Defence Research and Development Canada | Recherche et développement pour la défense Canada

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Torsional Hopkinson Testing

AlgoTuf 400F

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Contract number: W7701-103636/001/QCN

Contract Scientific Authority:
G. Toussaint, (418) 844-4000 ext 4469

Defence R&D Canada – Valcartier
Contract Report
DRDC Valcartier CR 2011-060
June 2012

Canada

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Defence Scientist, Weapons Effects and Protection Section

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Professor

Abstract

This report gives the results obtained when testing high strength steel (AlgoTuf 400F) at high strain rates using a torsion Hopkinson bar constructed at the University of Manitoba. Defence Research and Development Canada – Valcartier supplied the plate in which the specimens were machined through the thickness. Each specimen was machined with thin walls and two hexagonal ends. The specimens were tested with different angles of twists, which controlled the applied strain rate. Three specimens were tested at each angle of twist. The specimens were tested at the following angles of twist: 1.5°, 4°, 8° and 10° at room temperature and the 10° angle of twist was also tested at 200°C and at 500°C. Using a calculating procedure given in the report, shear stress – strain curves were obtained for all specimens and were presented. Also, an Excel spreadsheet was provided for each specimen tested.

Résumé

Ce rapport présente les résultats obtenus en testant un acier à haute résistance (AlgoTuf 400F) à haut taux de déformation en utilisant la barre de torsion de Hopkinson fabriquée à l'Université du Manitoba. Recherche et développement pour la défense Canada – Valcartier a fournit la plaque dans laquelle les échantillons ont été machinés à travers l'épaisseur. Chaque échantillon était machiné avec des parois minces et deux bouts hexagonaux. Les échantillons ont été testés à différents angles de torsion, lesquels contrôlaient le taux de déformation appliqué. Trois échantillons ont été testés pour chaque angle de torsion. Les échantillons ont été testés aux angles de torsion suivants : 1.5°, 4°, 8° et 10° à la température de la pièce et l'angle de torsion de 10° a aussi été testé à 200°C et à 500°C. En utilisant la procédure de calcul expliquée dans ce rapport, les courbes de contrainte – déformation en cisaillement ont été obtenues pour tous les échantillons et sont présentées. Également, un fichier Excel a été fourni pour chaque échantillon testé.

Executive summary

The University of Manitoba possesses a capability for evaluating and testing materials at very high strain rates and large strains using either a direct impact Hopkinson bar or a torsion Hopkinson bar. Research funded earlier by Defence Research and Development Canada – Valcartier (DRDC Valcartier) has resulted in better understanding of the deformation process at high strain rates. The current contract provided testing of a minimum of 15 specimens of a steel plate (AlgoTuf 400F) supplied by DRDC Valcartier. An extra set was added for a total of 18 specimens tested. For each specimen tested, a shear stress-strain curve was obtained. The specimens were divided into six groups of three specimens and were tested at the following angles of twist: 1.5°, 4°, 8° and 10° at room temperature. The 10° angle of twist was also tested at 200°C and at 500°C. The shear stress-strain curves were calculated using a procedure which is explained in this report.

The results show some scattering which was expected in these tests due to geometrical factors (very thin walled specimens), machining (difficulty in machining consistently very thin walled specimens) and micro-structural factors that are due to competing mechanisms which occur at high strain rates. These mechanisms are strain hardening and thermal softening which occur due to a significant rise in the temperature of the specimen during testing resulting in the formation of adiabatic shear bands.

The results obtained in this contract may further be used to better characterize the AlgoTuf 400F at high strain rate. For example, when doing finite element analysis, properties for the material models have to be defined and experimental tests are required to determine the constants of these models. Therefore, the results obtained in this contract should allow determining some constants of a material model such as the Johnson-Cook constitutive model.

Bassim M. N. 2012. Torsional Hopkinson Testing: AlgoTuf 400F. 2011-060. DRDC Valcartier.

Sommaire

L'Université du Manitoba a les capacités d'évaluer et de tester des matériaux à haut taux de déformation et à de grandes déformations en utilisant soit la barre d'impact direct de Hopkinson ou la barre de torsion de Hopkinson. Des recherches subventionnées précédemment par Recherche et développement pour la défense Canada – Valcartier a permis de mieux comprendre le procédé de déformation à haut taux de déformation. Le contrat actuel consistait à tester un minimum de 15 échantillons d'une plaque d'acier (AlgoTuf 400F) fournie par RDDC Valcartier. Un groupe supplémentaire a été ajouté pour un total de 18 échantillons testés. Pour chaque échantillon testé, la courbe de contrainte/déformation en cisaillement a été obtenue. Les échantillons étaient divisés en six groupes de trois échantillons et ont été testés aux angles de torsion suivants: 1.5°, 4°, 8° et 10 ° à la température de la pièce. L'angle de torsion de 10° a aussi été testé à 200°C et à 500°C. Les courbes contrainte/déformation en cisaillement ont été calculées à partir d'une procédure qui est expliquée dans ce rapport.

Les résultats démontrent une certaine dispersion qui était prévisible dans ces tests du aux facteurs géométriques (échantillons à paroi très mince), l'usinage (difficulté de machiner avec constance des parois très minces) et les facteurs micro-structuraux qui sont dus aux mécanismes en compétition qui surviennent à haut taux de déformation. Ces mécanismes sont l'écrouissage et l'adoucissement thermique qui surviennent lorsqu'il y a augmentation significative de la température de l'échantillon durant le test résultant en la formation de bandes de cisaillement adiabatiques.

Les résultats obtenus dans ce contrat pourront être utilisés dans le futur pour mieux caractériser l'AlgoTuf 400F à haut taux de déformation. Par exemple, pour effectuer des analyses par éléments finis, les propriétés des modèles de matériaux doivent être définies et des tests expérimentaux sont requis pour déterminer les constantes de ces modèles. Ainsi, les résultats obtenus dans ce contrat devraient permettre de déterminer certaines constantes d'un modèle de matériau tel que le modèle constitutif de Johnson-Cook.

Bassim M.N. 2012. Torsional Hopkinson Testing: AlgoTuf 400F. 2011-060. RDDC Valcartier.

Table of contents

List of figures

Acknowledgements

We would like to thank the Department of National Defence for sponsoring this research. Also, we would like to thank the Scientific Authority, Mrs. Geneviève Toussaint for technical input and comments.

Prof. M. N. Bassim

1. Introduction

This project was carried out to evaluate the dynamic response using a torsion Hopkinson bar of a selected steel (AlgoTuf 400F) supplied by DRDC Valcartier. The objective was to obtain shear stress – shear strain curves for a minimum of 15 specimens. An extra set was added for a total of 18 specimens tested. These specimens (three in each group) were tested as a function of angle of twist ranging from 1.5°, 4°, 8° and 10° at room temperature and at 10° angle of twist at 200°C and 500°C.

2. Experimental Procedure

2.1 Torsion Hopkinson Bar and Specimens

A schematic layout of the torsion split Hopkinson bar (TSHB) used in this study is shown in figure 1 [1]. It consists of incident and transmitter bars supported by Teflon bushings such that they are co-axial and can rotate freely. The test specimens are thin-walled tubes with hexagonal flanges as shown in Fig. 2. The hexagonal flanges of the specimens are slotted into the matching sockets at the specimen ends of the two bars, providing the required gripping mechanism for the specimen during torsional loading. Multi-axial strain gages (rosettes) are attached to the bars at equidistance from the specimen, and such that overlapping of incident and transmitted waves are avoided.

The system employs stored-torque technique of loading, in which the loading torque is stored between the clamp and the loading arm using various angles of twist. The clamp is sufficiently tightened prior loading to prevent rotation of the incident bar as pure torsion load is applied by a hydraulic jack connected to a rotating wheel attached to the loading arm.

On reaching the desired angle of twist, the clamp is further tightened until the load release pin breaks and the stored torque is released and generate elastic waves, which travel along the incident bar and deform the specimen. The strain gages installed on the incident bar captures the incidence and reflected waves, while that attached to the transmitter bar captures the waves that transmit through the specimen. The pulse signal from the strain gages are amplified by the signal conditioner and recorded by a 20 MHz mixed-signal oscilloscope.

The strain rate, strain and shear stress were calculated from the elastic wave signals captured as incident, reflected and transmitted waves using the equations described in section 2.

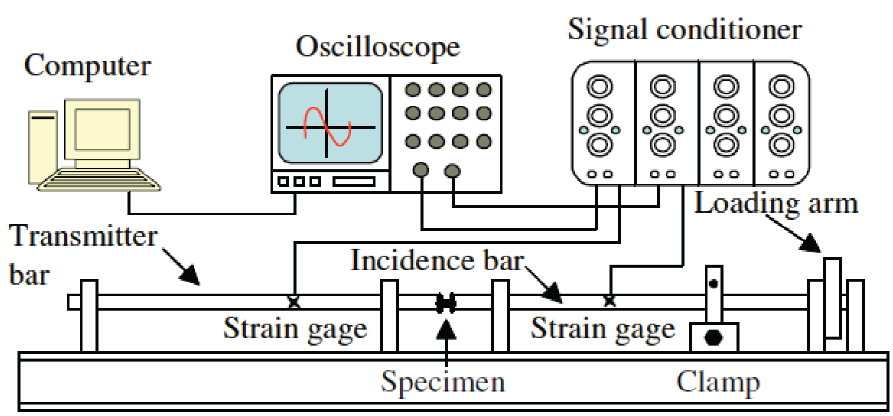


Figure 1. *Torsion Split Hopkinson Bar System [1]*

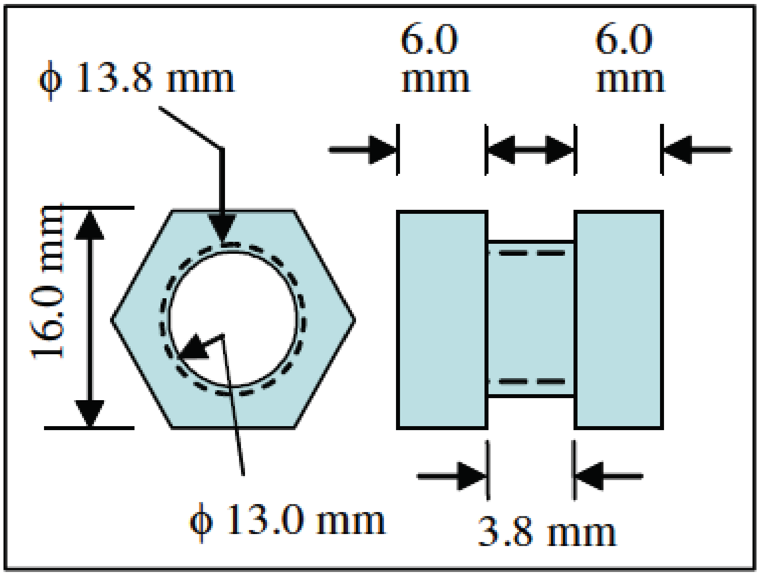


Figure 2. *Torsion test specimen [1]*

2.2 Calculation of Stress, Strain and Strain Rate

The calibration of the TSHB gives the mathematical relation between the shear strain and the voltage recorded by the strain gages. The equipment calibration involves placing of a solid hexagonal rod in between the incident and the transmitter bar. The end of the transmitter bar is fixed and the torque is applied at increasing angles of twist. The two strain gages record the corresponding voltage measurements. The mathematical relationship between the voltage measured by the strain gages and the corresponding value of shear strains on the bars is given by the linear plot of shear strain against the strength of signal voltage.

The corresponding maximum shear strain on the surface of the bar as the torque is applied is given by:

$$\gamma = \frac{c\phi}{L} \qquad 2.1$$

The shear strain in the specimen is given by equation 2.2:

$$\gamma_s = \frac{D_s\phi_2 - D_s\phi_1}{2L_s} \qquad 2.2$$

where ϕ_1 and ϕ_2 are the angles of twist in the incident and transmitter bars respectively. The mean diameter of the thin walled specimen is given by Ds and its length by Ls. The value of $\phi 2$ can be determined at the surface of the transmitter bar using the following equation.

$$\gamma_S = \frac{D}{2}\frac{\partial \phi_2}{\partial x} = \frac{D}{2C}\frac{\partial \phi_2}{\partial t} \quad 2.3$$

D is the diameter of the incident and transmitter bar

$$C = \sqrt{\frac{G}{\rho}} \quad 2.4$$

C is given by the velocity of wave propagation in the bar

$$\phi_2 = \frac{2C}{D}\int_0^t \gamma_T(t)dt \quad 2.5$$

Calculating the difference in strains due to the incident and reflected pulse gives the angle of twist in the incident bar ϕ_2.

$$\phi_1 = \frac{2C}{D}\int_0^t [\gamma_T(t) - \gamma_R(t)]dt \quad 2.6$$

Differentiating equation (2.2) and substituting equations (2.5) and (2.6) gives the following equation. The negative sign is due to the travel of reflected pulse in the opposite direction of the incident pulse.

$$\dot{\gamma}_S(t) = \frac{CD_s}{L_s D}[\gamma_T(t) - \{\gamma_I(t) - \gamma_R(t)\}] \quad 2.7$$

We also know that the total torque (T) stored in the bar before loading of the test specimen is

$$T = \frac{\phi J G}{L} \quad 2.8$$

The transmitted pulse is the difference between the incident and the reflected pulses for a state of homogeneous strain. Equation (2.8) reduces to:

$$\dot{\gamma}_{\mathrm{s}}(t) = \frac{2CD_{\mathrm{s}}}{L_{\mathrm{s}}D}\gamma_{\mathrm{R}}(t) \qquad 2.9$$

Integrating equation (2.7) gives the value of strain $\gamma_s t$ at time, t

$$\gamma_{\mathrm{s}}(t) = \int_0^t \frac{C}{L_{\mathrm{s}}}\frac{D_{\mathrm{s}}}{D}[\gamma_{\mathrm{T}}(t) - \{\gamma_{\mathrm{I}}(t) - \gamma_{\mathrm{R}}(t)\}]dt$$

2.10

Simplifying equation (2.10) shows

$$\gamma_{\mathrm{s}}(t) = \frac{CD_{\mathrm{s}}}{L_{\mathrm{s}}D}\sum[\gamma_{\mathrm{T}}(t) - \{\gamma_{\mathrm{I}}(t) - \gamma_{\mathrm{R}}(t)\}]\Delta t$$

.

2.11

The stress in thin-walled tube is given by the following equation based on Kolsky's work

$$\tau_{\mathrm{S}} = \frac{2Ts}{(\pi D_S^2)t_{\mathrm{s}}} \qquad 2.12$$

Where ts and Ts are wall thickness and average torque respectively. The average torque is calculated by:

$$T_{\mathrm{s}} = \frac{1}{2}(T_1 + T_2) \qquad 2.13$$

T_1 is given by the torque at the surface of the incident bar in terms of strain

$$T_1 = \frac{\pi G D^3(\gamma_I - \gamma_R)}{16}$$

2.14

T_2 is given by the torque at the surface of the transmitter bar in terms of strain

$$T_2 = \frac{\pi G D^3 \gamma_T}{16}$$

2.15

The stress in the thin-walled sample is given by equation (2.16) after substituting equation (2.13), (2.14) and (2.15).

$$\tau_{s(t)} = \frac{G D^3(\gamma_{I(t)} - \gamma_{R(t)} + \gamma_{T(t)})}{16 D_s^2 t_s} \quad 2.16$$

The transmitter pulse can be expressed as the difference between the incident and reflected pulses for a homogeneous state of strain. Equation (2.16) can be simplified to:

$$\tau_{s(t)} = \frac{G D^3}{8 D_s^2 t_s} \gamma_T \quad 2.17$$

Therefore, using equations (2.7), (2.11) and (2.16) can be used to determine strain rate, strain and stress respectively in a sample as a function of time.

2.3 Test Procedure

(a) Room temperature

The procedures below were followed when the specimens were tested using the torsion split Hopkinson bar at room temperature:

a. It was ensured that the jacking mechanism was at its lowest position and the pressure release valve of the hydraulic jack was closed
b. The clamp release applicator was loosen, the notch load release pin made from Aluminum 6061-T6 was inserted into the clamp and the pin was tightened
c. The load release applicator was then tightened with a wrench to sufficiently clamp the incident bar such that the incident bar does not rotate beyond the clamp when torque was applied at the loading end
d. The data acquisition system was then inspected, adjusted and zeroed to confirm proper connection and readiness to capture single event data
e. A torsional load was then applied on the incident bar up to the clamp using the hydraulic jack until the desired angle of twist was attained. This stores the applied torque in the clamped section of the bar
f. The specimen was then placed in the hexagonal socket and the transmitted bar was turned clockwise (looking down towards the clamp) until there is no further movement
g. The trigger was set on the data acquisition system to the desired trigger voltage
h. The loading pin at the bottom of the clamp was further tightened using a wrench until the fracture of the load release pin, thereby releasing the stored torque that generates the elastic waves that travels through the incident bar and deform the specimen at high strain rates
i. The elastic wave generated continues as incident wave at the incident bar until it reaches the specimen. This wave was captured by the strain gage on the incident bar as Incident wave
j. On reaching the specimen, the incident wave decomposes into Transmitted wave and Reflected wave
k. Partial energy from the incident wave is used in deforming the specimen and the strain gage at the transmitted bar captures the signal as Transmitted wave
l. The wave reflected back to the incident bar was captured by the strain gage as Reflected wave
m. These waves were then used in estimating the stress strain behavior of the specimens

(b) High temperature

Specimens that were tested at approximately 200^{O}C and 500^{O}C were heated in a horizontal tube furnace before testing. The steps followed in testing specimens at high temperatures were:

1. The horizontal tube furnace was heated to approximately 200 ^{O}C or 500 ^{O}C. A thermocouple was used to measure the approximate temperature of the furnace
2. Torsion specimens were placed in the furnace till specimens were heated to approximately 200 ^{O}C or 500 ^{O}C
3. Steps (a) to (e) for testing samples at room temperature were repeated. The trigger is set on the data acquisition system to the desired trigger voltage
4. The loading pin at the bottom of the clamp was further tightened using a wrench until the fracture of the load release pin, thereby releasing the stored torque that

generates the elastic waves that travels through the incident bar and deform the specimen at high strain rates

5. The elastic wave generated continues as incident wave at the incident bar until it reaches the specimen. This wave is captured by the strain gage on the incident bar as Incident wave
6. On reaching the specimen, the incident wave decomposes into Transmitted wave and Reflected wave
7. Partial energy from the incident wave is used in deforming the specimen and the strain gage at the transmitted bar captures the signal as Transmitted wave
8. The wave reflected back to the incident bar is captured by the strain gage as Reflected wave
9. These waves are then used in estimating the stress strain behavior of the specimens

3. Experimental Results

Results from all 18 tests performed at 1.5°, 4°, 8° and 10° angle of twist at room temperature and at 10° angle of twist at 200°C and 500°C are located in Appendix I. The appendix also includes Excel tables of the data obtained.

4. Observations and Conclusions

The torsion testing at high strain rates was conducted based on earlier work performed by Dr. N. Bassim to DRDC Valcartier [2]. The method of calculation of the shear stress, shear strain and strain rates are also included in the report and based on an approach in [3,4].

The following observations are made:

1. Torsion Hopkinson bar testing can be performed from strain rates of 10^2 s^{-1} to about 10^4 s^{-1}.

2. At the lower end of the strain rate, at 10^{-2} s^{-1}, the results may not be as accurate due to loss of resolution in the strain gages attached to the incident and transmitter bar.

3. There are variations in stress-strain curves among specimens tested at a given angle of twist. This is due to geometrical differences in the specimens in terms of the diameters of the thin wall, accuracy and difficulty of machining of the thin walls, and microstructural in terms of presence of flaws and discontinuities which trigger the formation of localized adiabatic shear bands which account for the competing deformation mechanisms of strain hardening and thermal softening which occur during testing in the torsion Hopkinson bar.

This report describes the testing of AlgoTuf 400F steel and presents the results obtained at 1.5°, 4°, 8° and 10° angle of twist at room temperature and at 10° angle of twist at 200°C and 500°C.

5. References

1. F. Yazdani, M.N. Bassim, A.G. Odeshi, The formation of adiabatic shear bands in copper during torsion at high strain rates, Procedia Engineering 1 (2009) 225-228.
2. M. Nabil Bassim, "Understanding of High Strain Rate in Armour Materials" CR 2010 final report, Contract W7701-063941/001/QCA (2011).
3. M. N. Ghaznafar, High Strain Rate Studies of Armor Materials, MSc Thesis, University of Manitoba (2010) 42-45.
4. Mechanical Testing and Evaluation. Vol. 8, in ASM Handbook, 505 - 515. American Society for Metals International, (2000) 505-515.

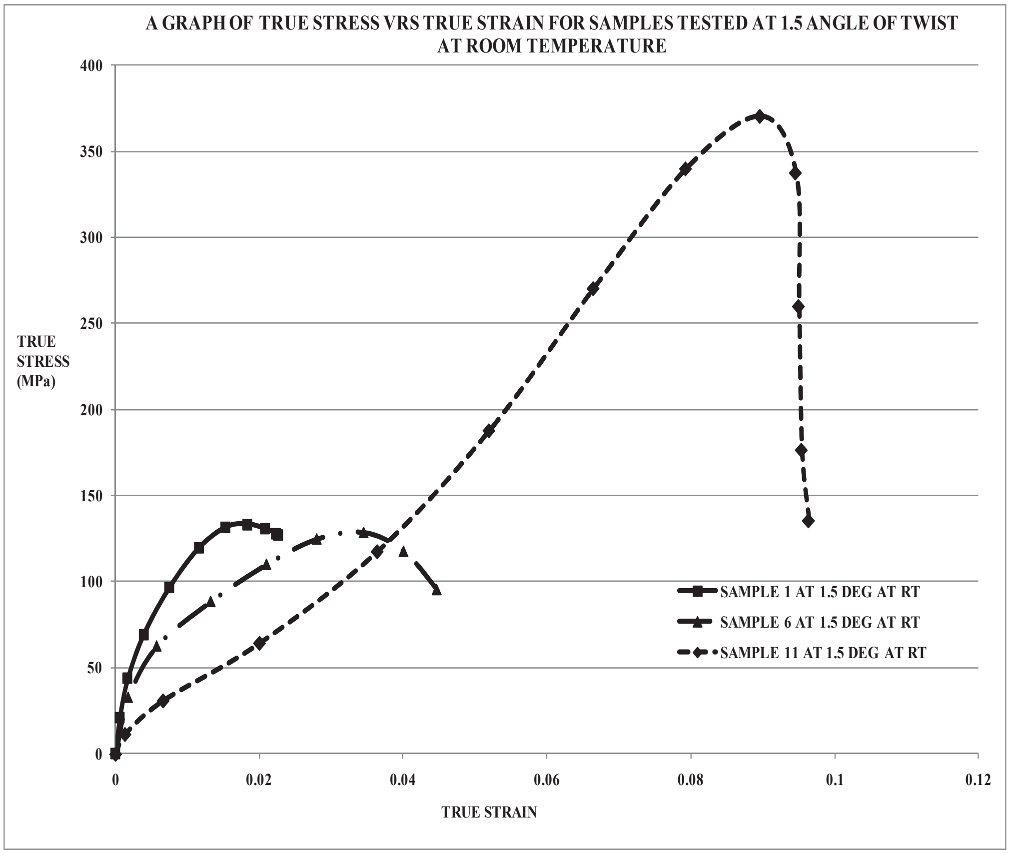
Annex 1: Testing results for all 18 specimens and corresponding Excel files

(A) ROOM TEMPERATURE TESTING OF TORSION SPECIMENS

(A.1) 1.5^{O} ANGLE OF TWIST AT ROOM TEMPERATURE

SAMPLE 11 AT 1.5 DEG			SAMPLE 1 AT 1.5 DEG			SAMPLE 6 AT 1.5 DEG	
STRAIN	STRESS		STRAIN	STRESS		STRAIN	STRESS
0	0		0	0		0	0
0.001302794	11.4972		0.000599619	21.2675		0.001787553	32.6348
0.006606941	31.0157		0.001698921	43.7165		0.005755276	62.3955
0.020016548	64.4379		0.003928754	69.4148		0.013266473	88.2622
0.036388331	117.646		0.00750773	96.5899		0.02102701	109.771
0.051936233	187.877		0.011580143	119.334		0.028017819	124.42
0.066433337	270.407		0.015340254	131.445		0.034542823	128.221
0.079287575	340.014		0.018338349	133.217		0.040085974	117.281
0.089632863	370.495		0.020768055	130.559		0.044702476	95.1229
0.094573695	337.608		0.022342055	127.753			
0.095003678	260.069		0.022685587	126.94			
0.095398798	176.603						
0.096387821	135.627						

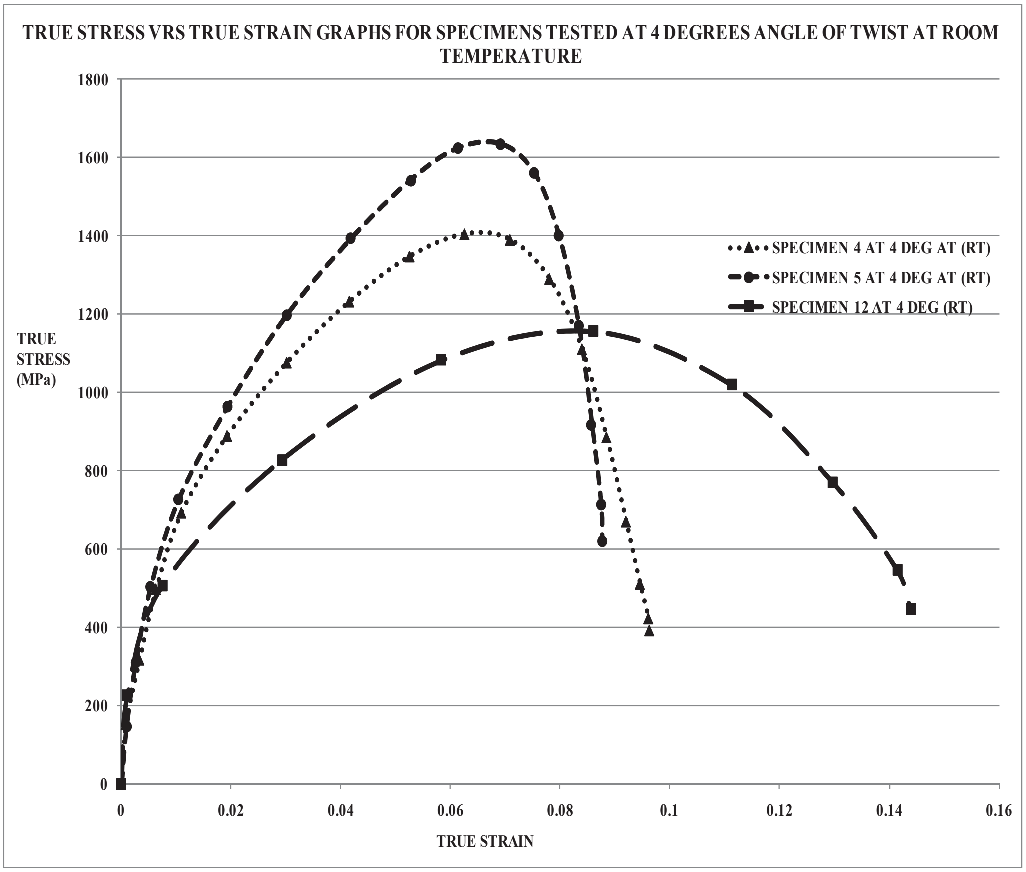
SPECIMEN	ANGLE OF TWIST	STRAIN RATE (S^{-1})	REMARKS
1	1.5°	98	DID NOT BREAK
6	1.5°	190	DID NOT BREAK
11	1.5°	332	DID NOT BREAK


A GRAPH OF TRUE STRESS VRS TRUE STRAIN FOR SAMPLES TESTED AT 1.5 ANGLE OF TWIST AT ROOM TEMPERATURE
TRUE STRESS (MPa)
400
350
300
250
200
150
100
50
0
0
0.02
0.04
0.06
0.08
0.1
0.12
TRUE STRAIN
SAMPLE 1 AT 1.5 DEG AT RT
SAMPLE 6 AT 1.5 DEG AT RT
SAMPLE 11 AT 1.5 DEG AT RT

(A.2) 4^{O} ANGLE OF TWIST AT ROOM TEMPERATURE

SPECIMEN 12 AT 4 DEGREES			SPECIMEN 4 AT 4 DEGREES			SPECIMEN 5 AT 4 DEGREES	
STRAIN	STRESS		STRAIN	STRESS		STRAIN	STRESS
0	0		0	0		0	0
0.001097345	226.866		0.000818865	152.464		0.000902021	146.829
0.007574087	508.021		0.003308579	317.455		0.002608211	311.367
0.029308799	828.479		0.006305457	497.571		0.005302386	502.561
0.05835051	1082.21		0.010955001	693.371		0.010431623	726.373
0.086145602	1156.48		0.019294959	889.634		0.019344533	962.835
0.111362334	1019.34		0.030177879	1076.71		0.030088313	1196.68
0.129723589	770.938		0.041599133	1232.7		0.041891715	1393.29
0.14148967	546.641		0.052583356	1347.86		0.052715972	1542.38
0.143946514	446.156		0.062593838	1404.93		0.061274963	1623.25
			0.070886066	1390.55		0.069116361	1634.09
			0.078068183	1290.7		0.075186639	1560.54
			0.084023625	1110.86		0.079679066	1401.79
			0.088491993	885.737		0.083337755	1170.83
			0.092056752	670.543		0.085731053	918.606
			0.094597117	511.305		0.087401271	713.836
			0.096131921	422.871		0.087586309	620.78
			0.096312124	392.248			

SPECIMEN	ANGLE OF TWIST	STRAIN RATE (S^{-1})	REMARKS
4	4°	472	DID NOT BREAK
5	4°	447	DID NOT BREAK
12	4°	640	DID NOT BREAK

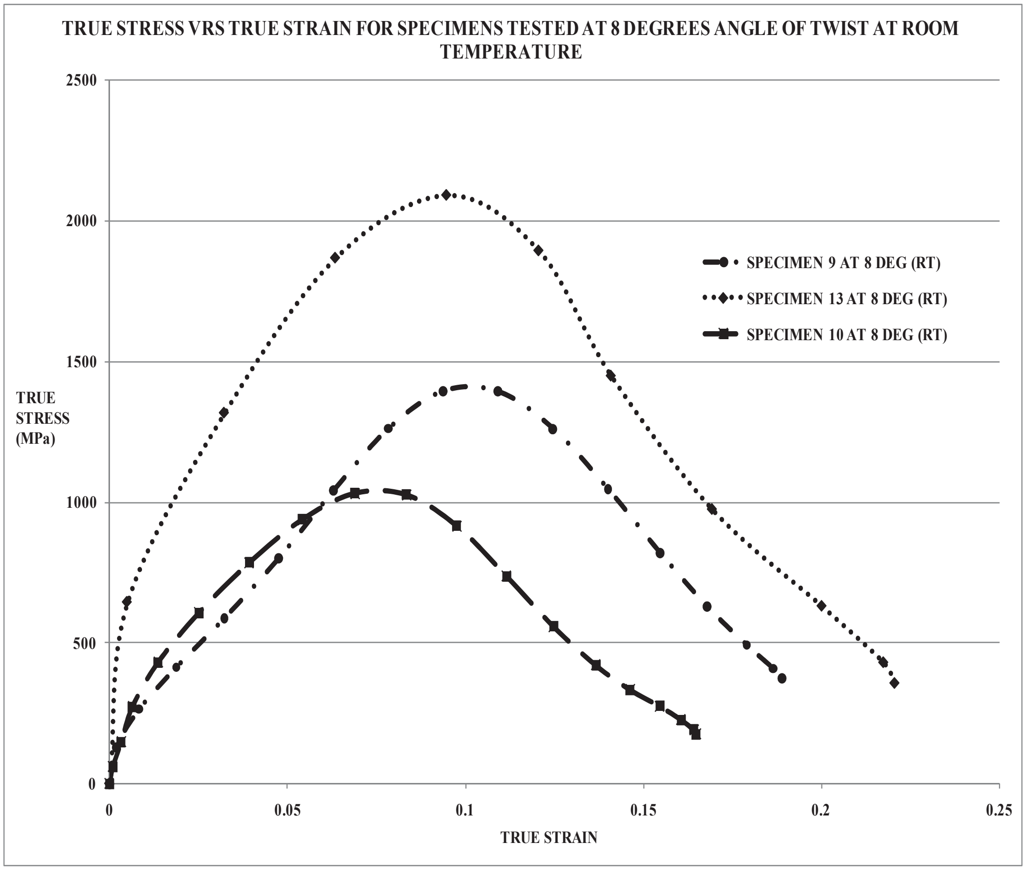


TRUE STRESS VRS TRUE STRAIN GRAPHS FOR SPECIMENS TESTED AT 4 DEGREES ANGLE OF TWIST AT ROOM TEMPERATURE
TRUE STRESS (MPa)
TRUE STRAIN
0
200
400
600
800
1000
1200
1400
1600
1800
0
0.02
0.04
0.06
0.08
0.1
0.12
0.14
0.16
SPECIMEN 4 AT 4 DEG AT (RT)
SPECIMEN 5 AT 4 DEG AT (RT)
SPECIMEN 12 AT 4 DEG (RT)

(A.3) 8° ANGLE OF TWIST AT ROOM TEMPERATURE

SPECIMEN 9 AT 8 DEG			SPECIMEN 13 AT 8 DEG			SPECIMEN 10 AT 8 DEG	
STRAIN	STRESS		STRAIN	STRESS		STRAIN	STRESS
0	0		0	0		0	0
0.001820862	128.573		0.004959292	644.446		0.000901151	61.3673
0.008278717	264.877		0.032238849	1316.26		0.003237128	148.818
0.018764818	414.544		0.063473427	1866.53		0.00640885	274.679
0.032283579	589.028		0.094714274	2089.48		0.013582982	431.268
0.047483914	800.93		0.120604024	1892.47		0.025070758	607.152
0.062909957	1041.47		0.14095336	1447.79		0.039230704	784.644
0.078336001	1261.48		0.169353161	974.129		0.054186582	938.464
0.093762045	1394.54		0.200177756	630.713		0.068973416	1031.36
0.109188088	1392.73		0.217527443	430.256		0.083488198	1025.56
0.124610966	1260.91		0.220661245	356.709		0.097595693	915.596
0.140033844	1047					0.111521188	738.015
0.154702673	820.211					0.124832751	557.844
0.167980213	629.022					0.136641553	421.353
0.17908171	492.718					0.146284371	334.17
0.186531985	408.817					0.154698691	275.304
0.188884671	375.266					0.160589348	228.229
						0.16415319	192.633
						0.164848643	176.665

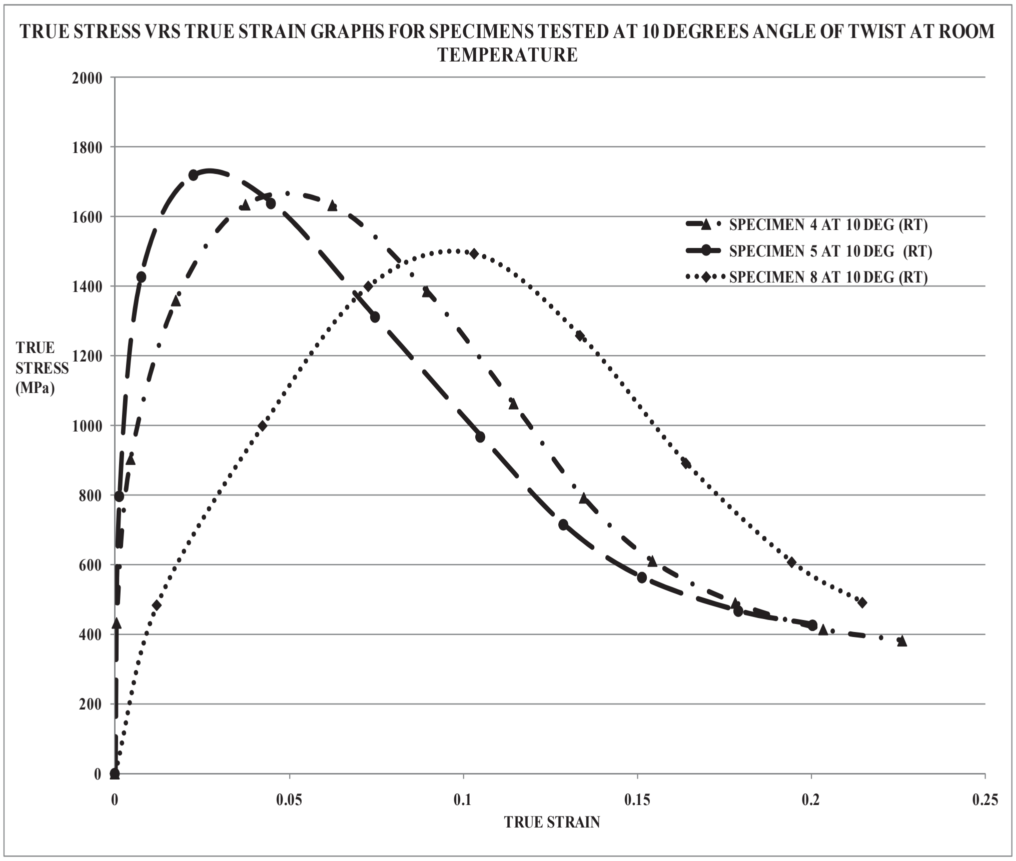
SPECIMEN	ANGLE OF TWIST	STRAIN RATE (S^{-1})	REMARKS
9	8°	927	DID NOT BREAK
10	8°	742	DID NOT BREAK
13	8°	882	DID NOT BREAK


TRUE STRESS VRS TRUE STRAIN FOR SPECIMENS TESTED AT 8 DEGREES ANGLE OF TWIST AT ROOM TEMPERATURE
2500
2000
1500
1000
500
0
TRUE STRESS (MPa)
SPECIMEN 9 AT 8 DEG (RT)
SPECIMEN 13 AT 8 DEG (RT)
SPECIMEN 10 AT 8 DEG (RT)
0
0.05
0.1
0.15
0.2
0.25
TRUE STRAIN

(A.4) 10^{O} ANGLE OF TWIST AT ROOM TEMPERATURE

SPECIMEN 4 AT 10 DEG (RT)			SPECIMEN 5 AT 10 DEG (RT)			SPECIMEN 8 AT 10 DEG (RT)	
STRAIN	STRESS		STRAIN	STRESS		STRAIN	STRESS
0	0		0	0		0	0
0.000529044	433.273		0.001190982	797.659		0.012055177	484.223
0.00454169	904.351		0.007406082	1428.29		0.042424007	999.932
0.017553502	1360.46		0.022478432	1718.35		0.07280416	1400.91
0.037549961	1635.77		0.044853287	1640.22		0.103203188	1494.65
0.062480907	1634.27		0.074621471	1311.55		0.133595924	1258.91
0.089661721	1386.66		0.105027292	969.179		0.163994951	891.928
0.114504544	1063.81		0.128866225	714.144		0.194400269	607.611
0.134665371	792.805		0.151216818	563.503		0.21469313	491.466
0.154379863	611.261		0.178998217	466.63			
0.17815362	490.637		0.200382245	427.51			
0.203407588	414.323						
0.226089119	382.015						

SPECIMEN	ANGLE OF TWIST	STRAIN RATE (S^{-1})	REMARKS
4	10°	1496	BROKE
5	10°	1518	BROKE
8	10°	1048	DID NOT BREAK

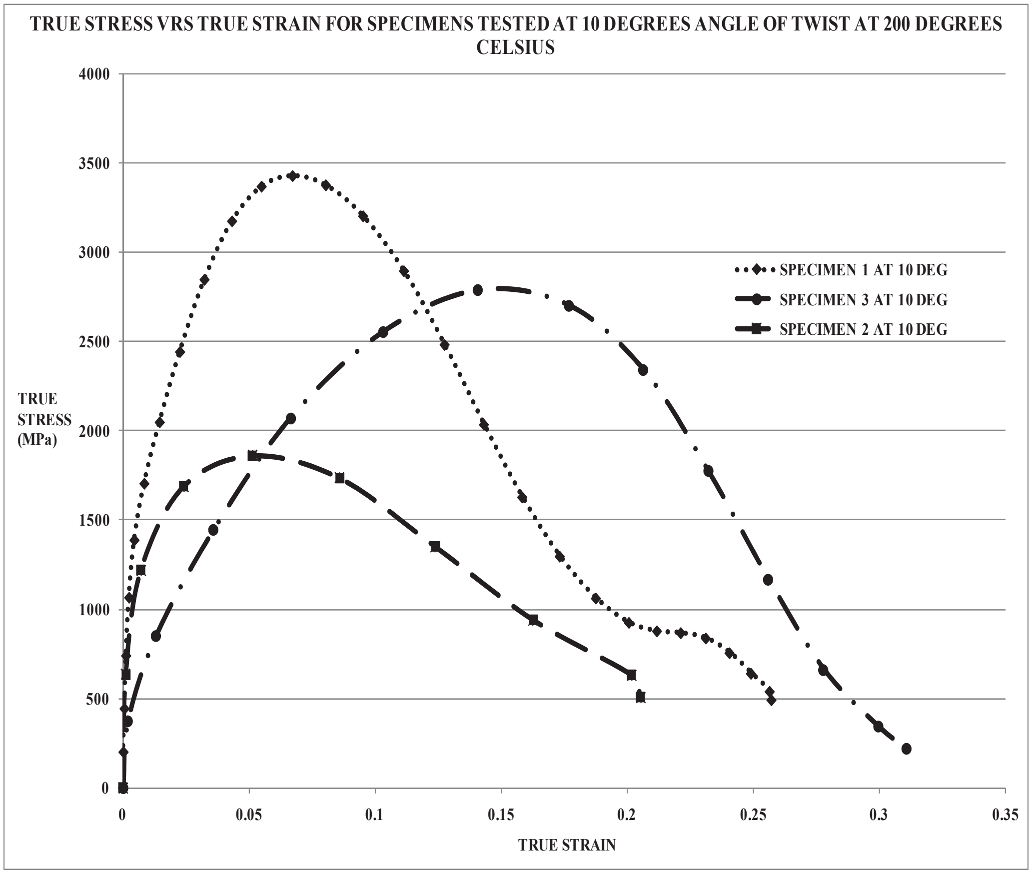

TRUE STRESS VRS TRUE STRAIN GRAPHS FOR SPECIMENS TESTED AT 10 DEGREES ANGLE OF TWIST AT ROOM TEMPERATURE
TRUE STRESS (MPa)
TRUE STRAIN
0
200
400
600
800
1000
1200
1400
1600
1800
2000
0.05
0.1
0.15
0.2
0.25
SPECIMEN 4 AT 10 DEG (RT)
SPECIMEN 5 AT 10 DEG (RT)
SPECIMEN 8 AT 10 DEG (RT)

(B) HIGH TEMPERATURE TESTING OF TORSION SPECIMENS

(B.1) TORSION SPECIMENS TESTED AT APPROXIMATELY 200^{O}C AT 10^{O} ANGLE OF TWIST

SPECIMEN 1 AT 10 DEG			SPECIMEN 2 AT 10 DEG			SPECIMEN 3 AT 10 DEG	
STRAIN	STRESS		STRAIN	STRESS		STRAIN	STRESS
0	0		0	0		0	0
0.000101482	201.381		0.001162605	635.404		0.001957182	372.146
0.000543975	444.581		0.007152597	1218.96		0.013128109	851.646
0.001172145	740.803		0.024118002	1689.03		0.035944843	1445.21
0.002360886	1066.9		0.051477304	1860.99		0.066460316	2071.12
0.004464609	1389.01		0.085998561	1735.98		0.103134569	2553.02
0.008398555	1705.64		0.123893204	1352.32		0.140938892	2786.18
0.014503648	2049.41		0.162702022	941.008		0.176753117	2701.11
0.022543557	2443.7		0.201718219	631.515		0.206547566	2337.83
0.032281953	2848.46		0.205341099	507.445		0.232058859	1774.46
0.043232429	3176.04					0.255956814	1169.16
0.054959667	3370.21					0.277962791	662.458
0.067277731	3429.7					0.299657842	342.611
0.080466952	3377.92					0.310903198	217.734
0.095283776	3204.17						
0.111454618	2896.5						
0.127615346	2483.53						
0.143259328	2036.21						
0.158450962	1628.97						
0.173348782	1297.15						
0.187719743	1062.17						
0.200851566	925.755						
0.211943979	878.459						
0.221425816	868.253						
0.231413941	838.133						
0.240767327	755.738						
0.249276526	640.735						
0.256701924	539.795						
0.257421203	492.313						

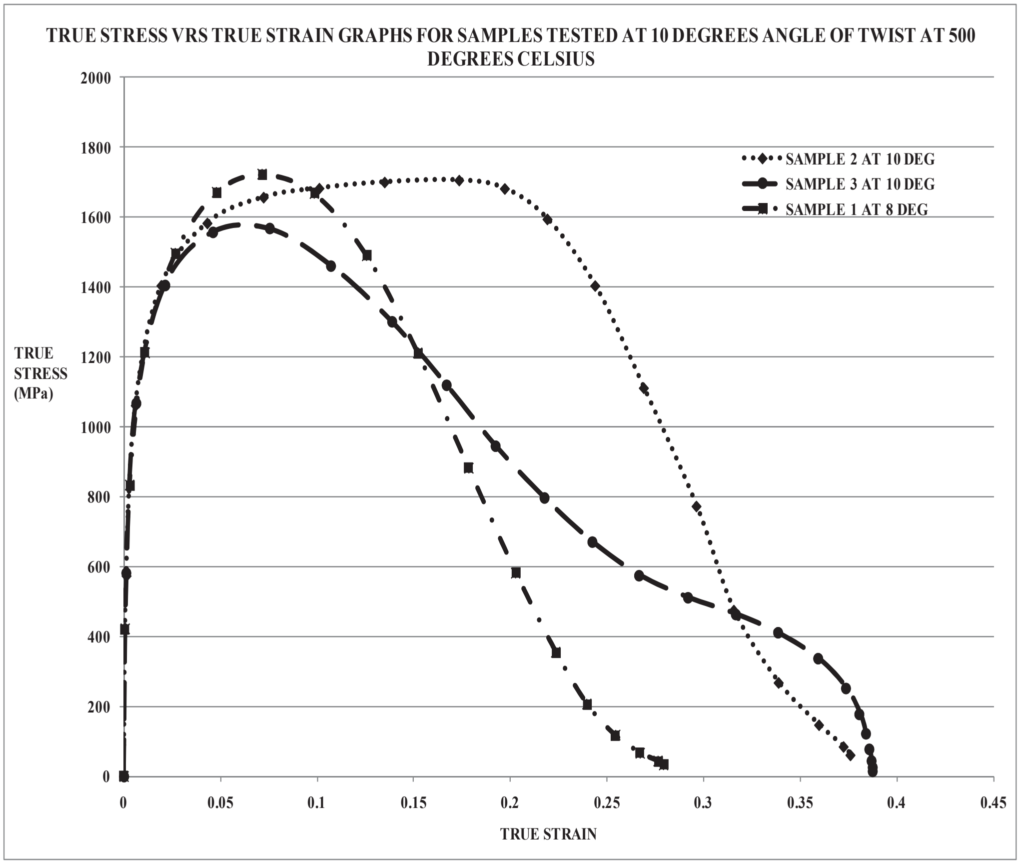
SPECIMEN	ANGLE OF TWIST	STRAIN RATE (S^{-1})	REMARKS
1	10°	1828	BROKE
2	10°	1986	BROKE
3	10°	1966	BROKE


TRUE STRESS VRS TRUE STRAIN FOR SPECIMENS TESTED AT 10 DEGREES ANGLE OF TWIST AT 200 DEGREES CELSIUS
TRUE STRESS (MPa)
TRUE STRAIN
0
500
1000
1500
2000
2500
3000
3500
4000
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
SPECIMEN 1 AT 10 DEG
SPECIMEN 3 AT 10 DEG
SPECIMEN 2 AT 10 DEG

(B.2) TORSION SPECIMENS TESTED AT APPROXIMATELY 500^{O}C AT 8^{O} AND 10^{O} ANGLES OF TWIST

SAMPLE 1 AT 8 DEG			SAMPLE 2 AT 10 DEG			SAMPLE 3 AT 10 DEG	
STRAIN	STRESS		STRAIN	STRESS		STRAIN	STRESS
0	0		0	0		0	0
0.0006464	421.715		0.001275067	573.986		0.001461609	580.723
0.003023711	833.424		0.006009832	1061.98		0.006221794	1067.61
0.01088614	1213.95		0.019309792	1405.23		0.021283931	1405.98
0.026634869	1495.93		0.043155357	1583.8		0.045941925	1557.47
0.047984329	1671.85		0.07229844	1657.69		0.075741379	1566.82
0.071705015	1722.88		0.101138442	1683.68		0.10721531	1461.85
0.098655673	1668.35		0.134960363	1701.13		0.138757852	1301.01
0.125704001	1491.26		0.173522911	1706.65		0.167326637	1117.71
0.152215925	1211.95		0.197164415	1682.61		0.19226579	946.334
0.178392557	883.783		0.219202895	1595.37		0.217642193	797.227
0.202972458	582.129		0.243908909	1404.7		0.242418856	671.38
0.223700481	354.847		0.26910353	1111.83		0.266757948	575.952
0.239753765	206.272		0.296365382	773.385		0.291803134	512.134
0.254295819	117.226		0.315680877	475.354		0.316467366	464.817
0.266924103	68.0346		0.338889067	268.121		0.338614124	409.945
0.27665131	42.8551		0.359819944	147.057		0.359542368	335.988
0.279540218	34.5176		0.372544475	84.6558		0.373648598	253.482
			0.376065962	60.7546		0.380864043	178.929
						0.383937596	120.677
						0.385874039	77.5358
						0.386673534	45.3286
						0.38737931	24.2548
						0.38744776	15.2089

SPECIMEN	ANGLE OF TWIST	STRAIN RATE (S^{-1})	REMARKS
1	8°	1355	DID NOT BREAK
2	10°	1700	DID NOT BREAK
3	10°	1384	DID NOT BREAK


TRUE STRESS VRS TRUE STRAIN GRAPHS FOR SAMPLES TESTED AT 10 DEGREES ANGLE OF TWIST AT 500 DEGREES CELSIUS
TRUE STRESS (MPa)
2000
1800
1600
1400
1200
1000
800
600
400
200
0
0
0.05
0.1
0.15
0.2
0.25
0.3
0.35
0.4
0.45
TRUE STRAIN
SAMPLE 2 AT 10 DEG
SAMPLE 3 AT 10 DEG
SAMPLE 1 AT 8 DEG

List of acronyms

DND	Department of National Defence
DRDC	Defence Research and Development Canada
SHB	Split Hopkinson Bar
TSHB	Torsion Split Hopkinson Bar
ASB	Adiabatic Shear Band

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This report gives the results obtained when testing high strength steel (AlgoTuf 400F) at high strain rates using a torsion Hopkinson bar constructed at the University of Manitoba. Defence Research and Development Canada – Valcartier supplied the plate in which the specimens were machined through the thickness. Each specimen was machined with thin walls and two hexagonal ends. The specimens were tested with different angles of twists, which controlled the applied strain rate. Three specimens were tested at each angle of twist. The specimens were tested at the following angles of twist: 1.5°, 4°, 8° and 10° at room temperature and the 10° angle of twist was also tested at 200°C and at 500°C. Using a calculating procedure given in the report, shear stress – strain curves were obtained for all specimens and were presented. Also, an Excel spreadsheet was provided for each specimen tested.

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Torsion, Split Hopkinson Bar, Adiabatic Shear Band

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