agreement in true stress and tensile instability point between most of the labs. The true stress at 10 % plastic strain ranged from 707 to 777 MPa for a variation of approximately 70 MPa. The results from Labs F and H show relatively higher stresses. The results from Lab F show a lower tensile instability point compared to the other labs.

The true stress-true plastic strain results for the nominal strain rate of 10 s^{-1} are shown in Figure 44. There is reasonable close agreement in true stress and tensile instability point between most of the labs. The true stress at 10 % plastic strain ranged from 743 to 809 MPa for a variation of approximately 66 MPa. The results from Labs H and J show relatively higher stresses.

The true stress-true plastic strain results for the nominal strain rate of 100 s^{-1} are shown in Figure 45. There is reasonable close agreement in true stress between most of the labs. There is more scatter in the tensile instability point compared to lower strain rates. The true stress at 10 % plastic strain ranged from 745 to 858 MPa for a variation of approximately 113 MPa. The results from Lab H show relatively higher stresses.

The true stress-true plastic strain results for the nominal strain rate of 250 s^{-1} are shown in Figure 46. There is reasonable close agreement in true stress and tensile instability point between most of the labs. The true stress at 10 % plastic strain ranged from 801 to 874 MPa for a variation of approximately 73 MPa. The results for Lab H show relatively higher stresses. The results for Lab C show a relatively larger tensile instability point.

The true stress-true plastic strain results for the nominal strain rate of 500 s^{-1} are shown in Figure 47. There is reasonable close agreement in true stress between most of the labs. The true stress at 10 % plastic strain ranged from 775 to 872 MPa for a variation of approximately 97 MPa. The results from Labs B, C, G and I show a comparatively larger tensile instability point.

The true stress-true plastic strain results for the nominal strain rate of 1000 s^{-1} are shown in Figure 48. There is reasonable close agreement in true stress and tensile instability point between most of the labs. The true stress at 10 % plastic strain ranged from 833 to 882 MPa for a variation of approximately 49 MPa.

Figure 49 plots the tensile instability point (from the true stress-true plastic strain results) against the log of the strain rate for each lab. There is variation in the tensile instability point between labs, but the results for most labs are reasonably self-consistent. This suggests that the strain measurement systems for these labs are consistent in measuring the strain response across the range of strain rates tested.

3.5 Flow Stress Comparisons

The flow stress at 1, 2, 4, 6 and 10% engineering strain were plotted against the log of the strain rate and classified by the type of load measurement system. The classification of the load measurement systems consist of: servo-hydraulic system and conventional load cell, servo-hydraulic system and piezo-electric load cell, servo-hydraulic system and strain gage, servo-hydraulic system and sensing block and bar systems.

Mild Steel

The flow stress for mild steel at 1, 2, 4, 6 and 10% engineering strain plotted against the log of the strain rate are shown in Figures 50 to 54.

The flow stress at 1% strain for mild steel shows that the different load measurement systems are capable of providing consistent results although the results with the sensing block system appear to be lower than the other labs. The outlying flow stress values from labs using different measurement systems suggest that individual lab testing practices are the cause of the scatter as other labs using the same measurement systems are able to provide consistent results.

The flow stress at 2% strain for mild steel shows less scatter than for 1% strain though there is greater scatter towards the higher strain rate tests. The results using the sensing block measurement system are more consistent with the other measurement systems.

The flow stress at 4, 6 and 10% strain for mild steel show good agreement for all of the tests even at higher strain rates for all load measurement systems.

The slope of the regression lines for 1, 2, 4, 6 and 10% strain are: 75.5, 75.3, 60, 53.9 and 49.7. This is consistent with the observed behavior of mild steel showing less strain rate sensitivity as strain increases.

DP590

The flow stress for DP590 at 1, 2, 4, 6 and 10% engineering strain plotted against the log of the strain rate are shown in Figures 55 to 59.

The flow stress at 1% strain for DP590 shows that the different load measurement systems are capable of providing consistent results although the results with the sensing block system appear to be lower than the other labs. The outlying flow stress values from labs using different measurement systems suggest that individual lab testing practices are the cause of the scatter as other labs using the same measurement systems are able to provide consistent results.

The flow stress at 2% strain for DP590 shows less scatter than for 1% strain though there is greater scatter towards the higher strain rate tests. The results using the sensing block measurement system are more consistent with the other measurement systems.

The flow stress at 4, 6 and 10% strain for DP590 show good agreement for all of the tests even at higher strain rates.

The slope of the regression lines for 1, 2, 4, 6 and 10% strain are: 51.6, 46.2, 31.3, 30.6 and 30. This indicates higher strain rate sensitivity at strains below 2% that decreases and becomes constant as strain increases past 4%. The strain rate sensitivity beyond 4% strain is consistent with the observed behavior of DP590 showing constant strain rate sensitivity as strain increases.

4.0 Conclusions

The following conclusions were made based on the results of the round robin study:

1. Many of the labs have designed a high strain rate specimen that provides mechanical behavior results similar to standard quasi-static tests. Other labs have used a specimen that produces results that cannot be compared to conventional quasi-static results as easily.

2. The differences in the strain rate calculation used by the labs that provided their calculation method differ. Based on the plots of flow stress, it appears that the impact of the different calculations is minor, though a common method for calculating strain rate will make comparison of the results between different labs easier.

3. The results showed that some labs were able to overcome the difficulties in providing quality high strain rate data through the use of good testing procedures and other practices. These practices should be identified and shared so that the quality of high strain rate data from all testing labs can be improved.

Figures

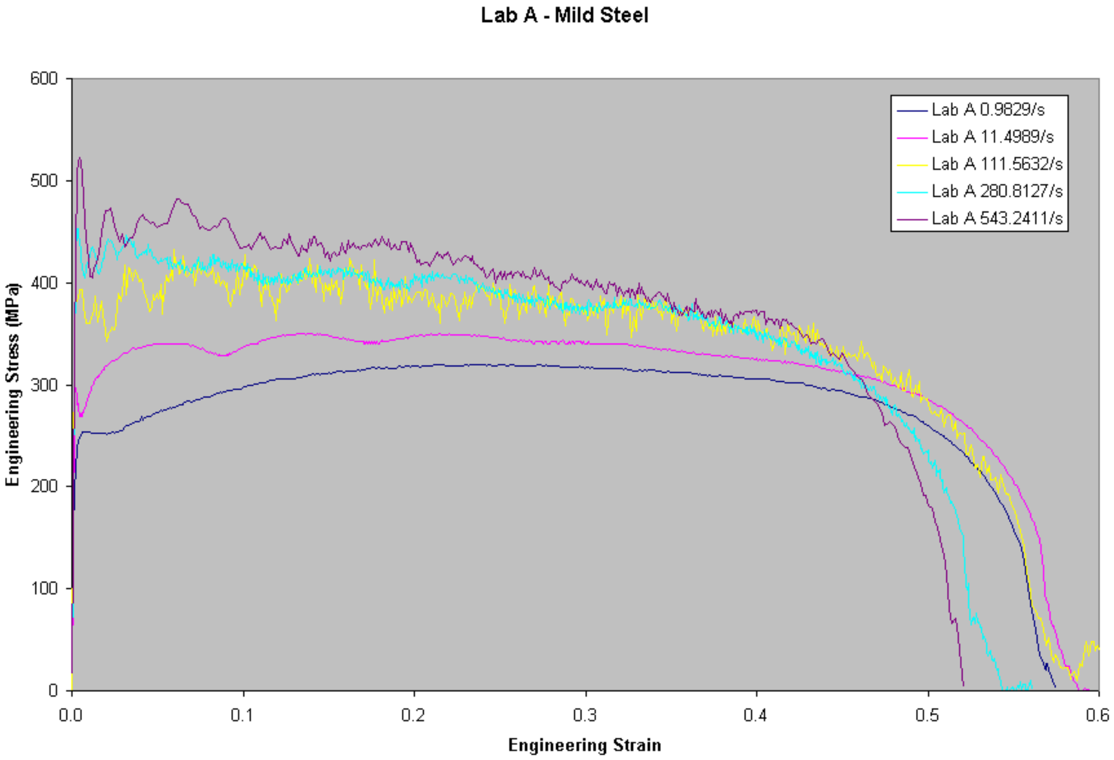


Figure 1: Mild steel high strain rate results for Lab A

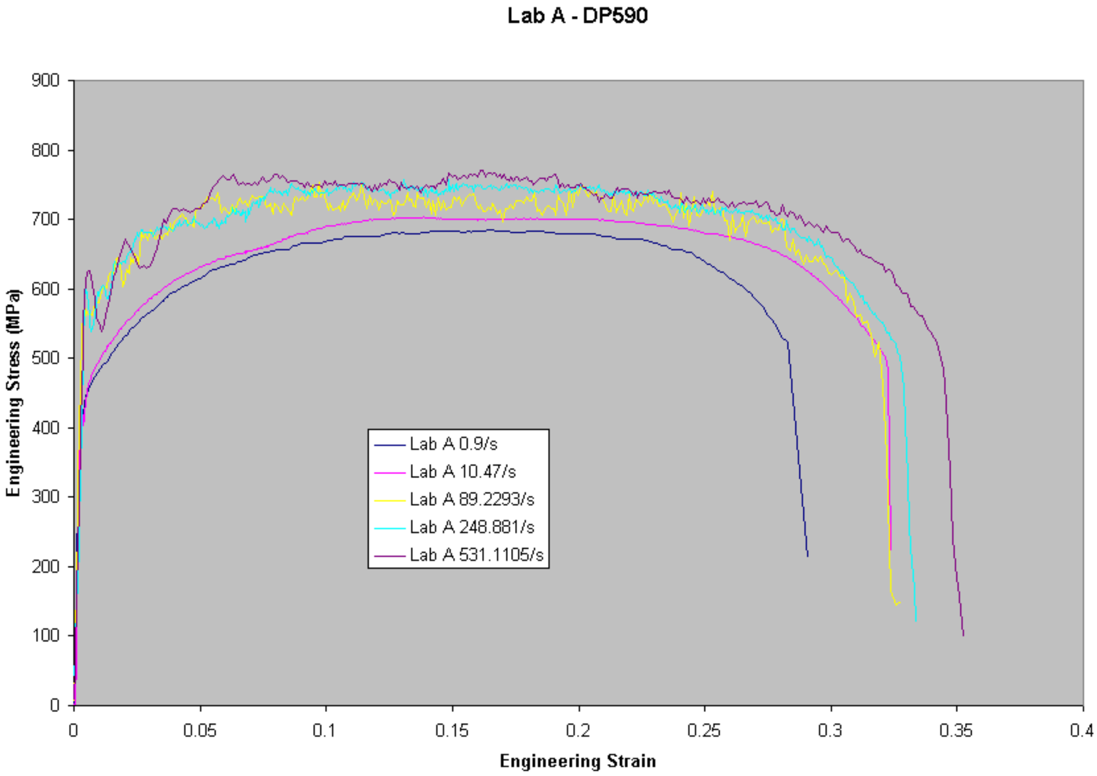


Figure 2: DP590 high strain rate results for Lab A

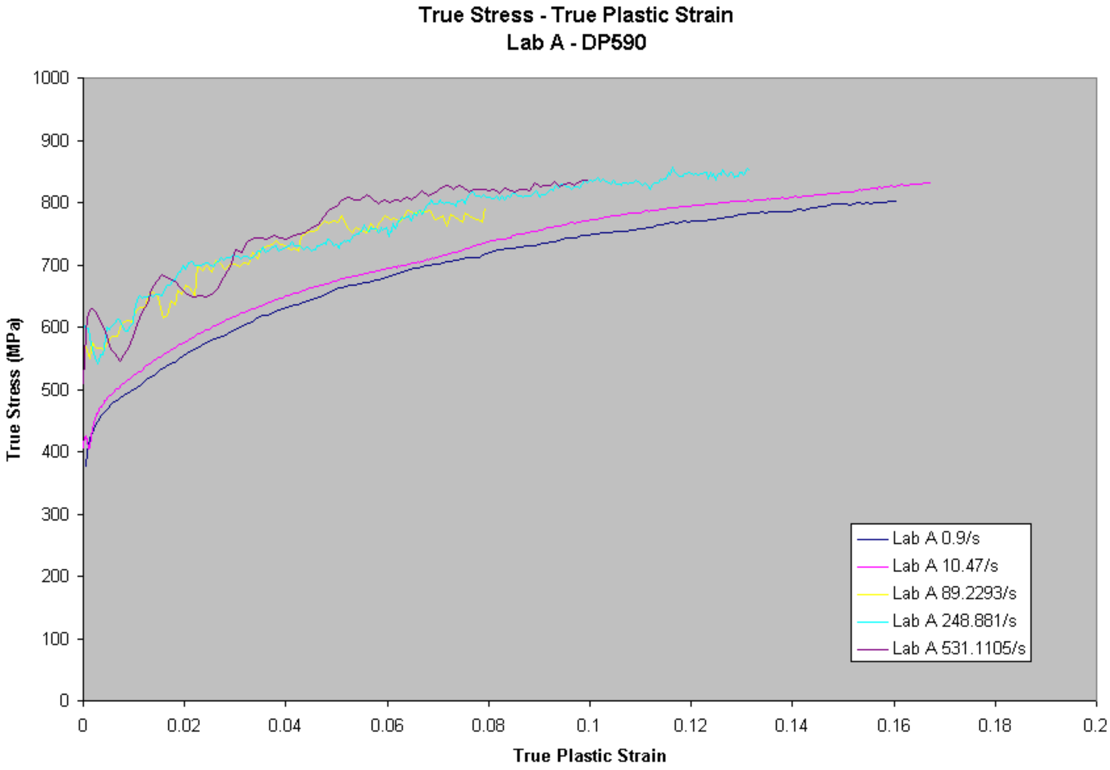


Figure 3: DP590 true stress-true plastic strain results for Lab A

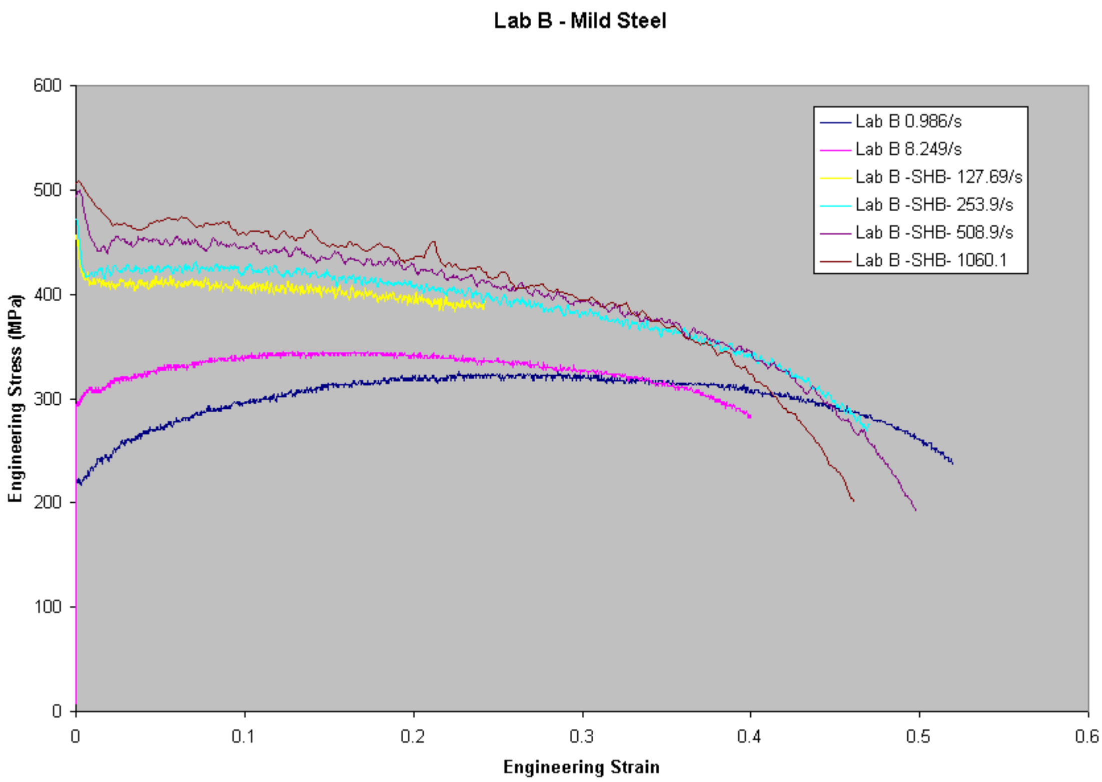


Figure 4: Mild steel high strain rate results for Lab B

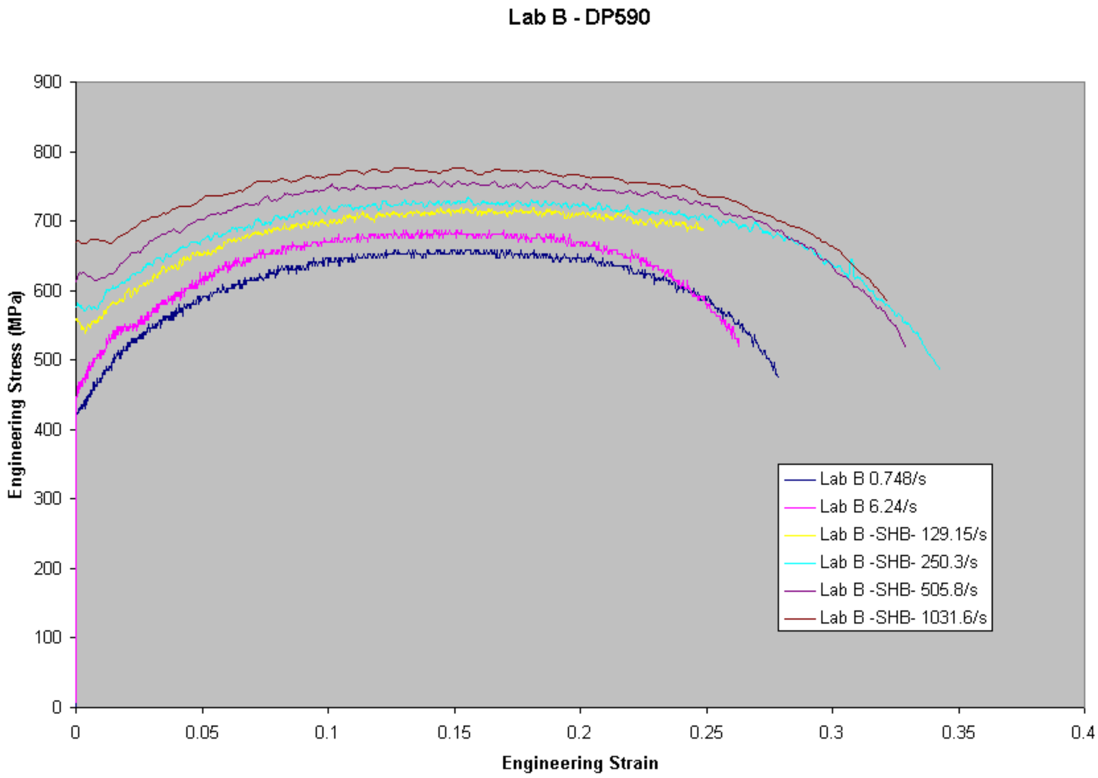


Figure 5: DP590 high strain rate results for Lab B

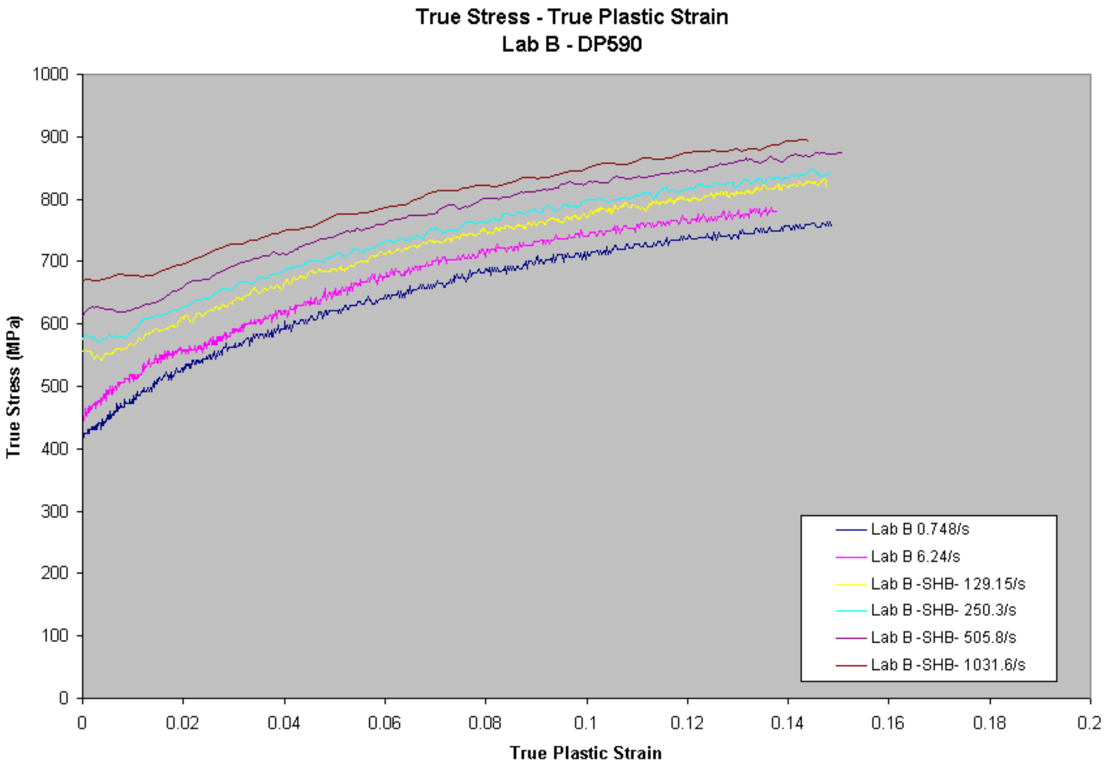


Figure 6: DP590 true stress-true plastic strain results for Lab B

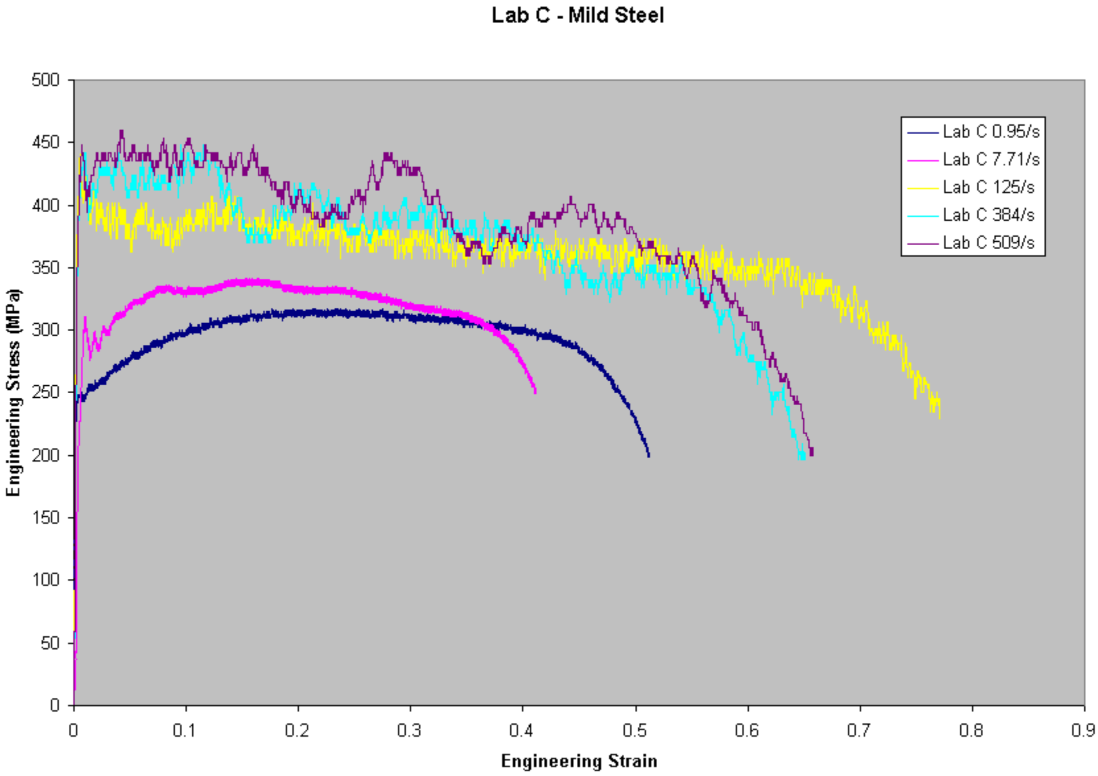


Figure 7: Mild steel high strain rate results for Lab C

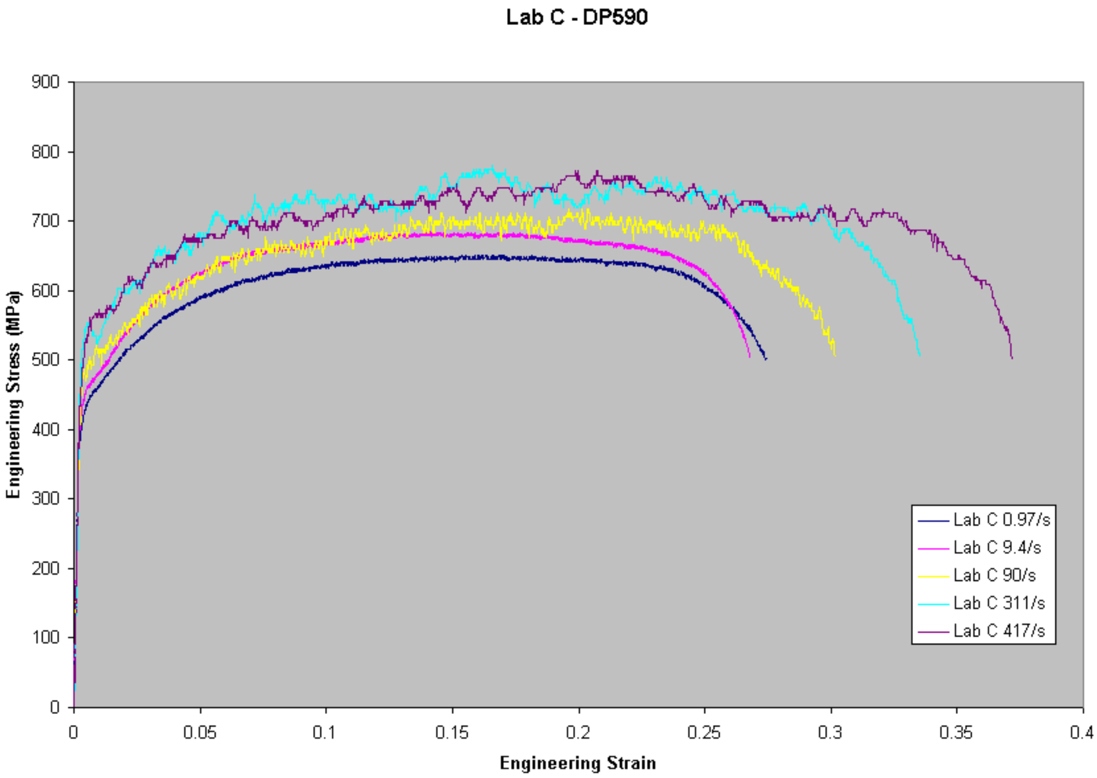


Figure 8: DP590 high strain rate results for Lab C

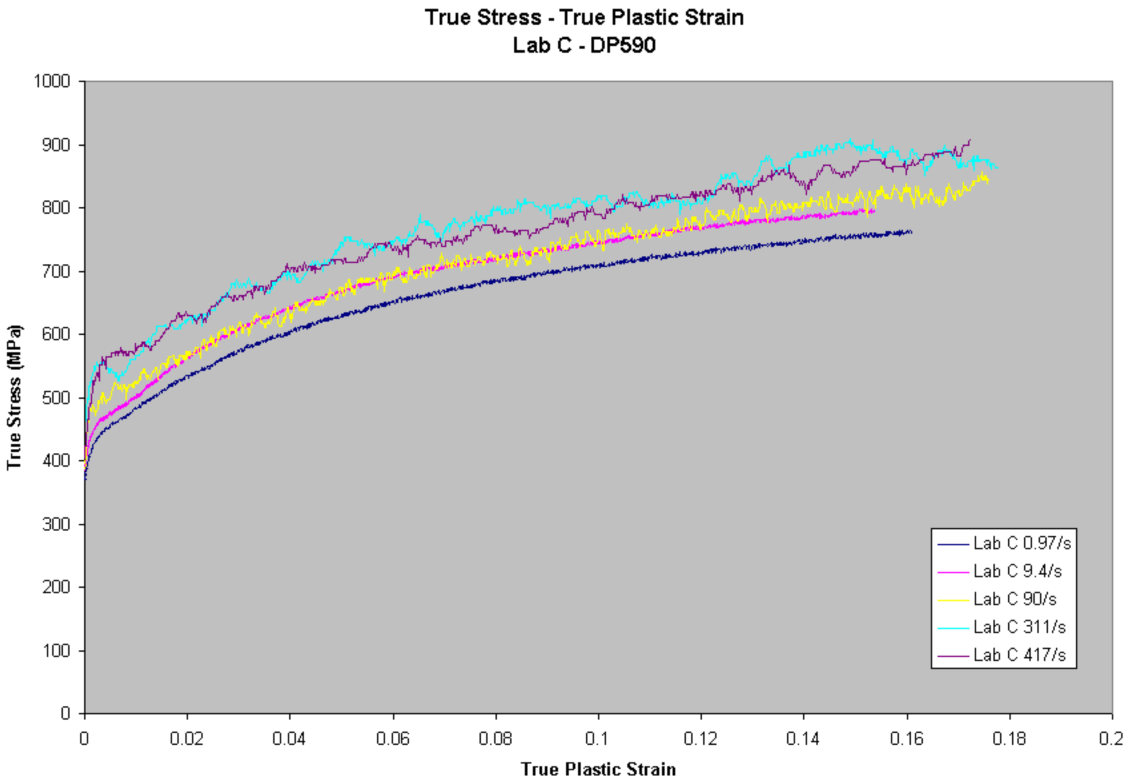


Figure 9: DP590 true stress-true plastic strain results for Lab C

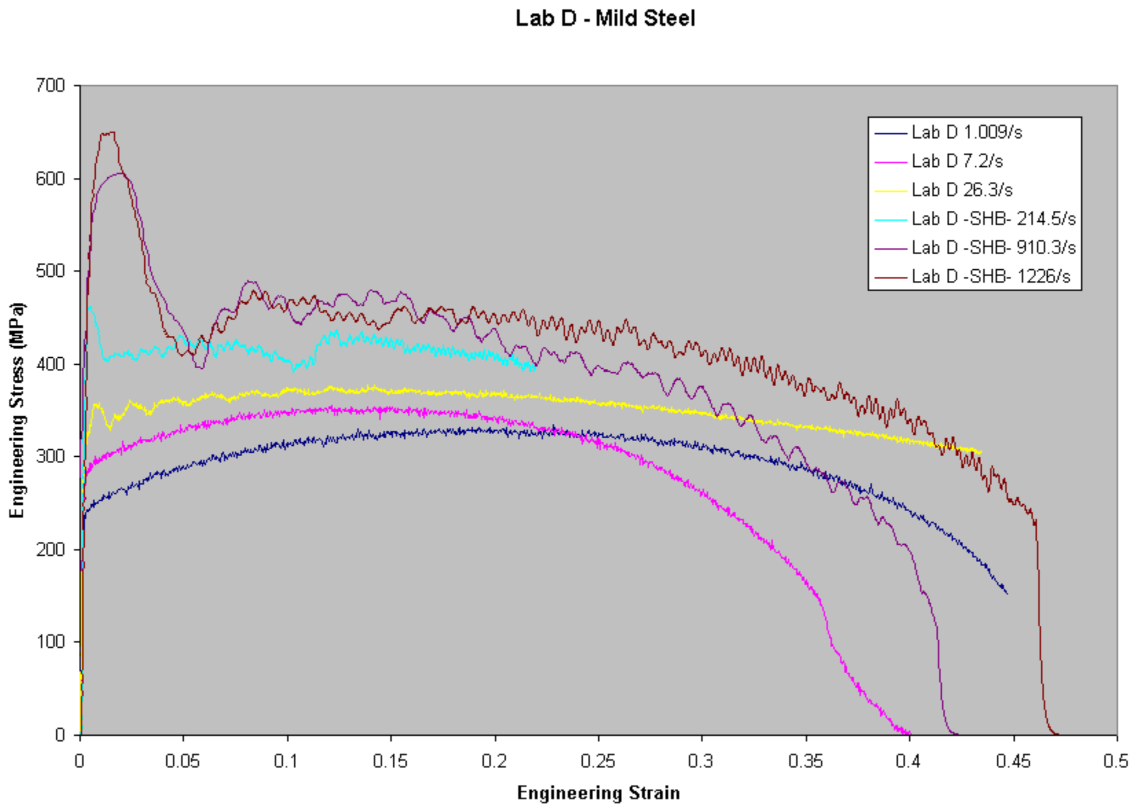


Figure 10: Mild steel high strain rate results for Lab D

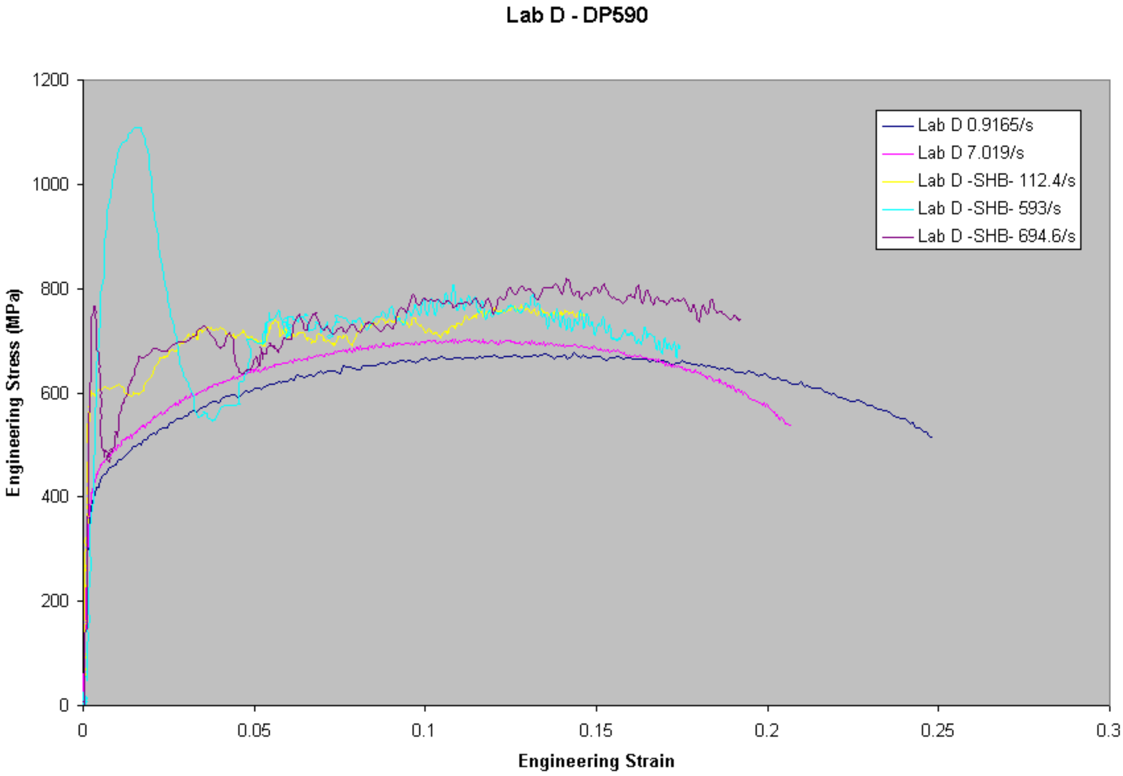


Figure 11: DP590 high strain rate results for Lab D

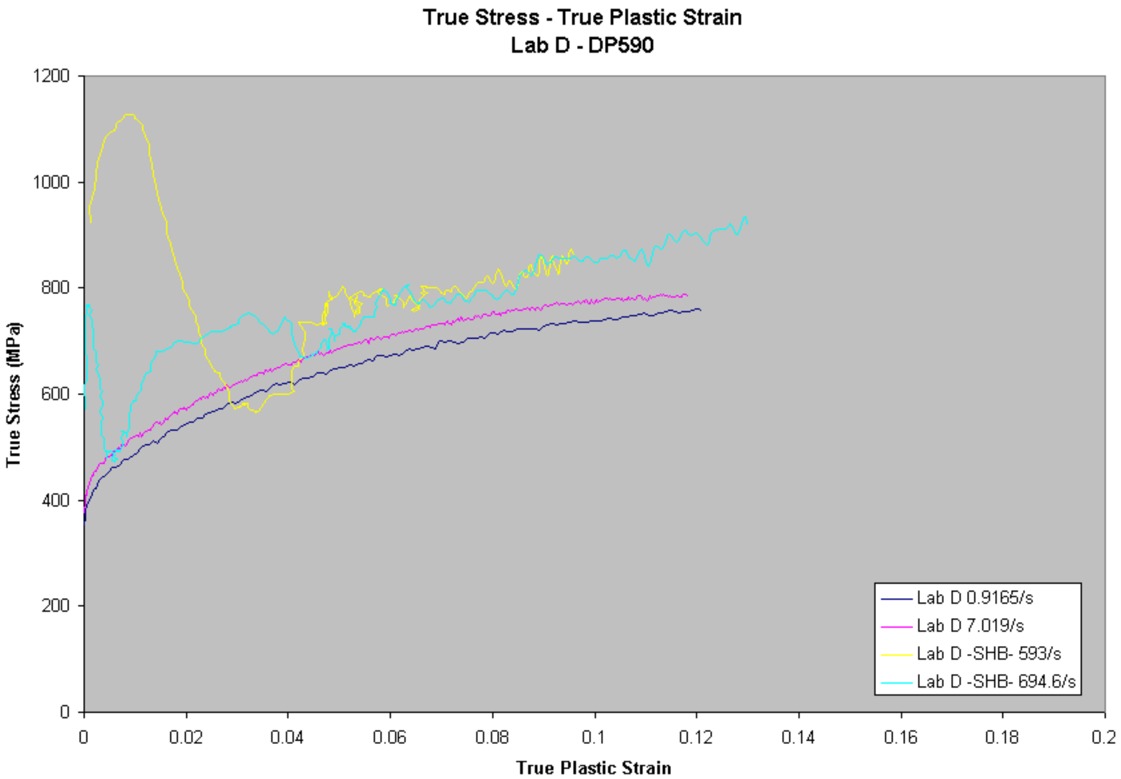


Figure 12: DP590 true stress-true plastic strain results for Lab D

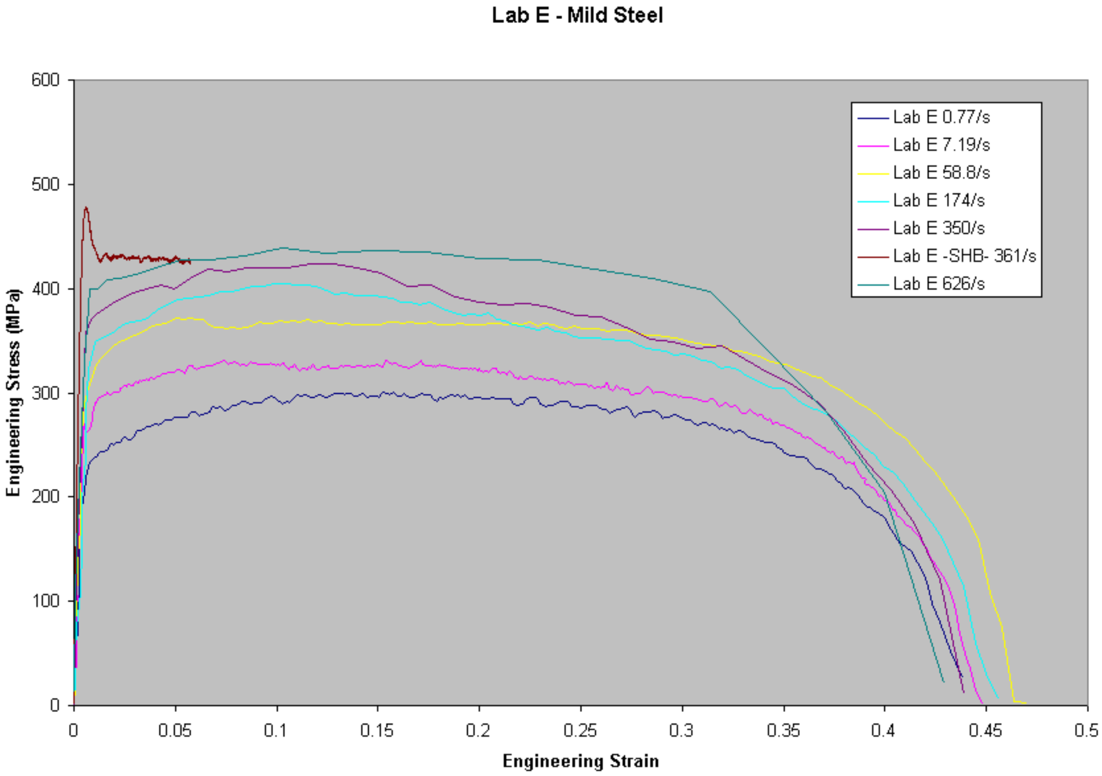


Figure 13: Mild steel high strain rate results for Lab E

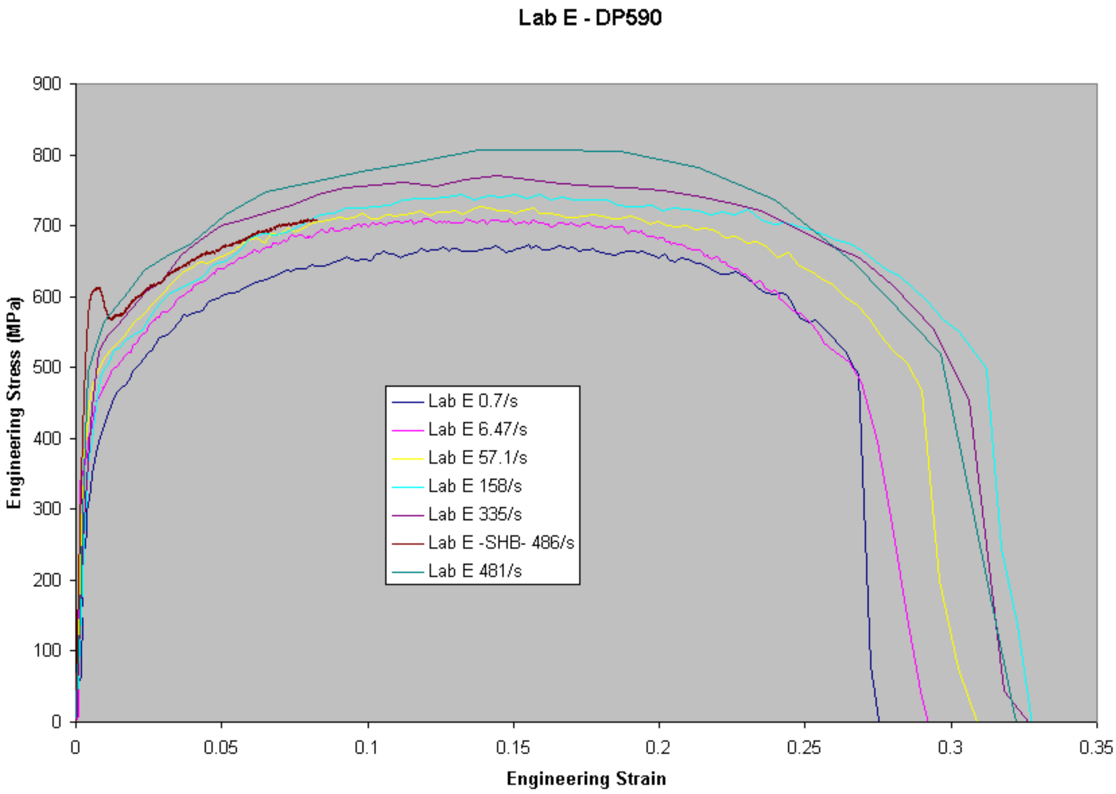


Figure 14: DP590 high strain rate results for Lab E

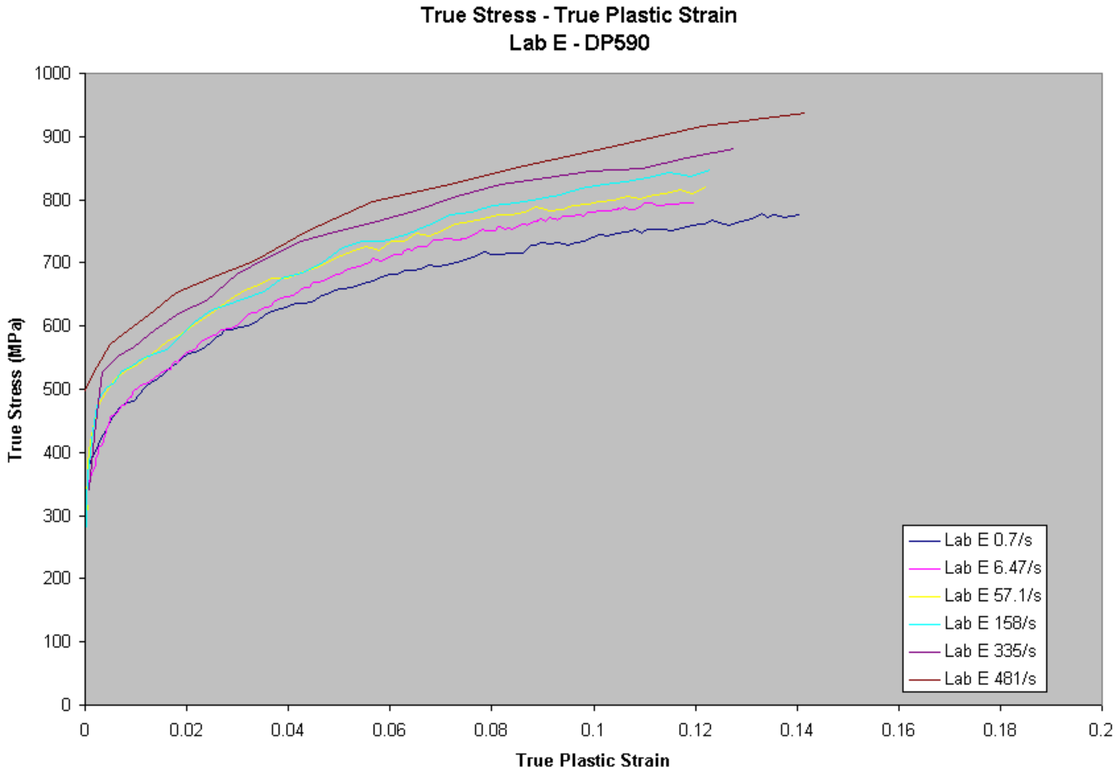


Figure 15: DP590 true stress-true plastic strain results for Lab E

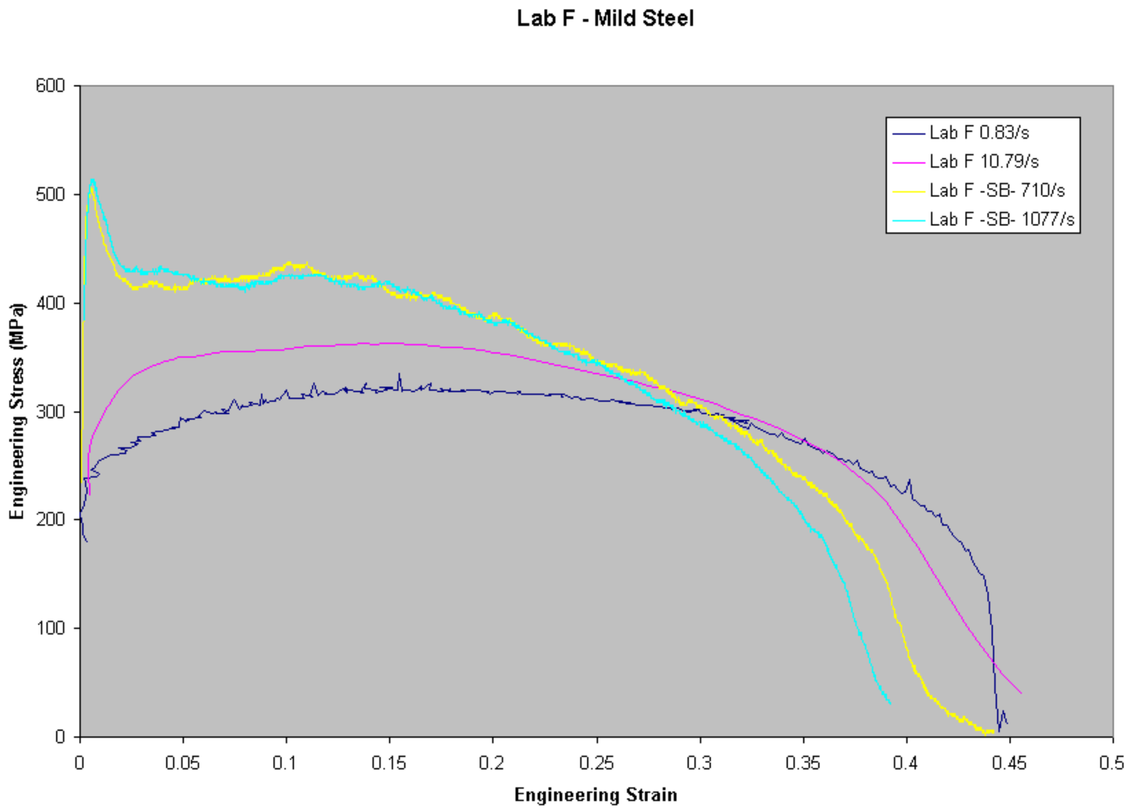


Figure 16: Mild steel high strain rate results for Lab F

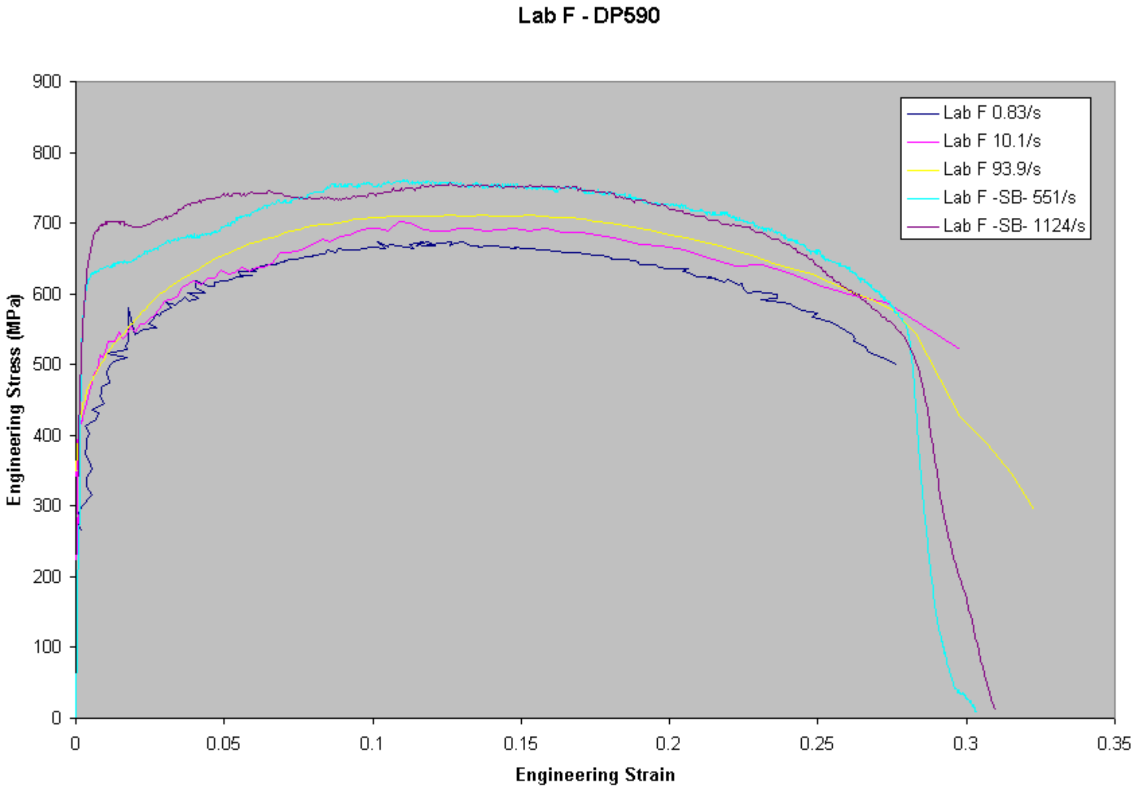


Figure 17: DP590 high strain rate results for Lab F

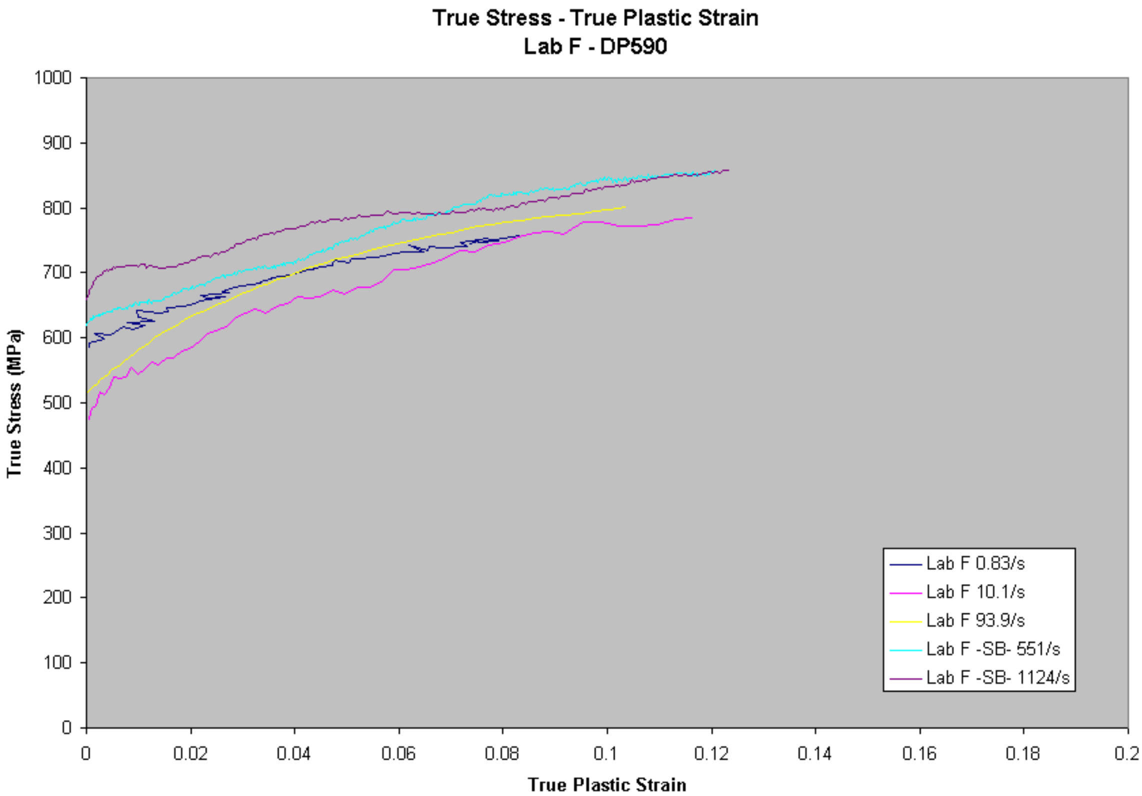


Figure 18: DP590 true stress-true plastic strain results for Lab F

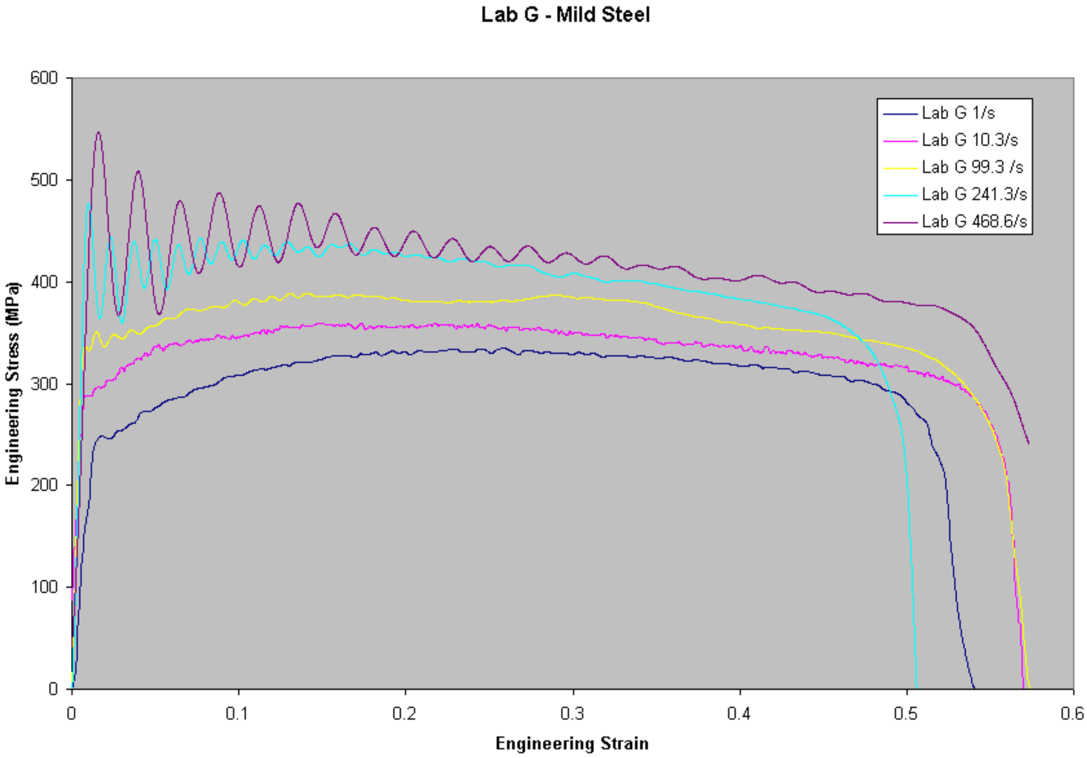


Figure 19: Mild steel high strain rate results for Lab G

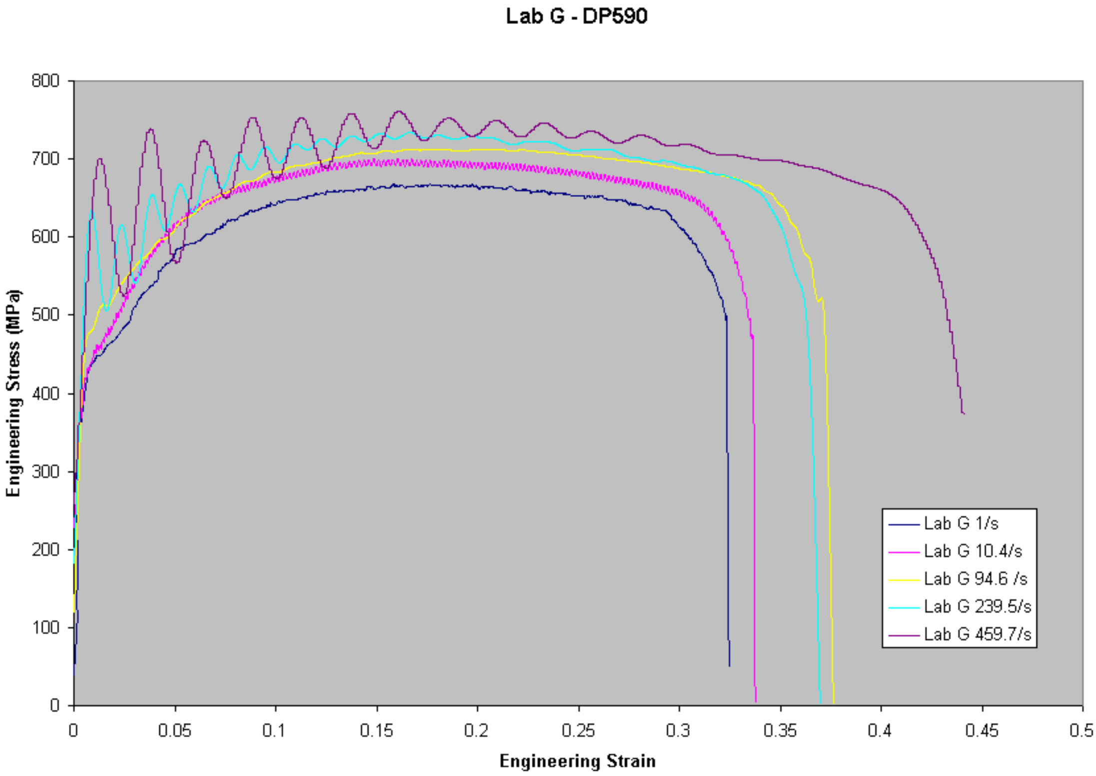


Figure 20: DP590 high strain rate results for Lab G

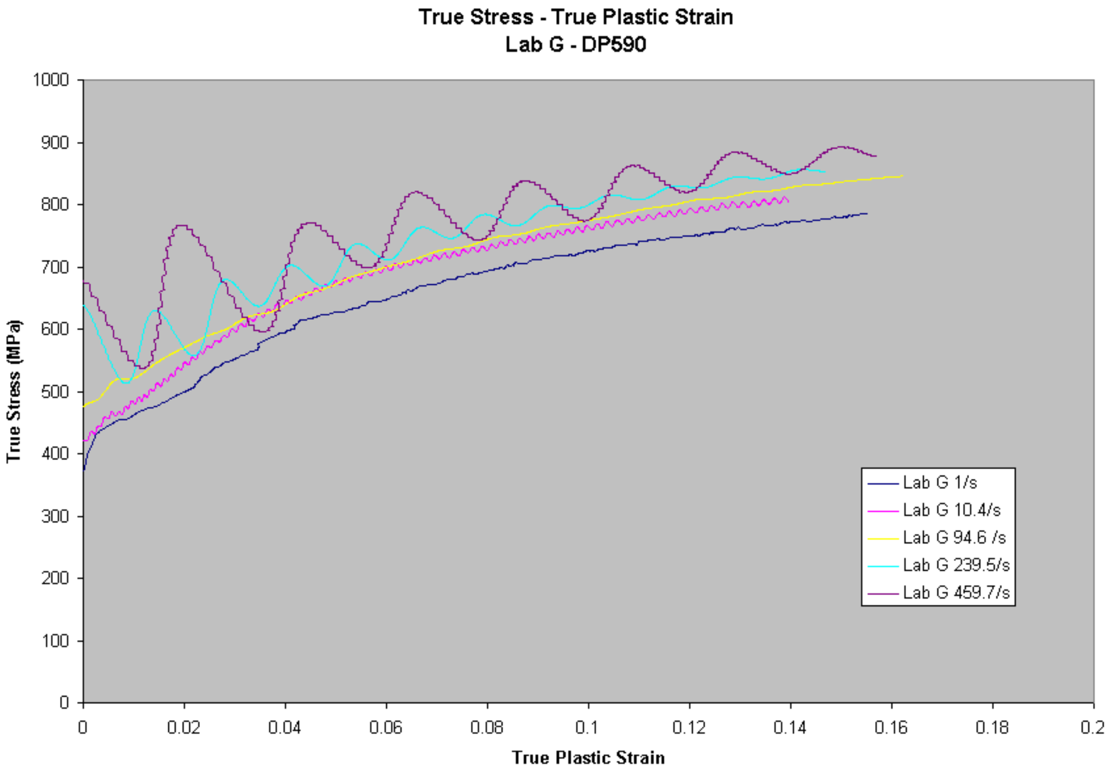


Figure 21: DP590 true stress-true plastic strain results for Lab G

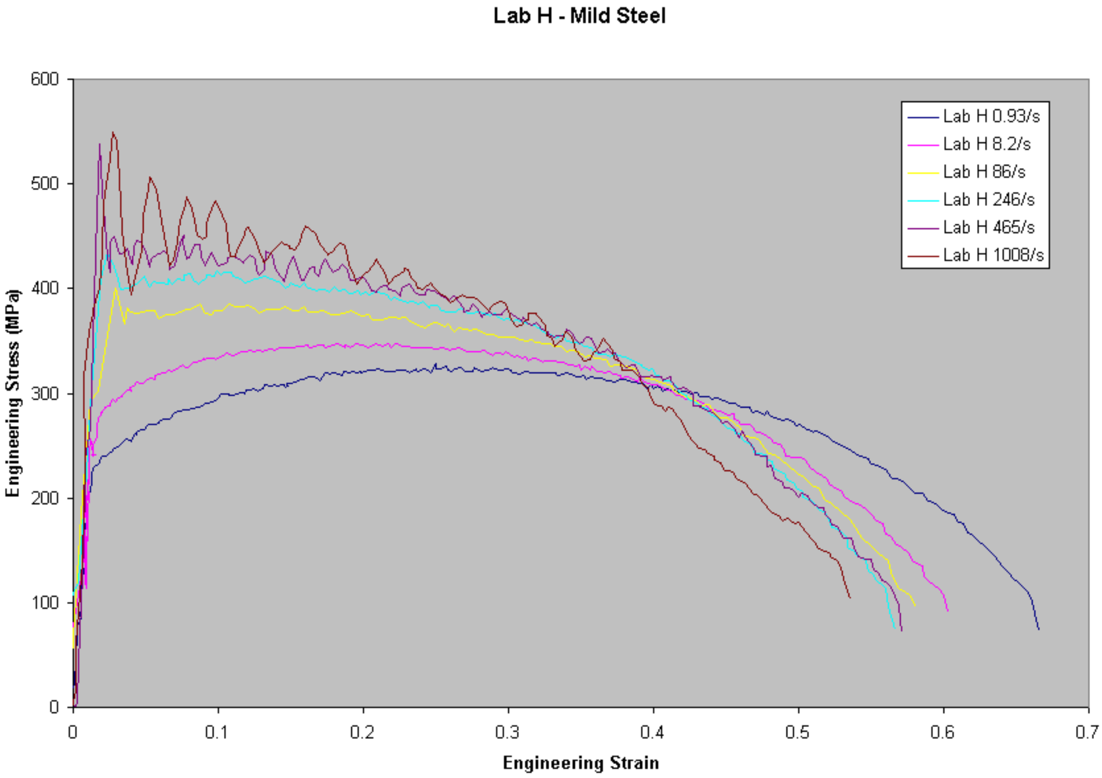


Figure 22: Mild steel high strain rate results for Lab H

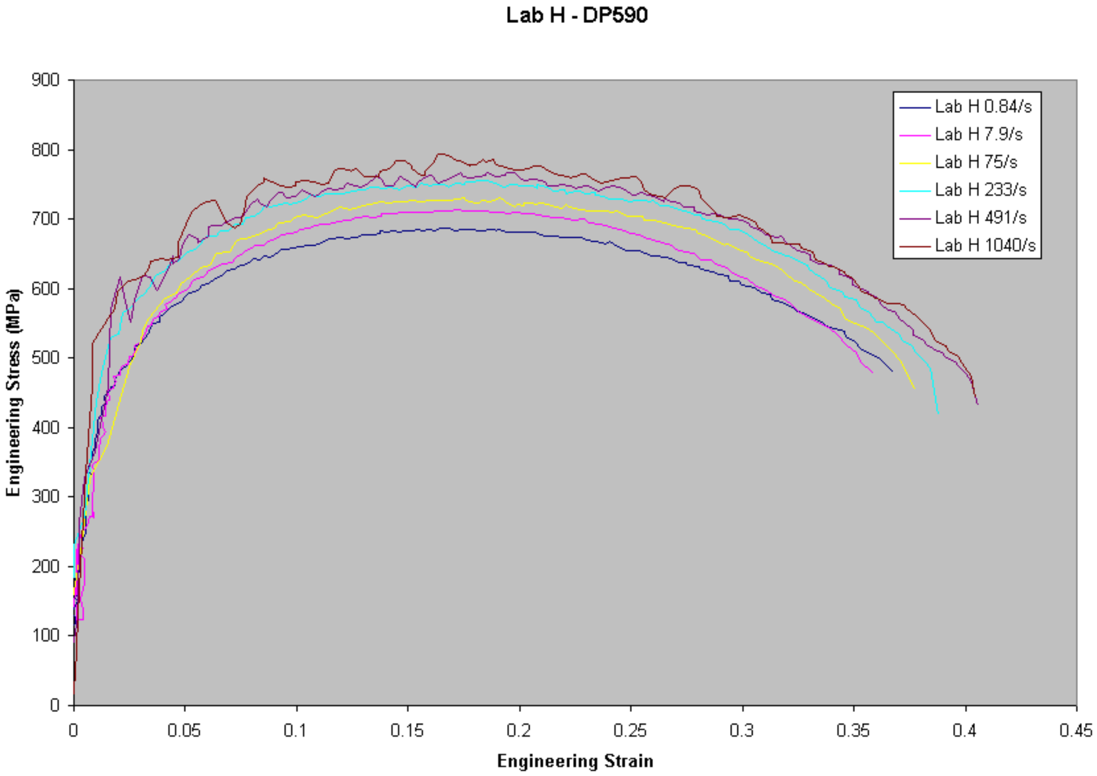


Figure 23: DP590 high strain rate results for Lab H

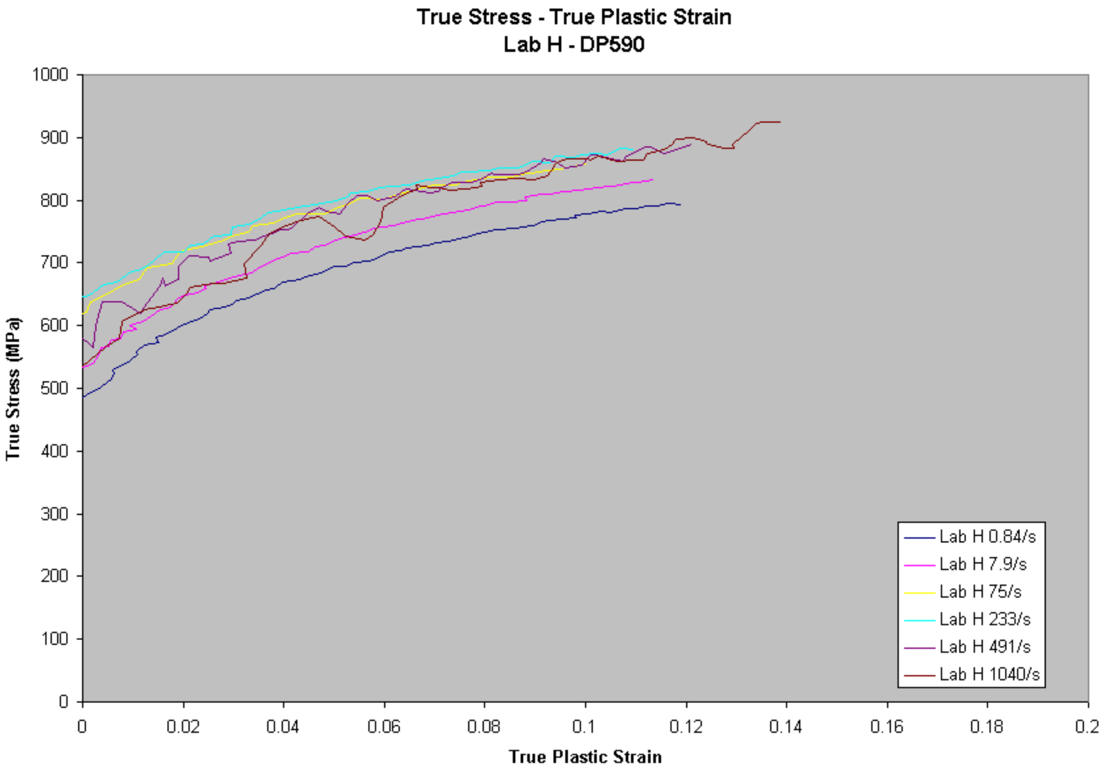


Figure 24: DP590 true stress-true plastic strain results for Lab H

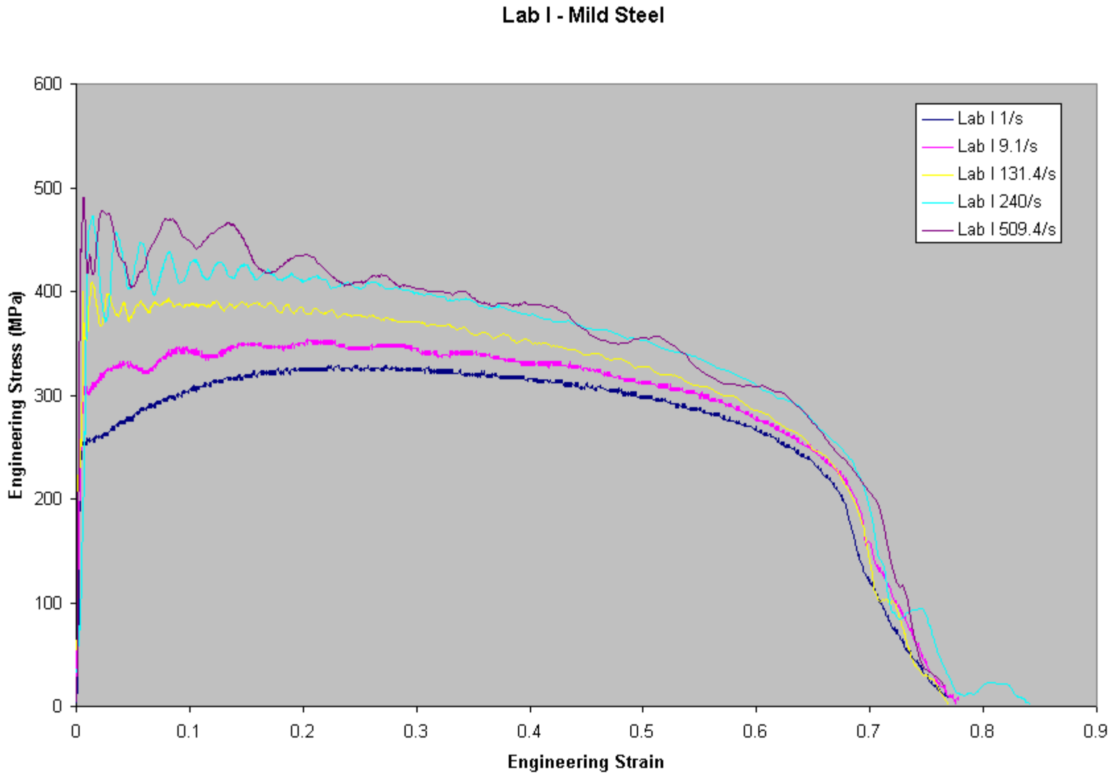


Figure 25: Mild steel high strain rate results for Lab I

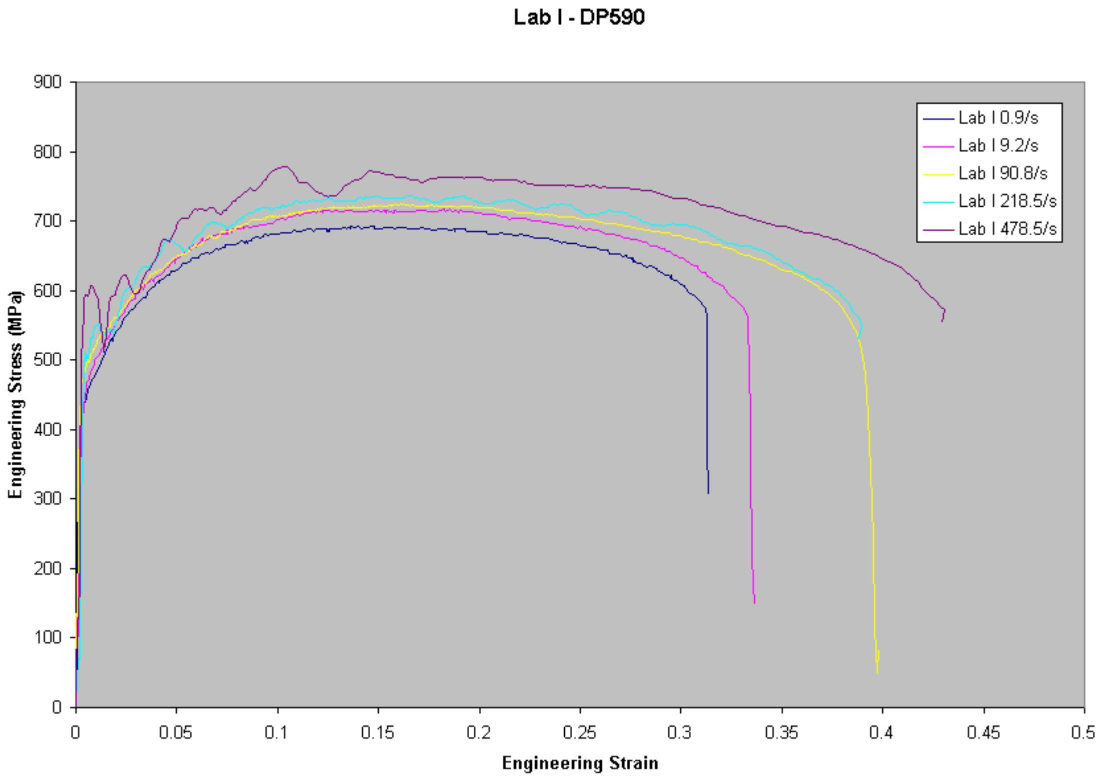


Figure 26: DP590 high strain rate results for Lab I

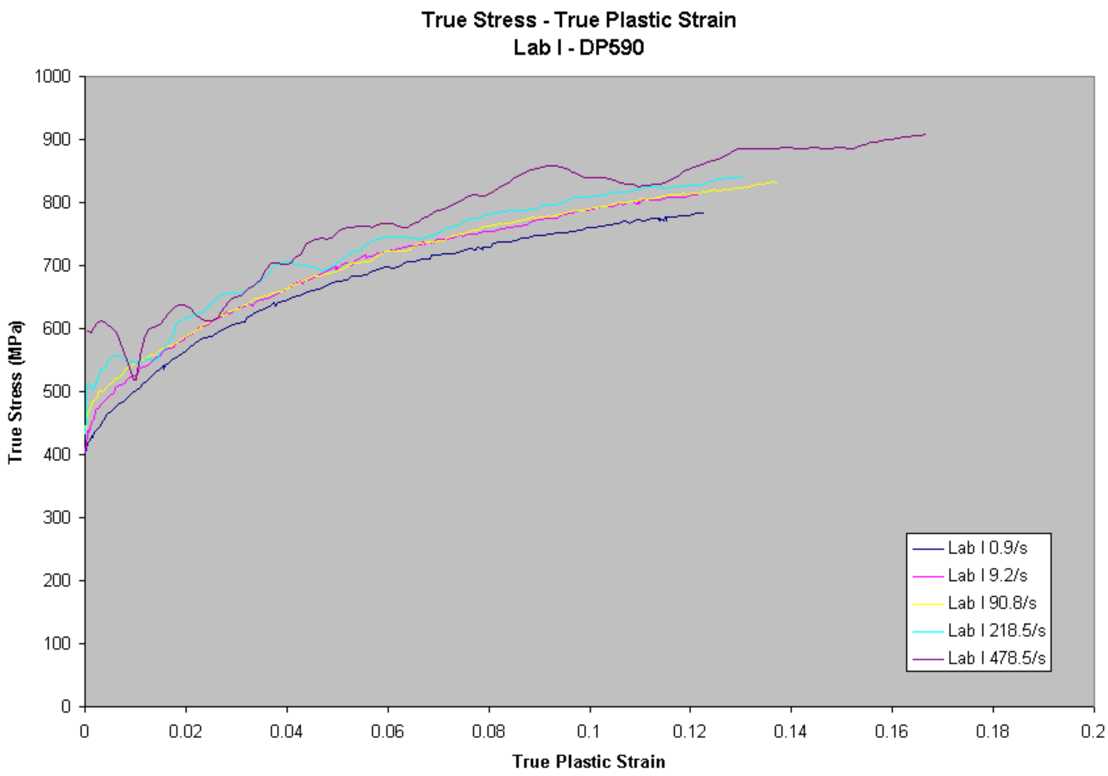


Figure 27: DP590 true stress-true plastic strain results for Lab I

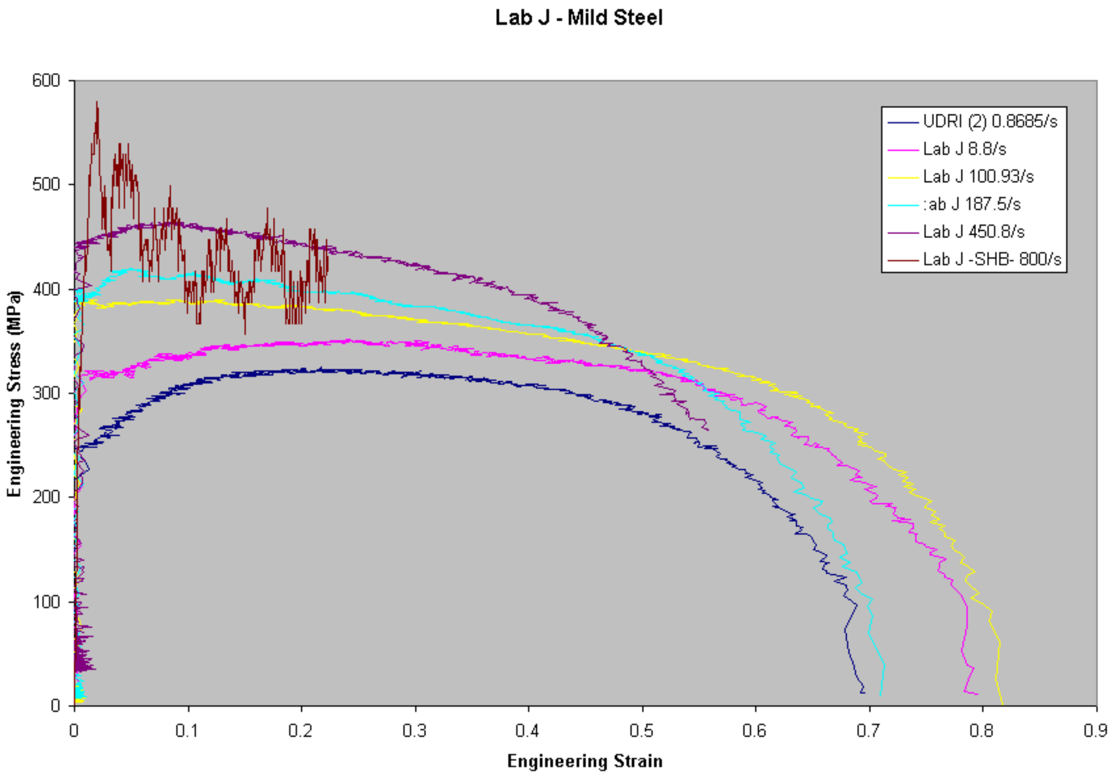


Figure 28: Mild steel high strain rate results for Lab J

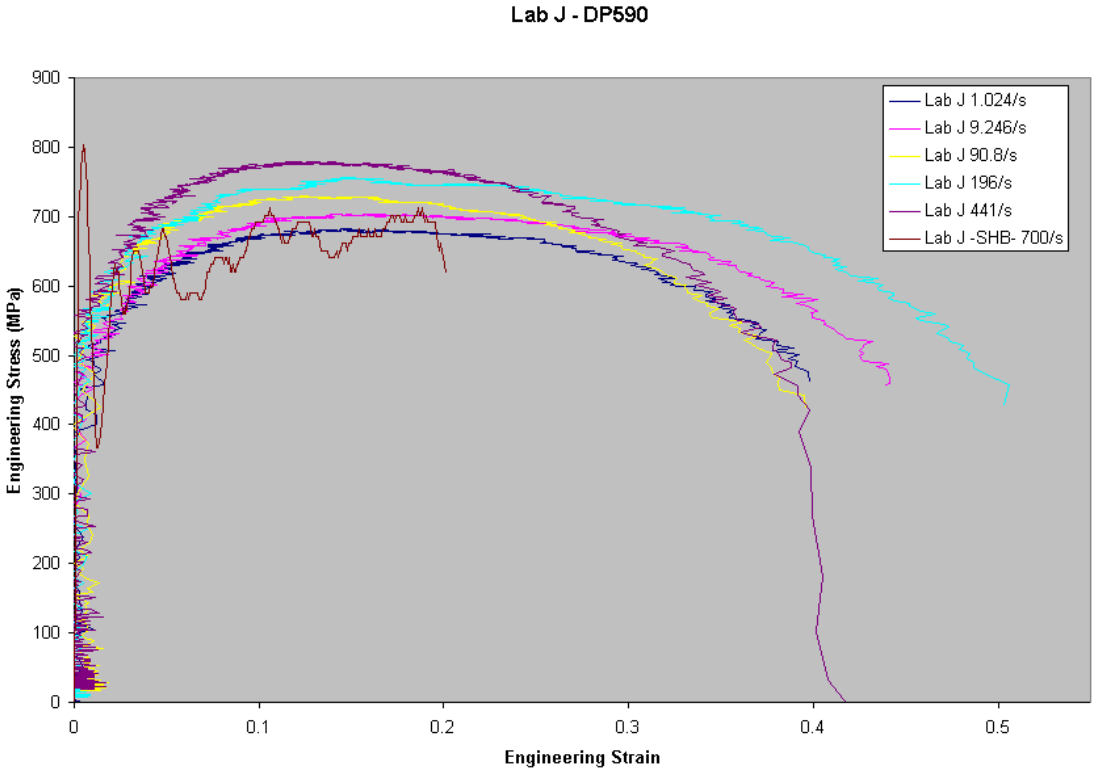


Figure 29: Mild steel high strain rate results for Lab J

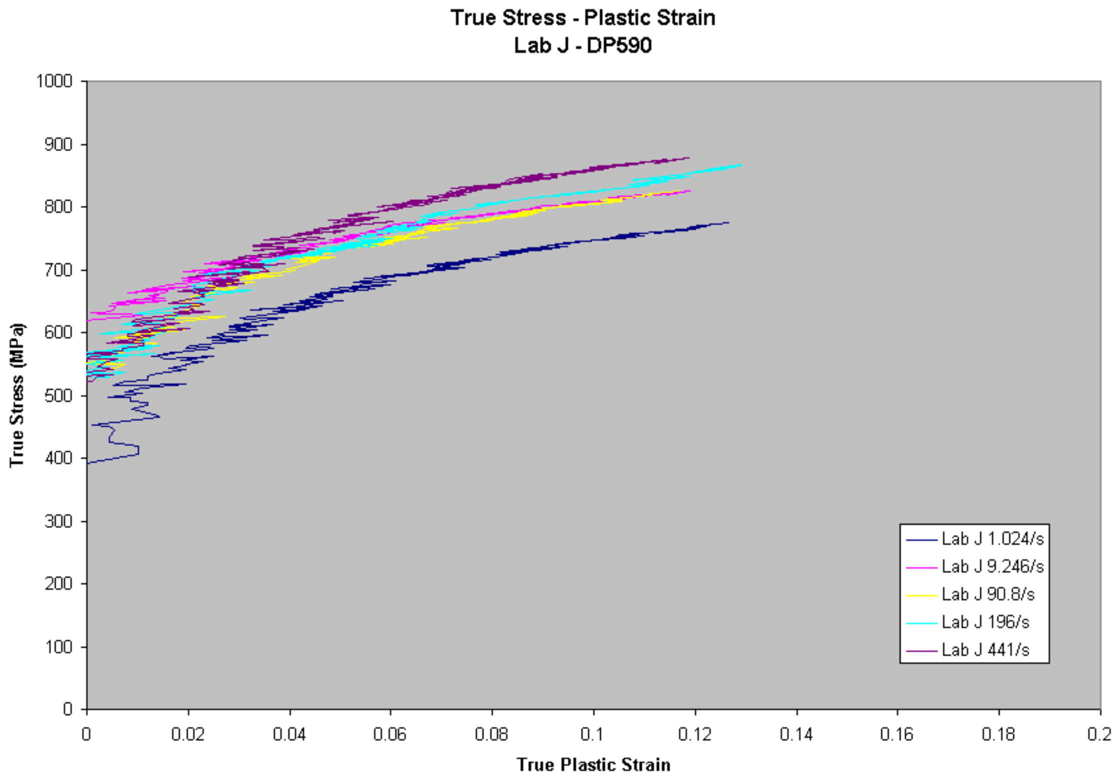


Figure 30: DP590 true stress-true plastic strain results for Lab J

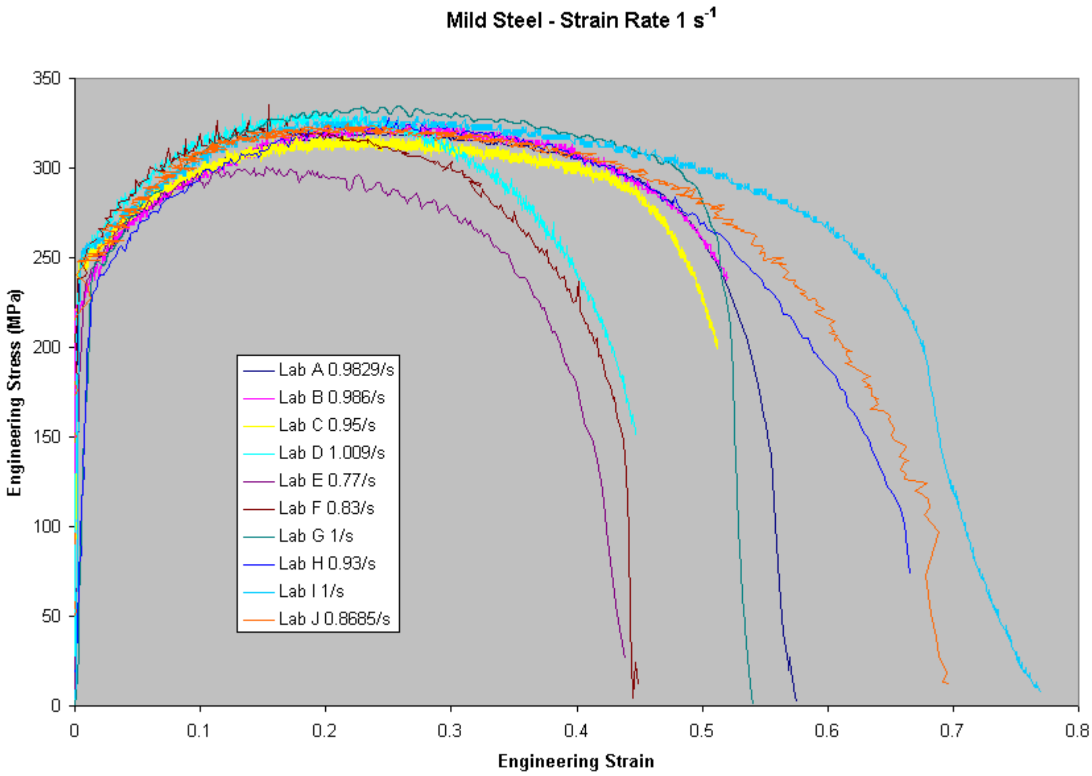


Figure 31: Mild steel high strain rate results for nominal strain rate of 1 s^{-1}

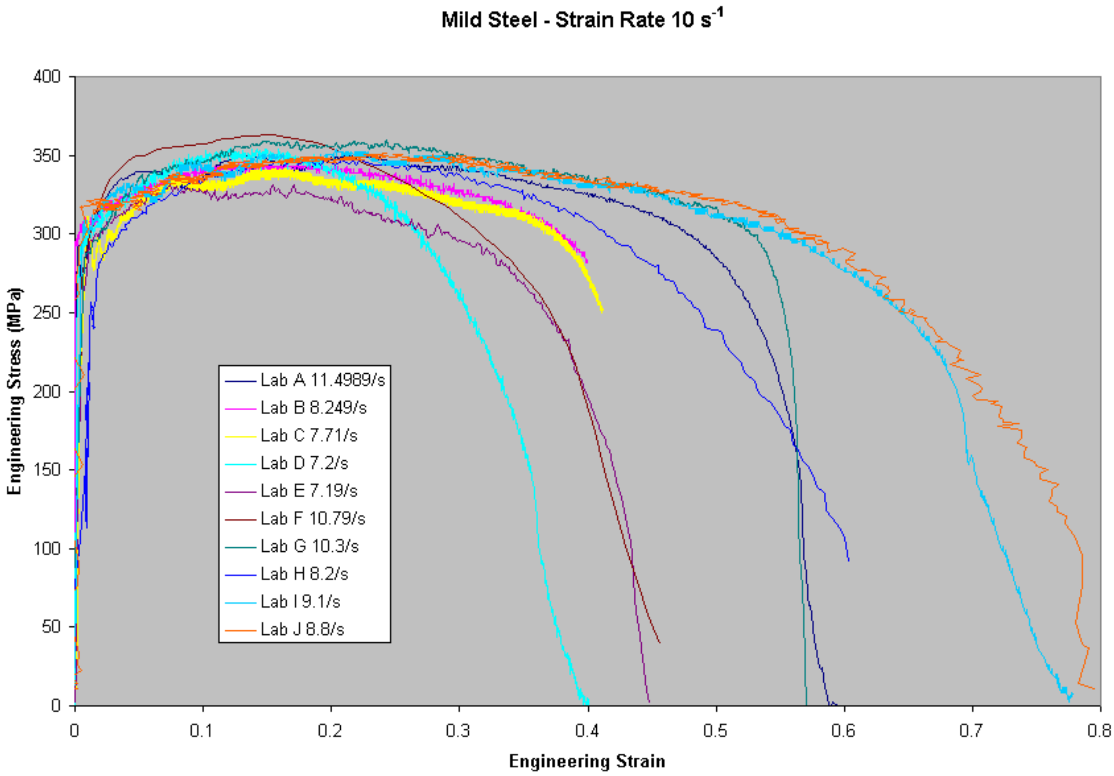


Figure 32: Mild steel high strain rate results for nominal strain rate of 10 s^{-1}

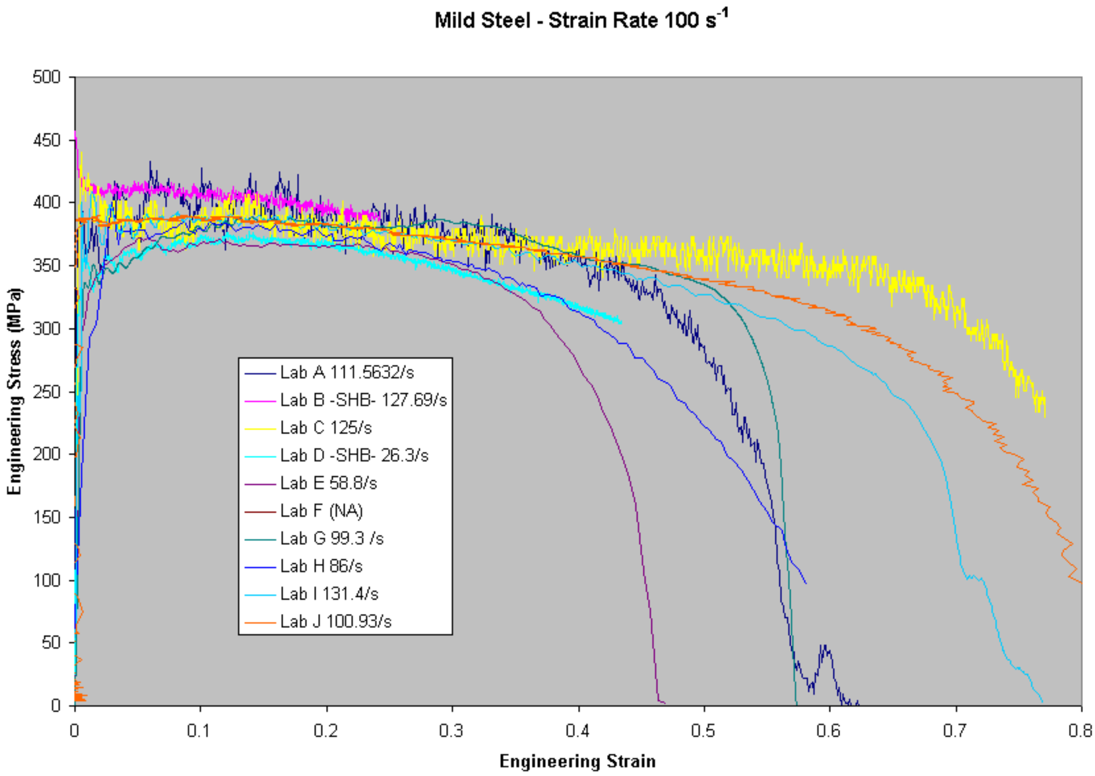


Figure 33: Mild steel high strain rate results for nominal strain rate of 100 s^{-1}

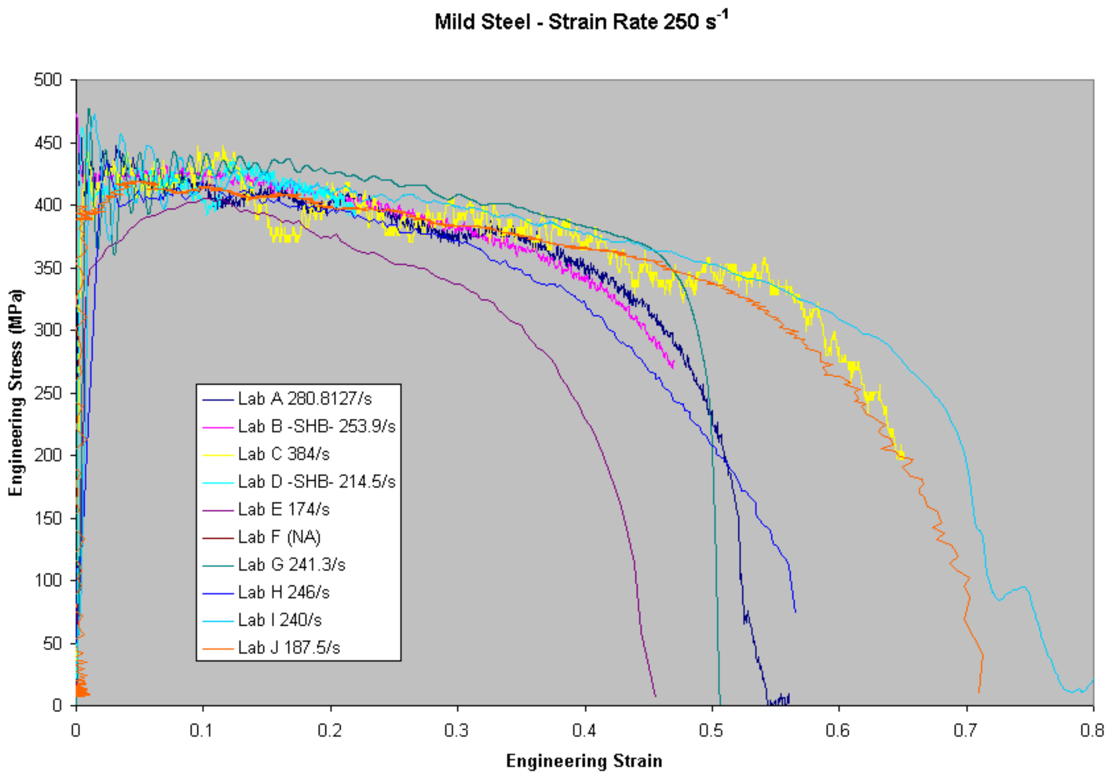


Figure 34: Mild steel high strain rate results for nominal strain rate of 250 s^{-1}

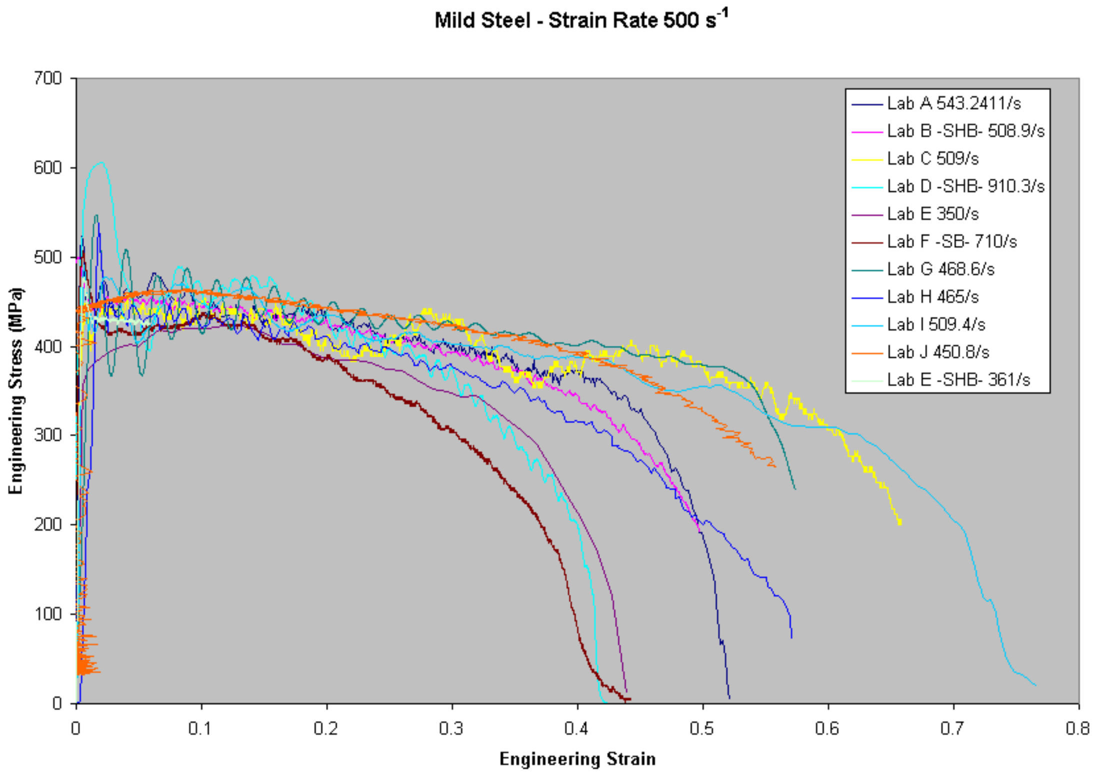


Figure 35: Mild steel high strain rate results for nominal strain rate of 500 s^{-1}

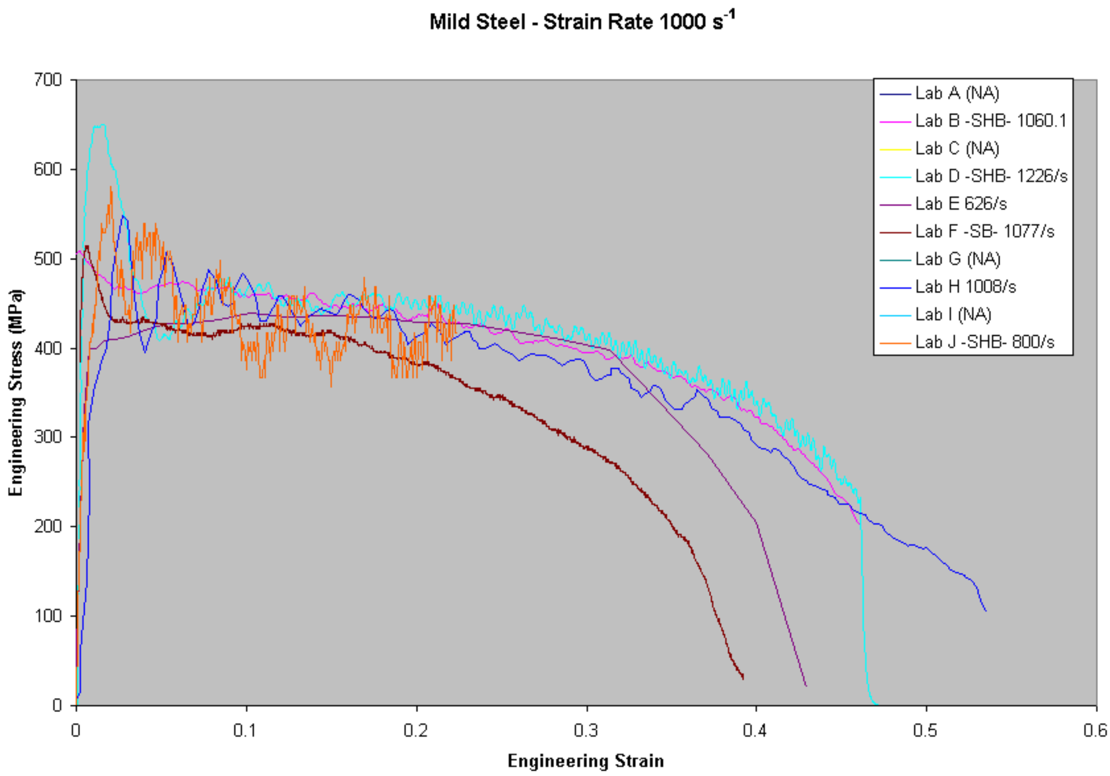


Figure 36: Mild steel high strain rate results for nominal strain rate of 1000 s^{-1}

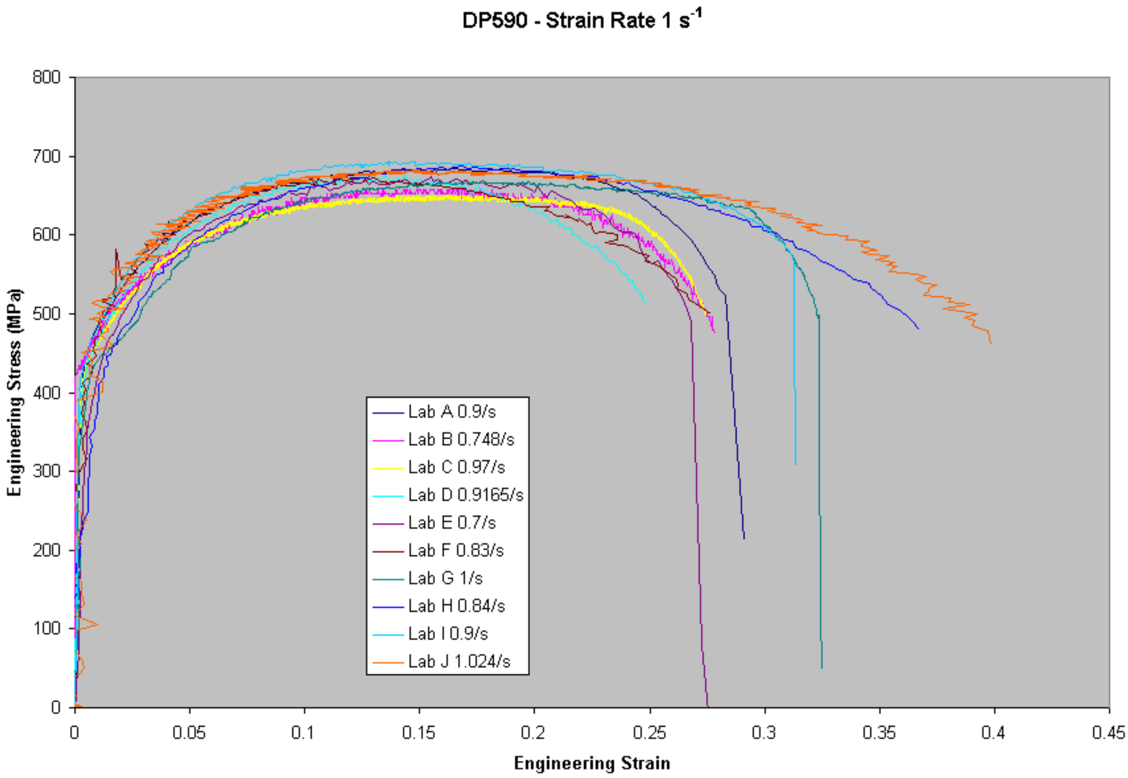


Figure 37: DP590 high strain rate results for nominal strain rate of 1 s^{-1}

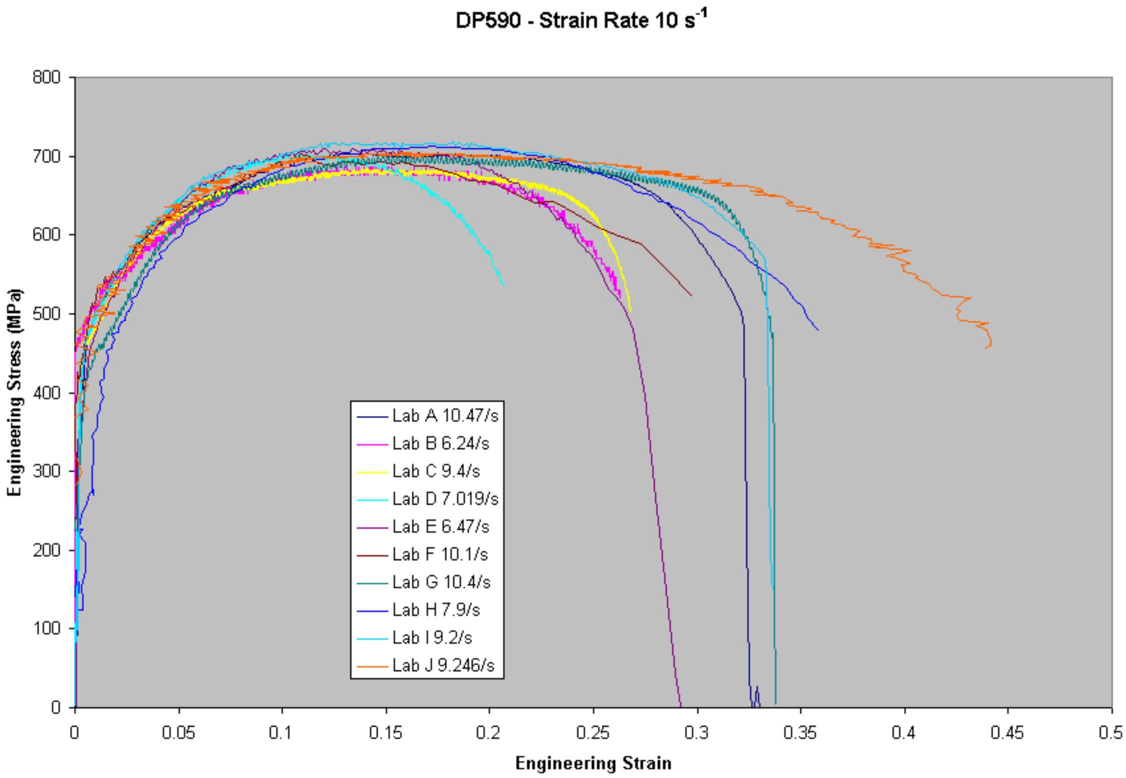


Figure 38: DP590 high strain rate results for nominal strain rate of 10 s^{-1}

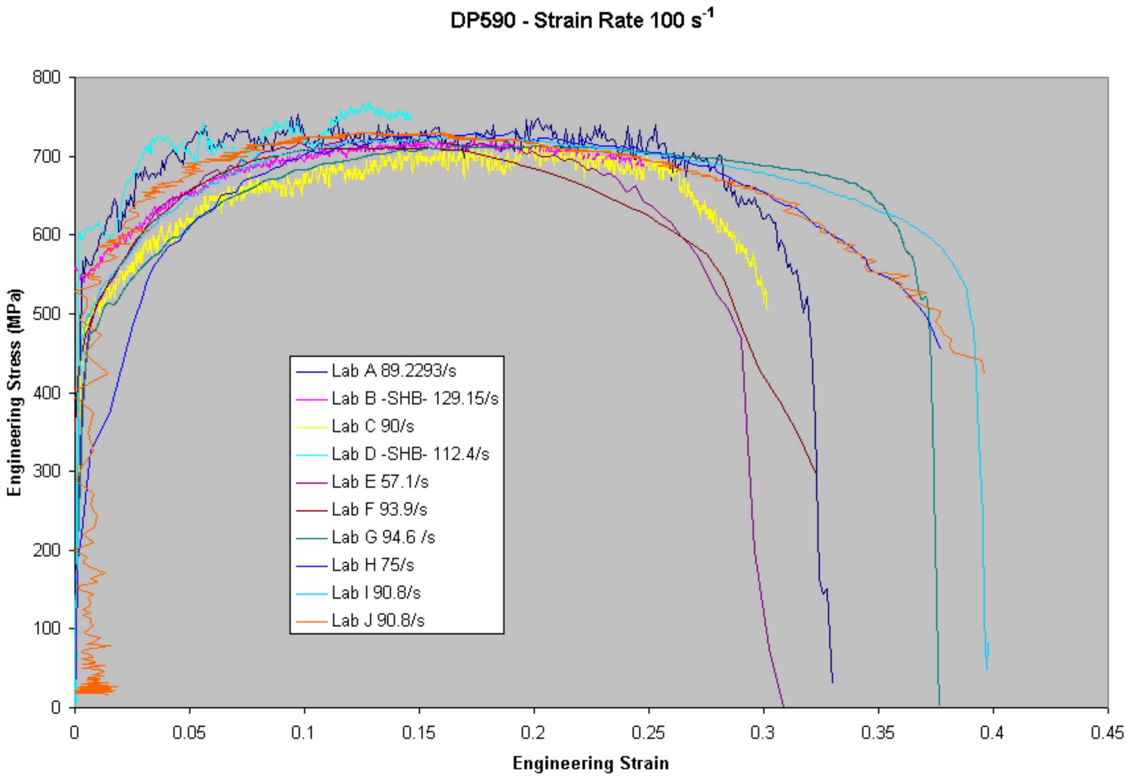


Figure 39: DP590 high strain rate results for nominal strain rate of 100 s^{-1}

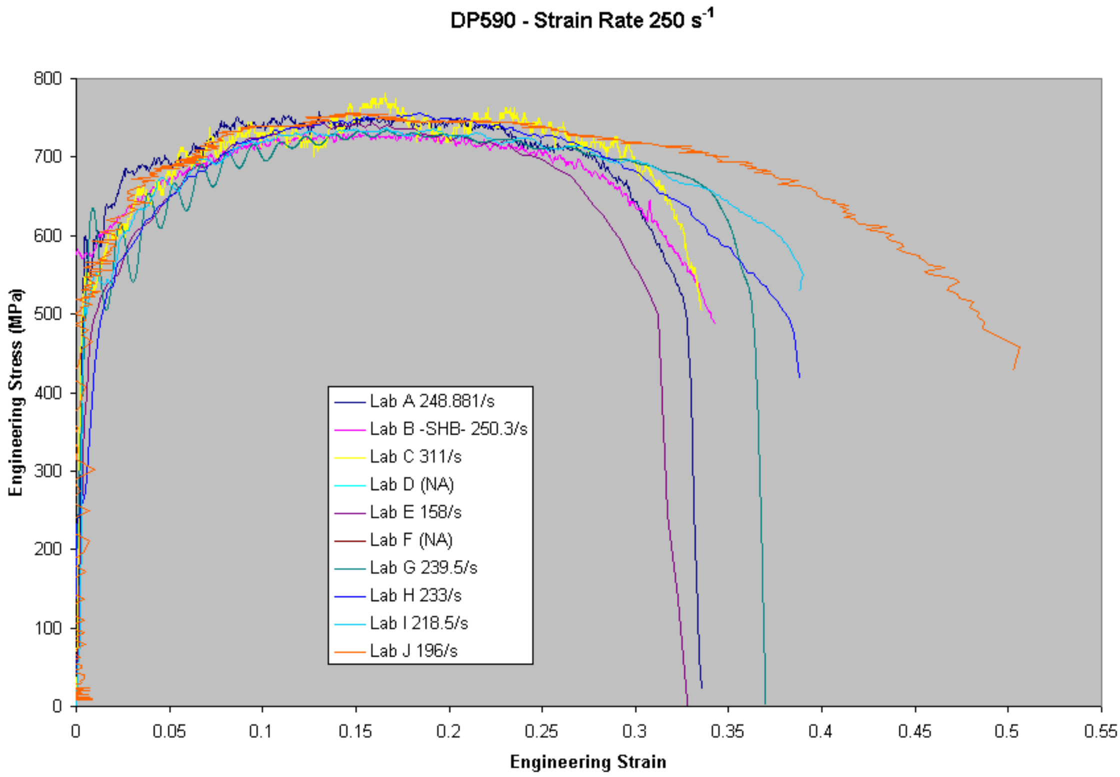


Figure 40: DP590 high strain rate results for nominal strain rate of 250 s^{-1}

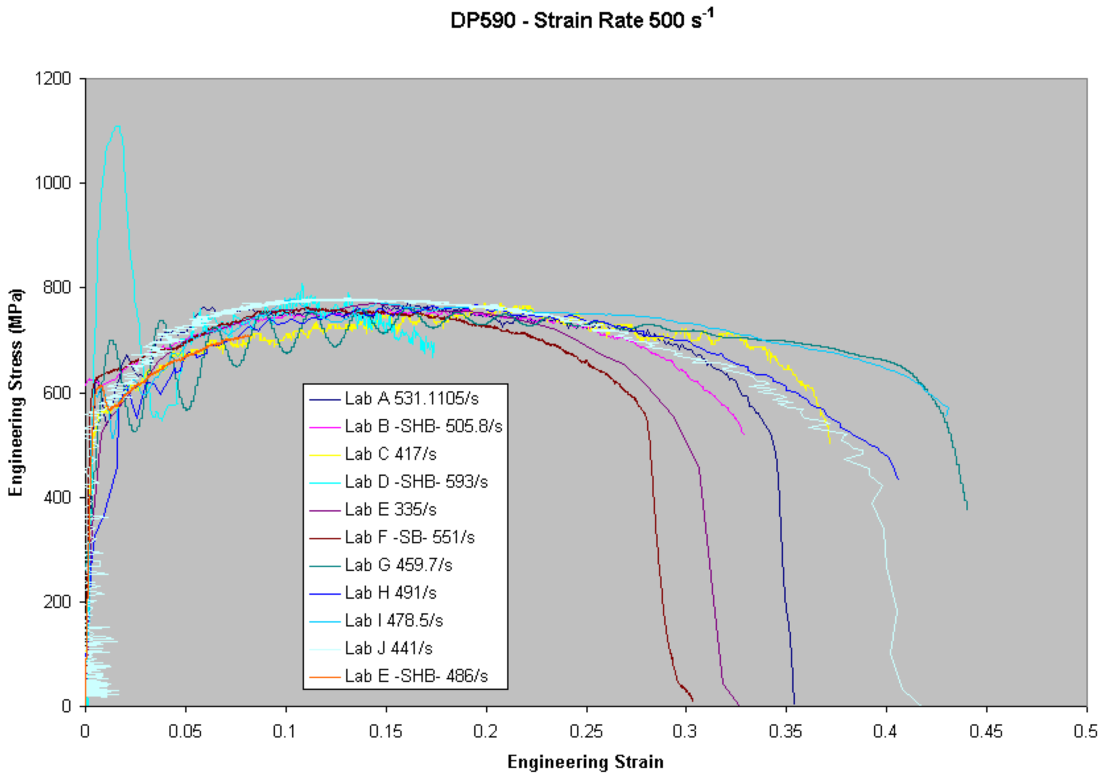


Figure 41: DP590 high strain rate results for nominal strain rate of 500 s^{-1}

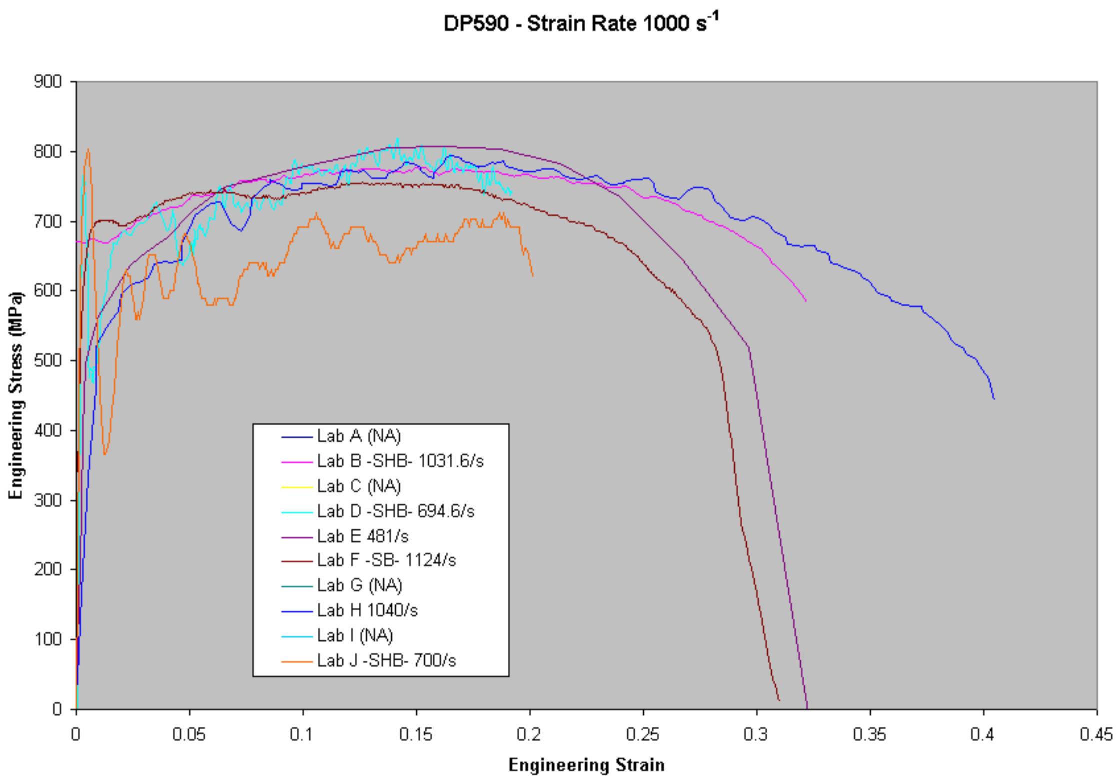


Figure 42: DP590 high strain rate results for nominal strain rate of 1000 s^{-1}

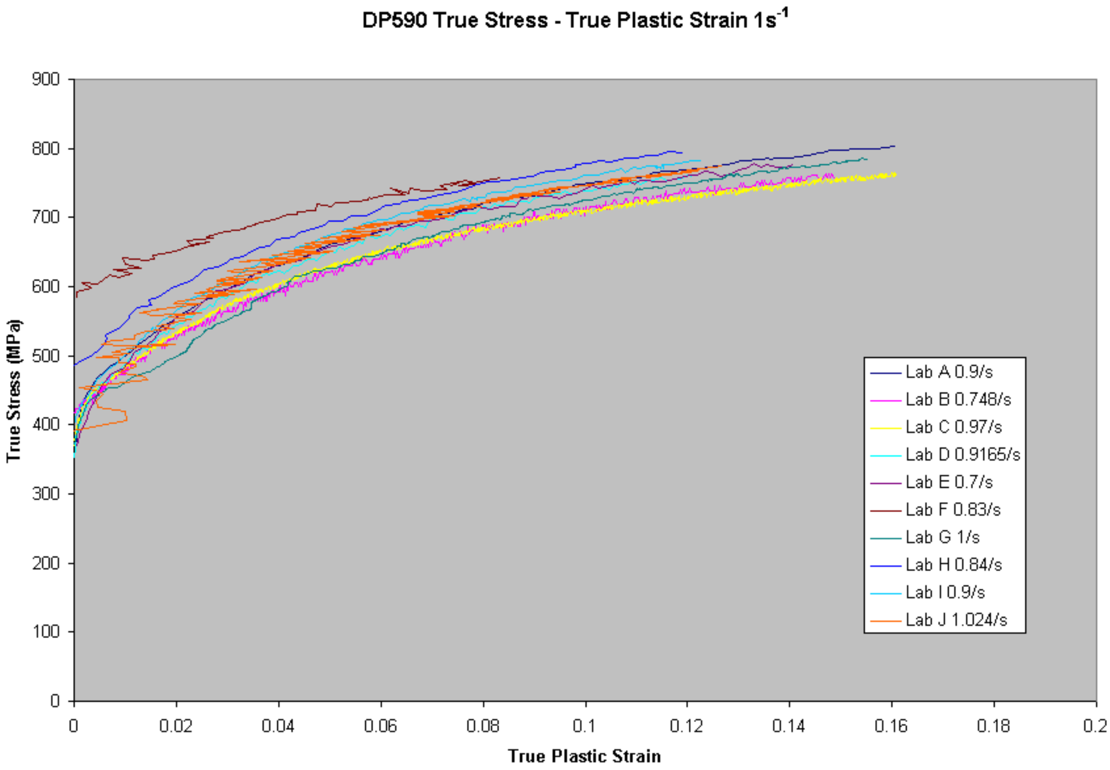


Figure 43: DP590 true stress-plastic strain for nominal strain rate of 1 s^{-1}

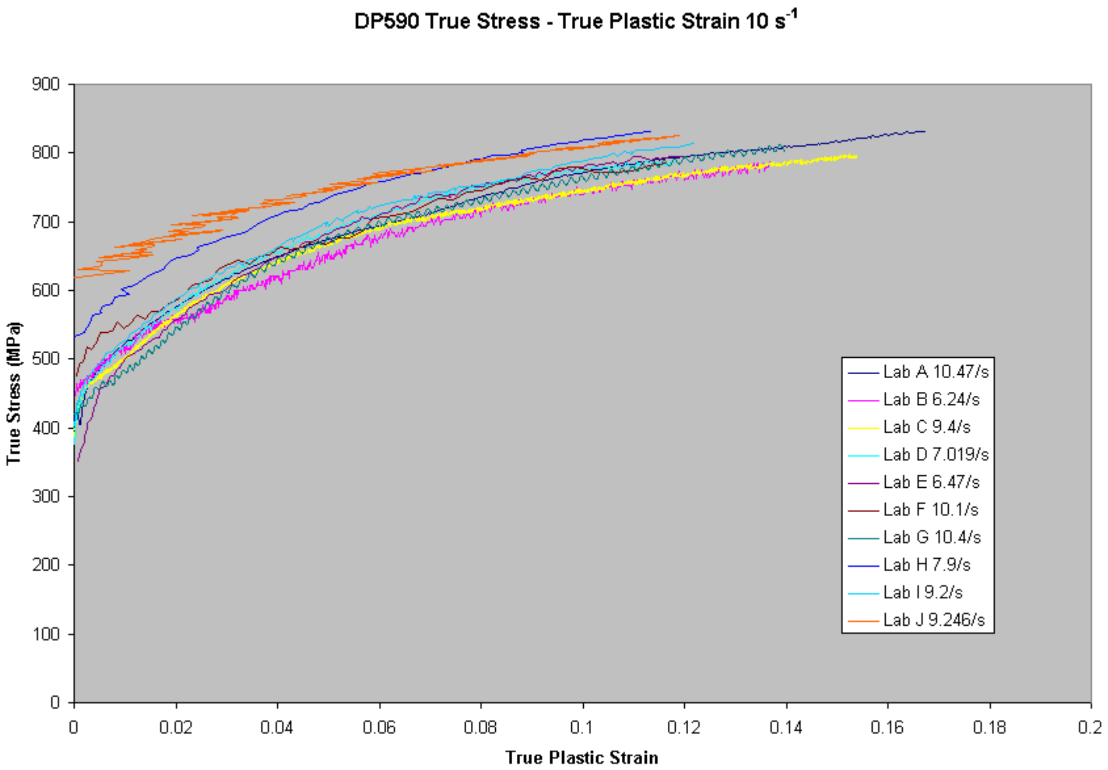


Figure 44: DP590 true stress-plastic strain for nominal strain rate of 10 s^{-1}

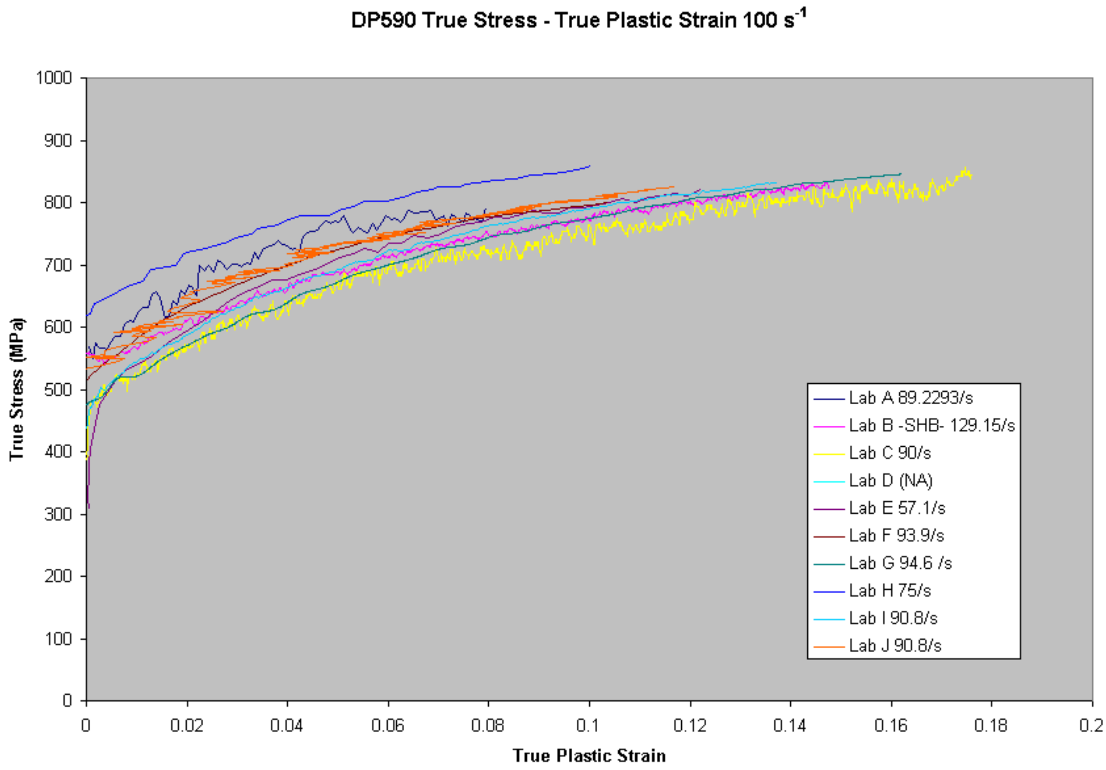


Figure 45: DP590 true stress-plastic strain for nominal strain rate of 100 s^{-1}

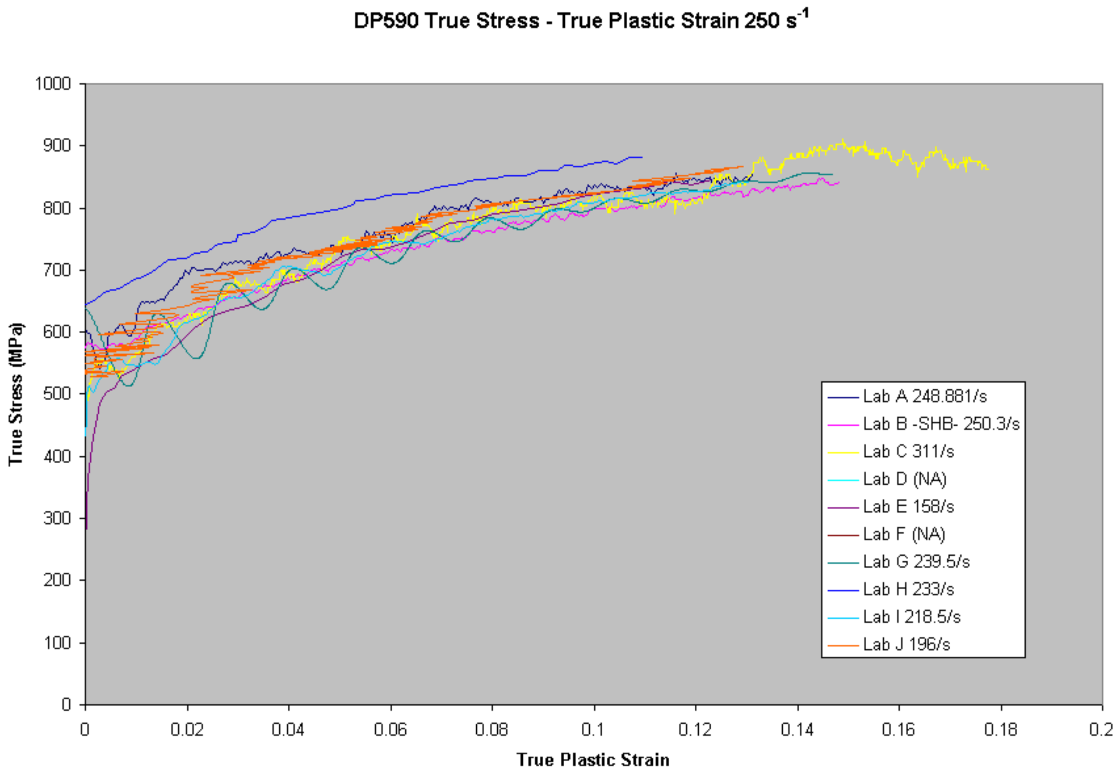


Figure 46: DP590 true stress-plastic strain for nominal strain rate of 250 s^{-1}

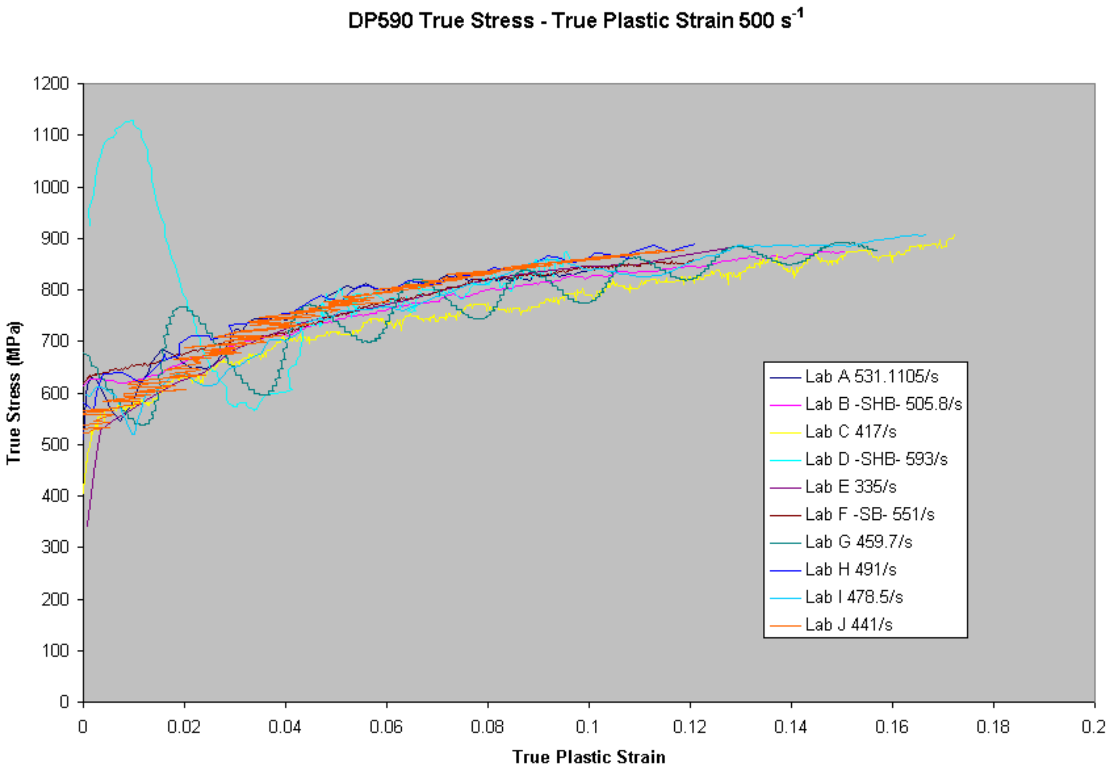


Figure 47: DP590 true stress-plastic strain for nominal strain rate of 500 s^{-1}

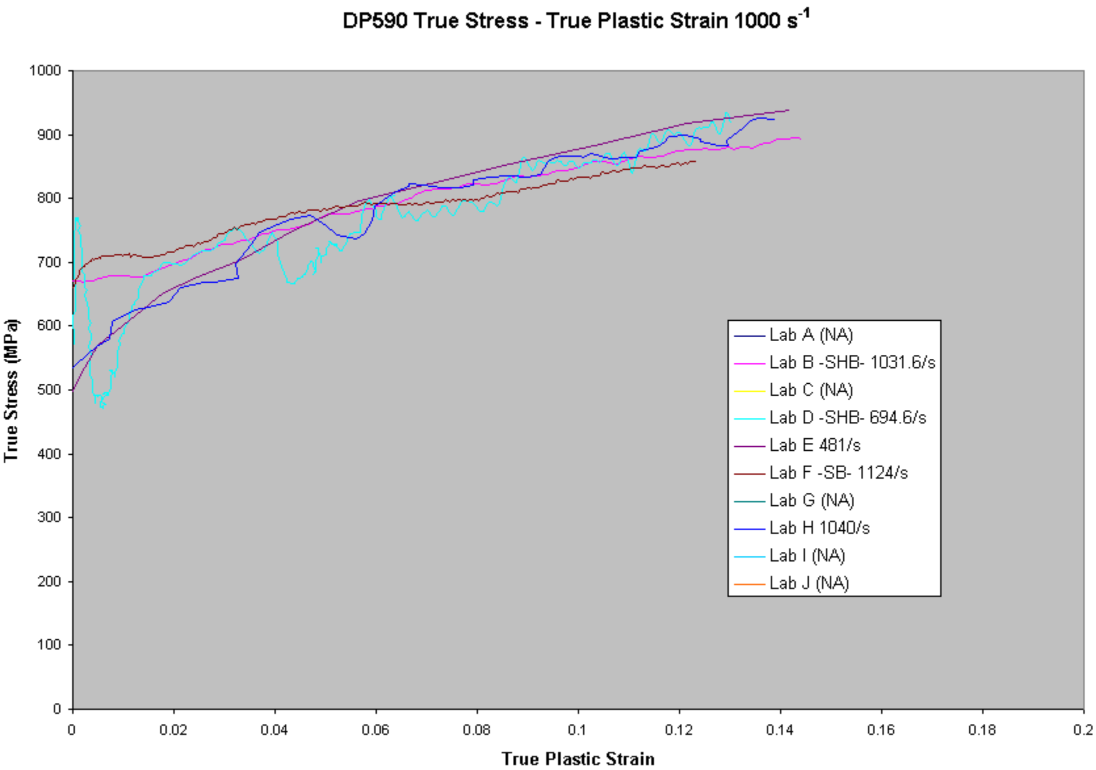


Figure 48: DP590 true stress-plastic strain for nominal strain rate of 1000 s^{-1}

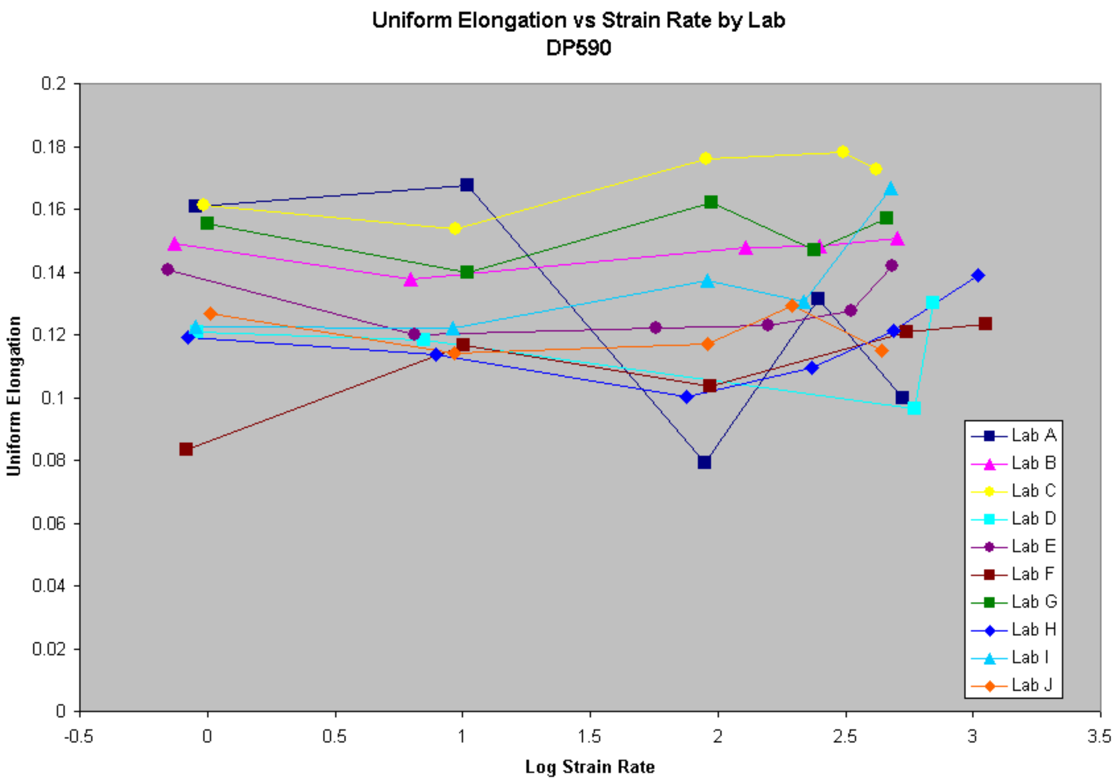


Figure 49: Uniform Elongation vs. Log Strain Rate for DP590

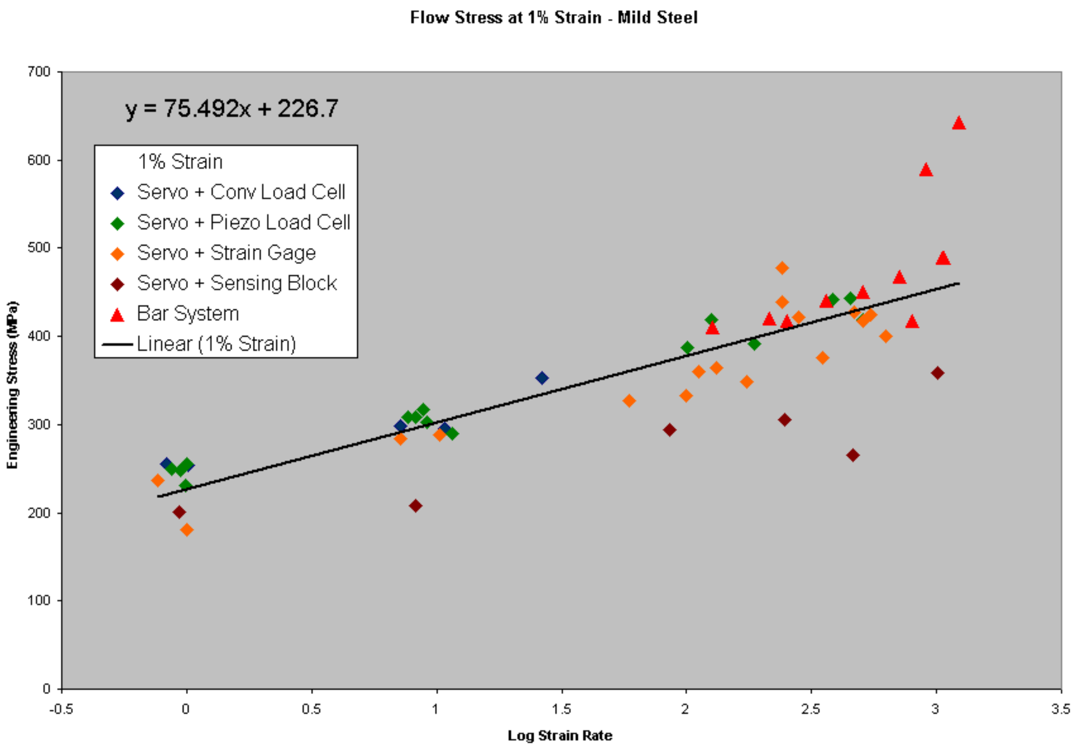


Figure 50: Flow stress at 1% strain for mild steel

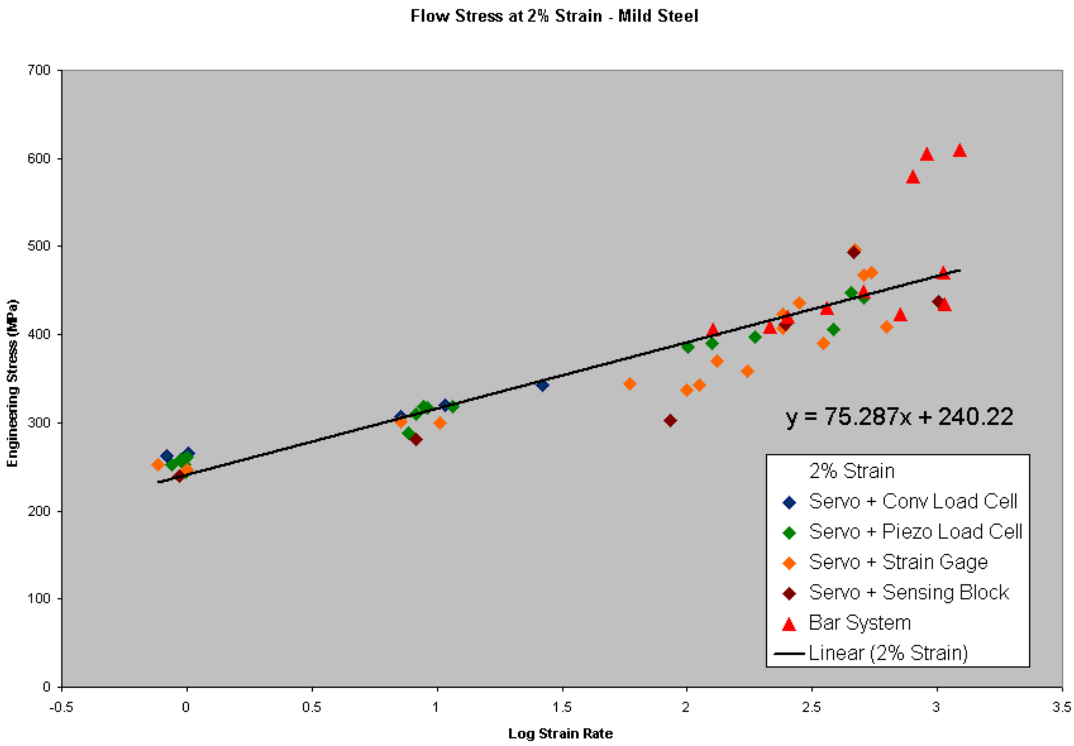


Figure 51: Flow stress at 2% strain for mild steel

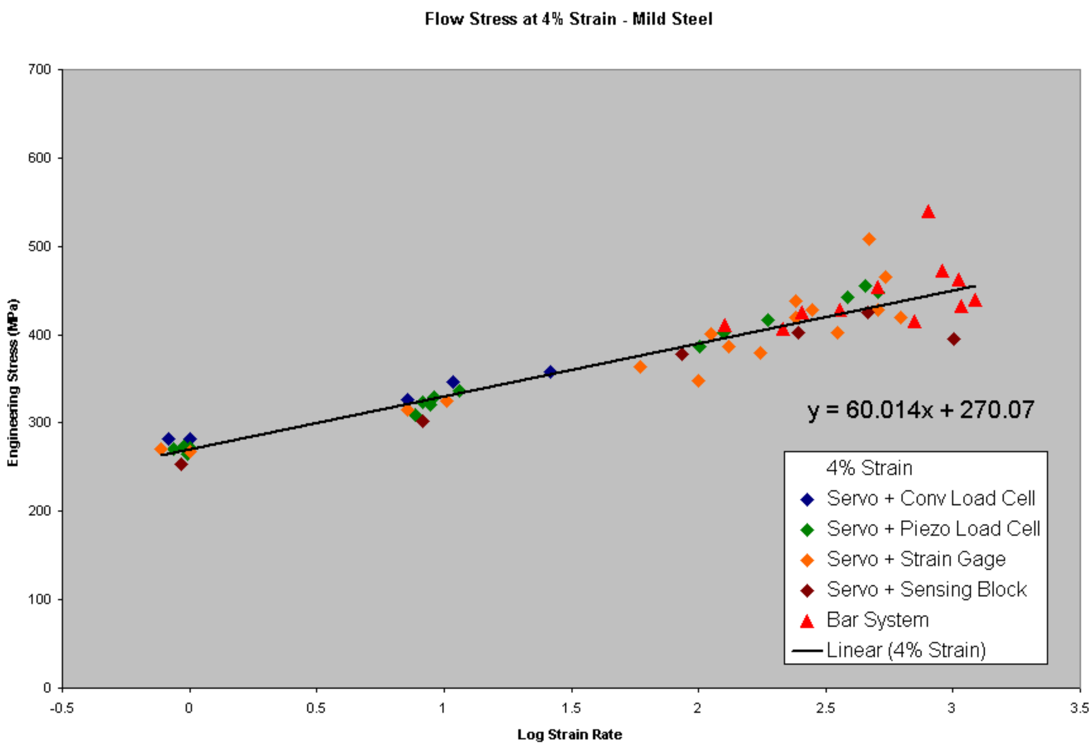


Figure 52: Flow stress at 4% strain for mild steel

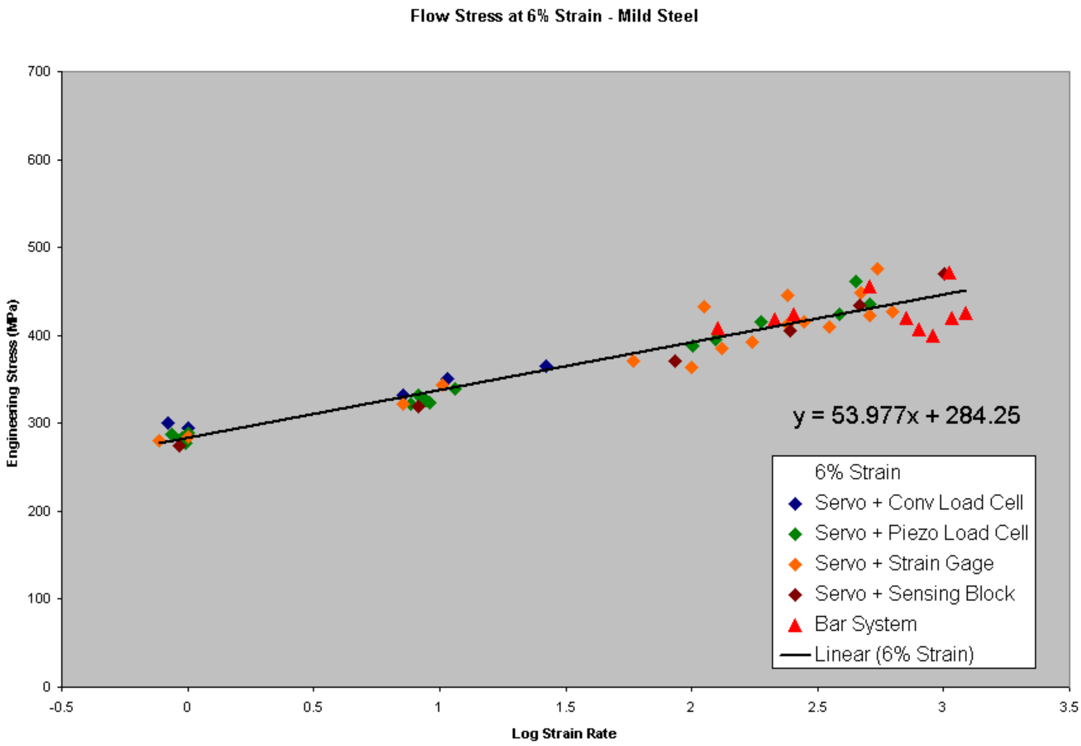


Figure 53: Flow stress at 6% strain for mild steel

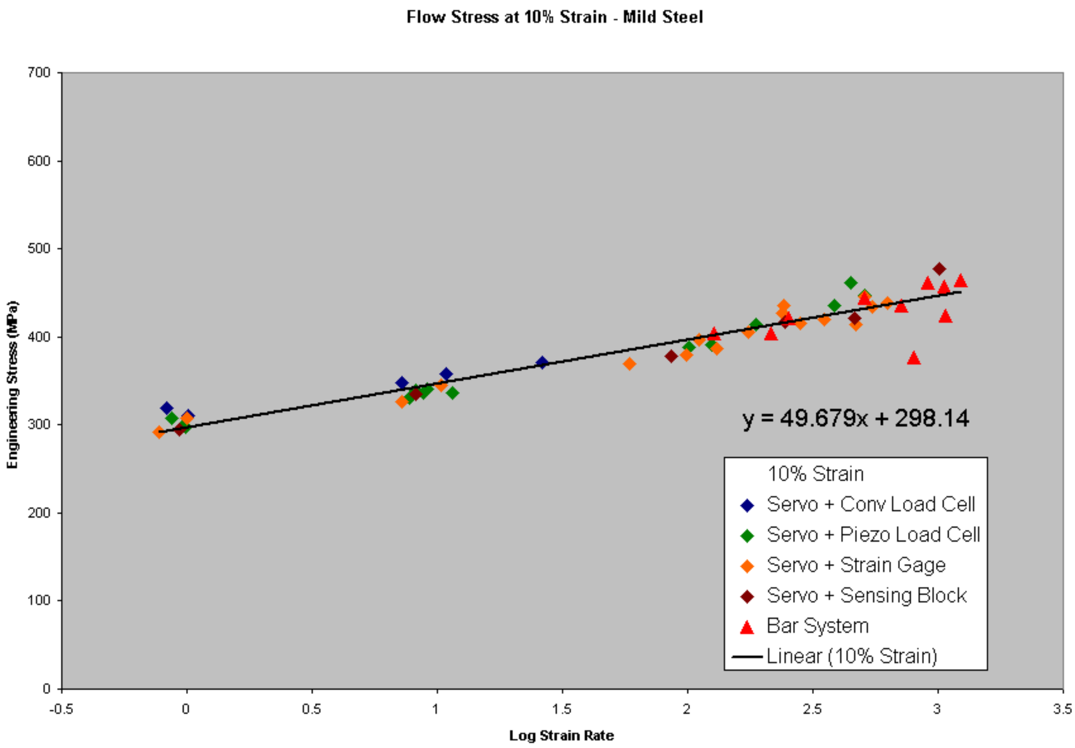


Figure 54: Flow stress at 10% strain for mild steel

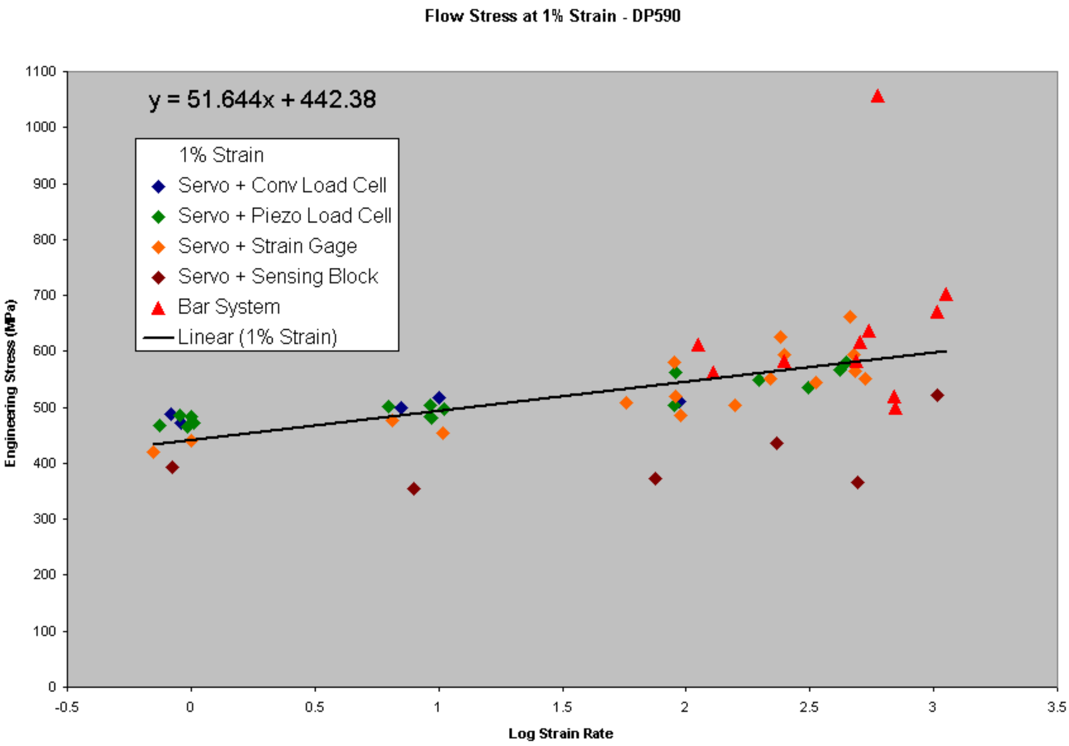


Figure 55: Flow stress at 1% strain for DP590

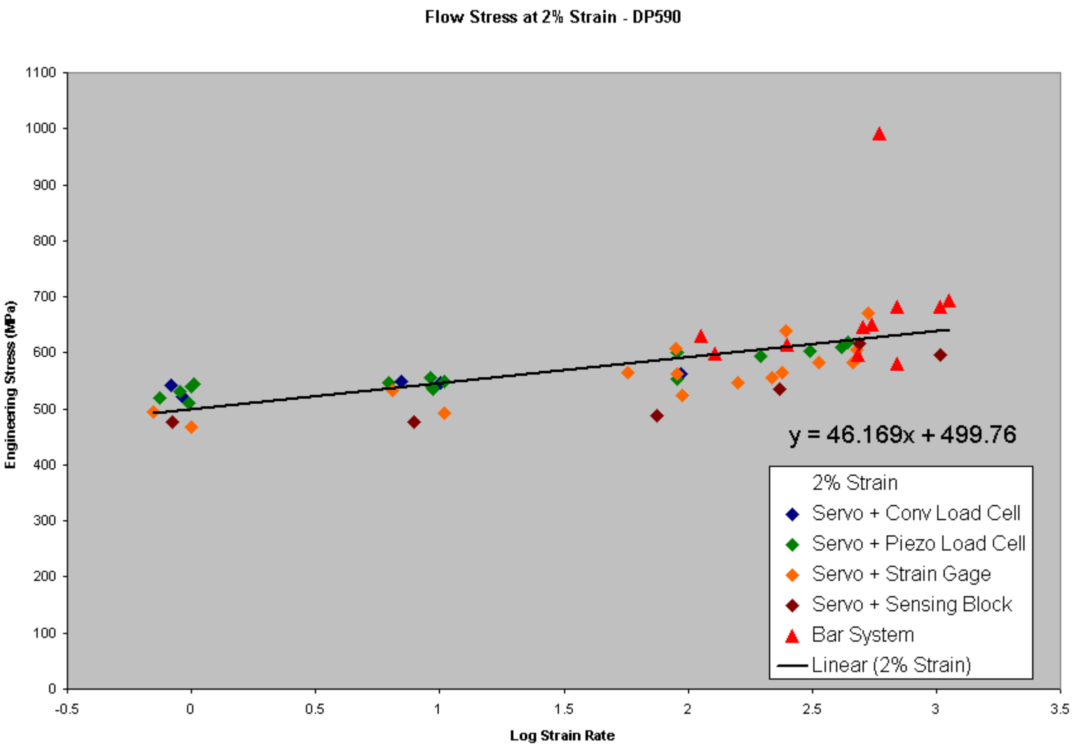


Figure 56: Flow stress at 2% strain for DP590

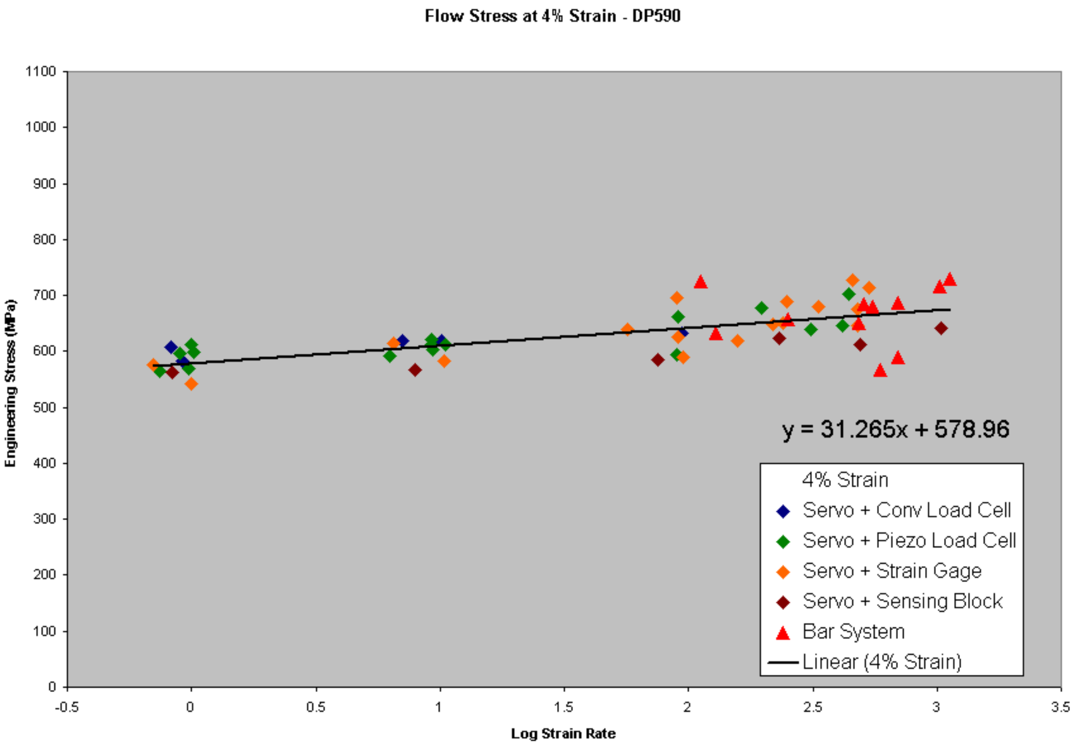


Figure 57: Flow stress at 4% strain for DP590

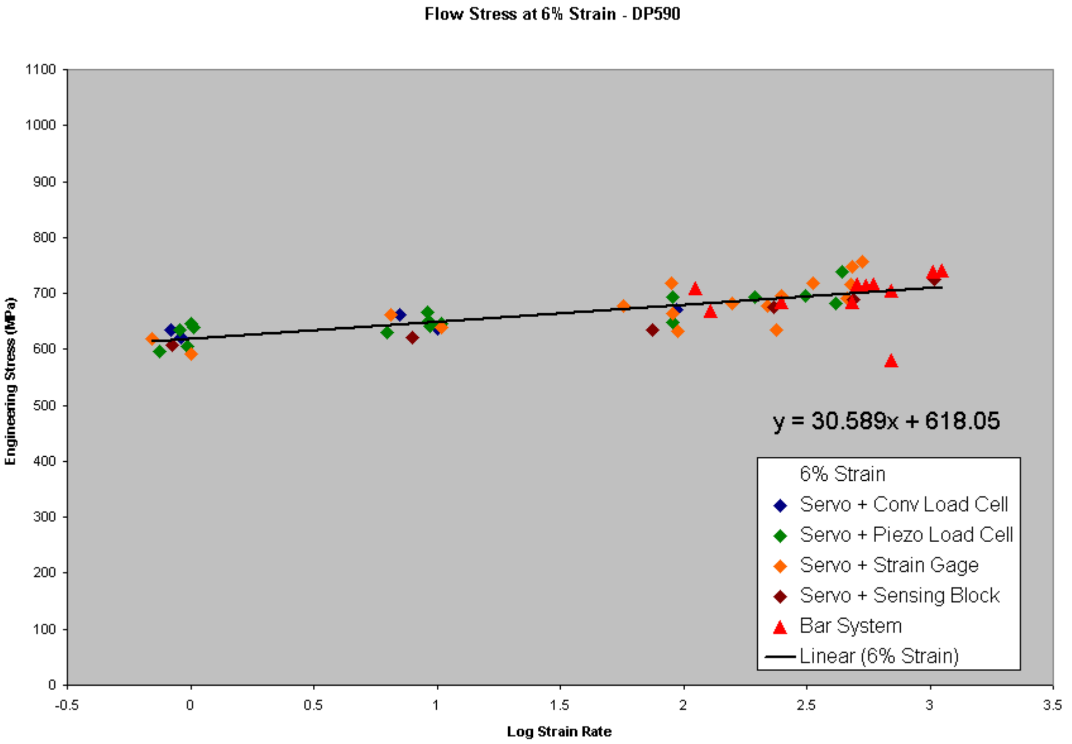


Figure 58: Flow stress at 6% strain for DP590

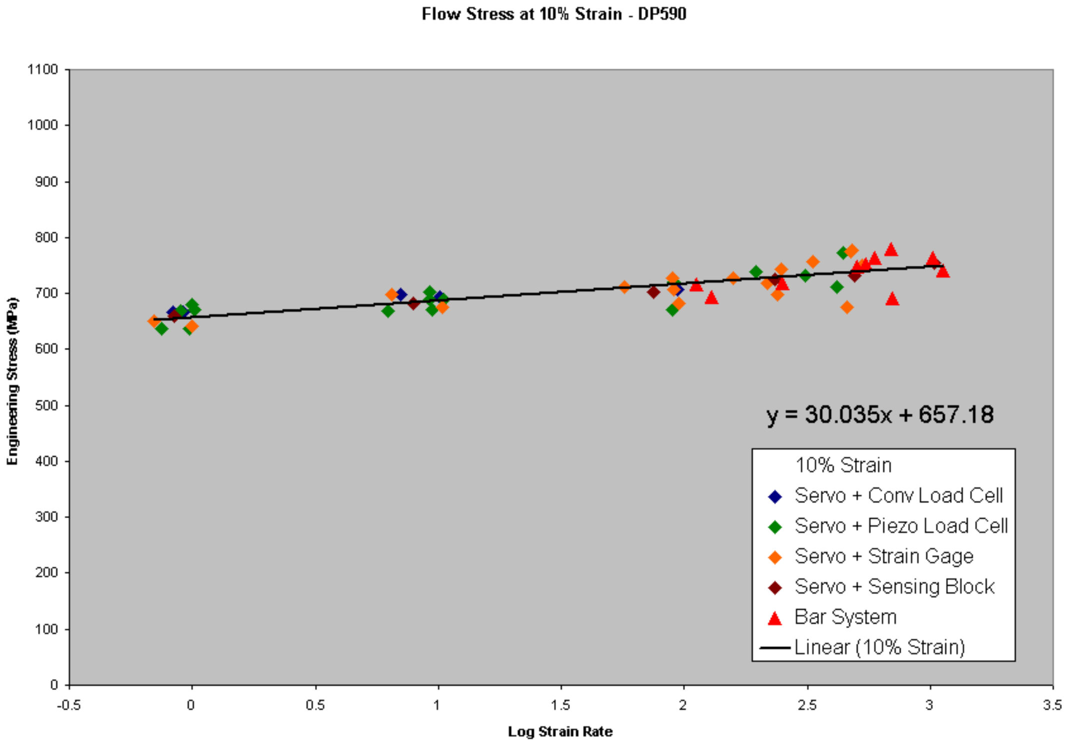
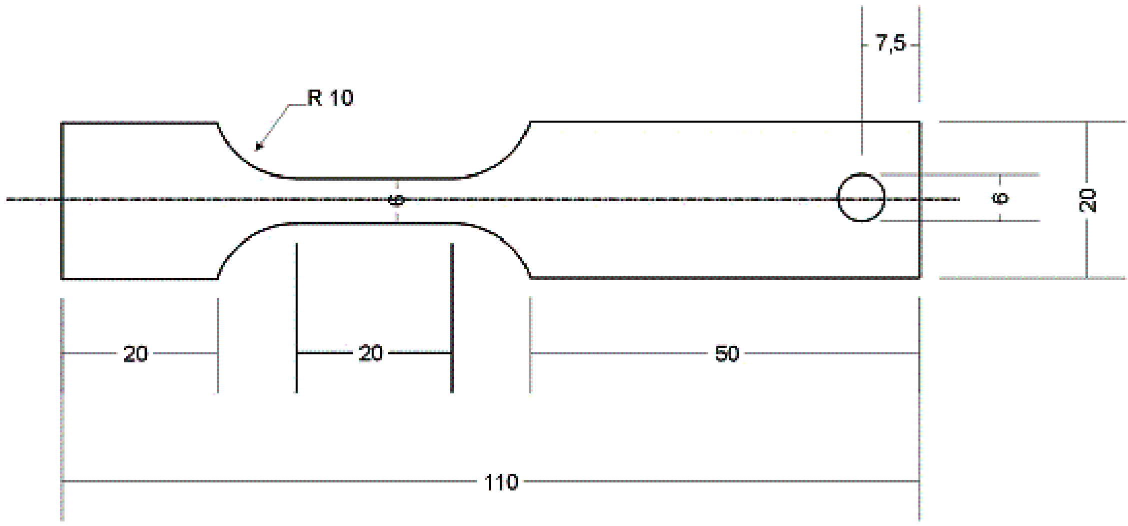


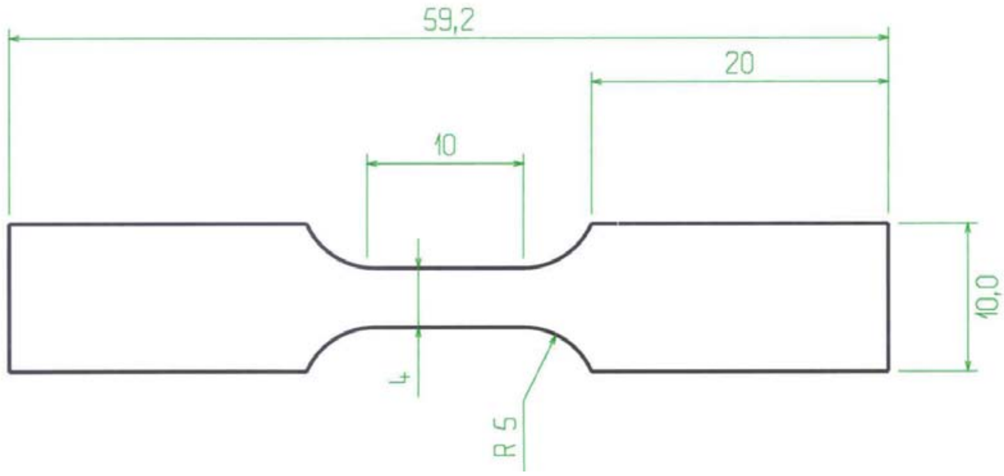
Figure 59: Flow stress at 10% strain for DP590

Appendix A: High Strain Rate Specimen Geometry

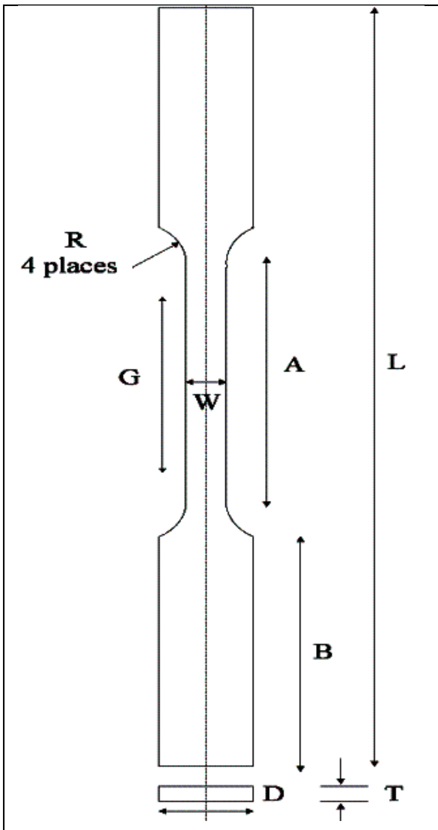
Lab A



Lab B



Lab C



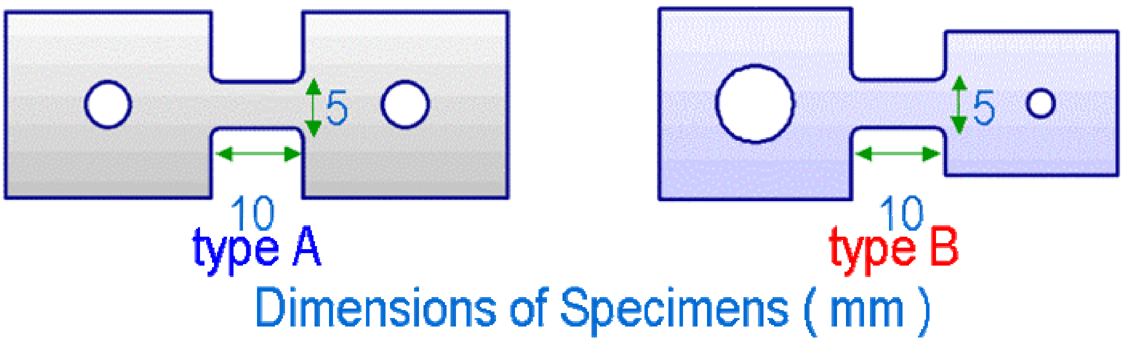
Symbol	Region	Dimension	Notes
A	Length of Reduced Section	1 ¼ in.	
B	Length of “Short” Grip Section	2.5 in.	
D	Width of Grip Section	0.575 +/- 0.005 in.	5,6
G	Gage Length	1.000 +/- 0.003 in.	
L	Overall Length	6 in.	
R	Radius of Fillet	0.25 in.	4
T	Thickness	Thickness of Material	3

Notes:

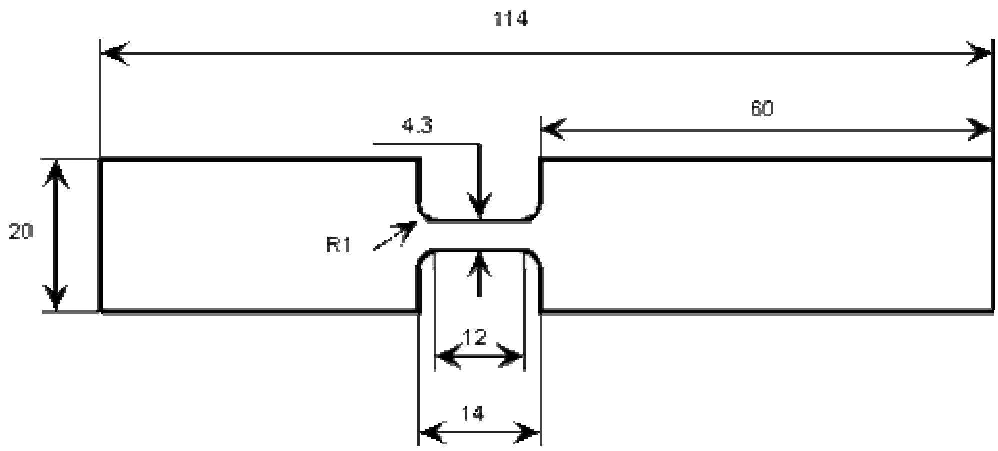
1. The ends of the reduced section shall not differ in width by more than 0.001 in. Also, there may be a gradual decrease in width from the ends to the center, but the width at each end shall not be more than 0.003 in. larger than the width at the center.
2. The edges of the reduced section shall be machined parallel over the gage length of the sample within a tolerance of 0.0005 in.
3. The material surface may be left in the as-received condition.
4. The radii of the fillets shall be equal to each other within a tolerance of 0.05 in. and the centers of curvature of the two fillets at a particular end shall be located across from each other on a line perpendicular to the centerline within a tolerance of 0.10 in.
5. Grip section edges shall be machined parallel within a tolerance of 0.05 in. Final grip section width shall be at least 0.555.
6. The ends of the specimen shall be symmetrical in width with the centerline of the reduced section within 0.005 in.

Lab D

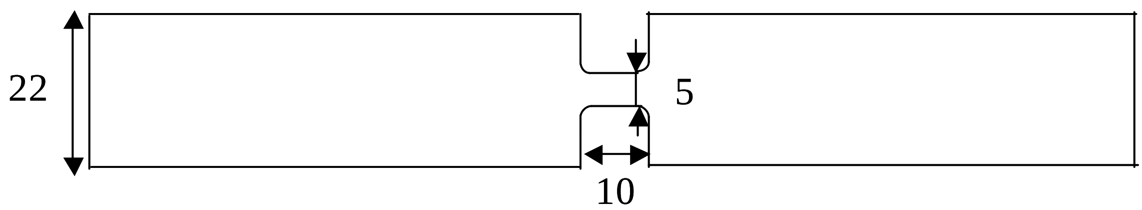
Strain rate	Test method	Test specimen
10^{-3}/~ 10^{1}/sec.	High-Speed Machine	type A
10^{2}/sec.	One Bar Method	type B



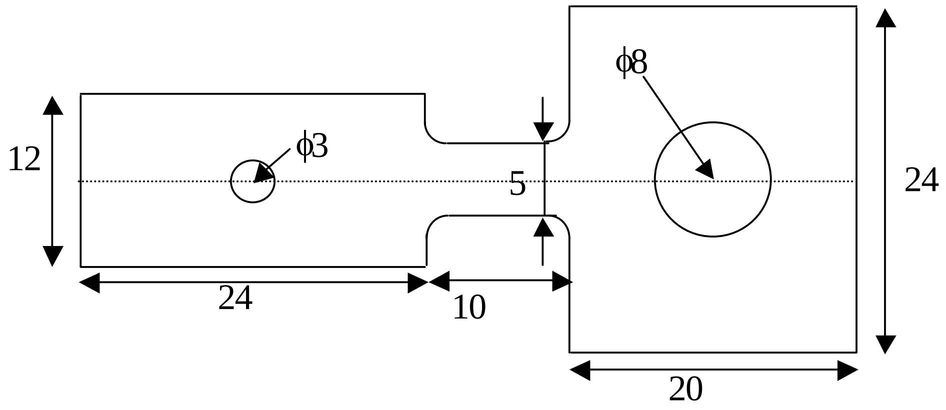
Lab E



Lab F

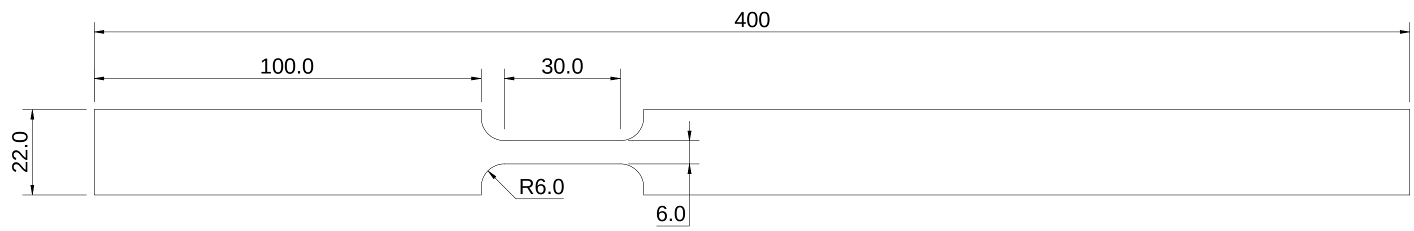


Conventional load frame and Servo-hydraulic system

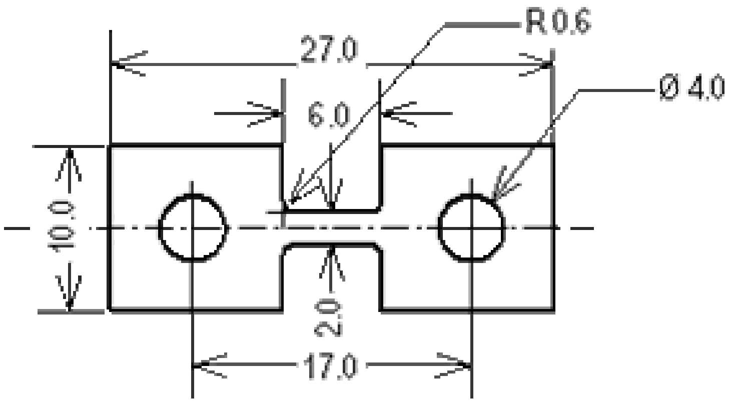


Bar system (one bar method)

Lab G



Lab H



Lab I