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DETERMINATION OF THE TRANSVERSE PROPERTIES OF ESR 4340 STEEL.(U)
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DETERMINATION OF THE TRANSVERSE PROPERTIES OF ESR 4340 STEEL

SEPTEMBER 1980

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Final Report

Contract Number DAAG46-78-C-0045

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Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

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ABSTRACT

The results of the various tests (Double Ligament, Tensile, and Double Torsion) indicate that the differences between the longitudinal (X) and long transverse (Y) properties of heat 9060 (step-forged 1-7/8 and 1.0 inch plate portions) are at best minor in nature. The same is true with the 0.4 inch-thick cross-rolled ESR 4340 plate (heat 2780). The most significant property differences exist between X and Y direction properties on the one hand and those of through thickness (Z) direction on the other. On comparing the above results with data obtained for heat 9060 at other forging reductions, an increasing sensitivity of ductility (decrease) to increasing reduction is apparent in the Z direction. Scanning Electron Microscope work indicates that the degree of colonization present among the non-metallic inclusions present may be related to the range of ductility-related properties encountered in any particular orientation.

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FINAL REPORT

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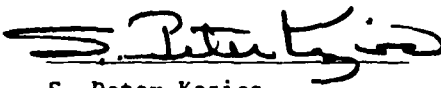
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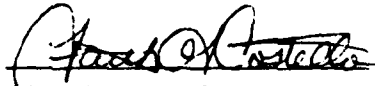
SUBJECT: Final Report
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Determination of the Transverse Properties of ESR
4340 Steel
Covering period from August 3, 1978 to June 20, 1980.

DATED: June 20, 1980


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PREFACE

The present writer (J. T. Berry) and his students would like to acknowledge the support received from AMMRC during the conduct of the present project. The counsel, cooperativeness and infinite patience of the present monitor, Mr. A. A. Anctil, are worthy of special note. The author must also acknowledge the provision of facilities at Georgia Tech by Dr. S. P. Kezios, Director of the School of Mechanical Engineering, and also the provision of certain specialized test facilities by the Lockheed Georgia Company.

The graduate students contributing to the actual test program were:

Mr. Rudy C. Stotz
Mr. Ravindra H. Ganatra
Mr. Pramod V. Lodhia

Mr. Stotz was responsible for performing the double ligament tests and supervising the tensile testing. He also undertook the scanning electron microscopy (SEM) of the associated fracture surfaces. Mr. Ganatra was responsible for a significant portion of the double torsion and compact tension tests and associated SEM work. He was assisted in these tests by Mr. Lodhia. Early preparatory aspects of test sample production and testing equipment readiness involved two further graduate students, Mr. M. K. Eid and Mr. Hamidi-Sakr.

Finally, special mention should be made of the invaluable cooperative tests conducted by Mr. Oppenheimer, who also supplied so many helpful practical suggestions to the undersigned and his students regarding testing technique, of Messrs. Harry Vaughan and Virgil McCollum who had the arduous task of producing the many specimens involved, and lastly of the incredible efforts of Mrs. Rebecca Rees in the production of the various interim and final report documents.

1. INTRODUCTION

The present investigation was oriented towards the determination of the transverse and short transverse mechanical properties of electroslog remelted AISI 4340 high strength steel ($H_{RC} \approx 58$) in the form of 0.4, 1.0 and 1-7/8 inch (10, 25 & 45 mm) plate.

The properties involved included conventional tensile properties determined using standard ASTM test bars, where such a procedure was feasible and the tensile properties observed using the double ligament test (DLT), which facilitates the evaluation of properties in the Z or through thickness direction in material as thin as 0.20 in. (5 mm) in section. Also included in the tests scheduled were fracture toughness determinations using the double torsion (DT) test, and where applicable the ASTM Compact Tension test.

Fractographic and other metallographic procedures were utilized to correlate the behavior of material in the above tests with microstructural variables.

The present report, which is the final report on this project, describes the results of these tests which were performed on material drawn from two sources:

Plate S-I (0.4 in. material)

Table I - Heat 2780

Plates S-II and -III (1.0 and 1.75 in. material)

Table II - Heat 9060

As will be seen from the tables, plate S-I and plates S-II and -III were drawn from different heats, although both heats were of electroslog remelted grade 4340. The tables also detail certain aspects of the mechanical processing of the plates.

II. SPECIMEN FABRICATION

All specimen fabrication and heat treatment, etc. were to be carried out by the investigating team or by organizations under their direction. No difficulties in machining the as-received mill-annealed 4340 plates were encountered and no problems materialized during heat treatment.

Prior to receiving the plates, a thorough investigation was performed with respect to fabricating and testing AISI 4340 steel DLT bars. Materials from previous ESR 4340 heats, in the form of Charpy bars from 3 x 3, 5 x 5,

and 7 x 7 inch forgings were furnished by AMMRC, together with details of the mechanical properties involved. DLT specimens (Fig. 1) were cut from the above Charpy bars and a study made of

- (a) grinding and slotting techniques
- (b) testing ramifications.

The DLT specimen blanks were marked on their ends with a carbide tipped scribe, assuring proper identification of number and orientation. Simultaneous surface grinding of six (6) blanks was undertaken to insure reproducible flatness and parallelism of surfaces, a 10 inch diameter, 60 grit alumina vitreous bonded wheels being employed on a surface grinder at approximately 1750 rpm. All surfaces were ground to about 0.001 inch oversize, at which point specimens were ground individually to size. Ends of the specimens were cut using a 6 inch diameter 0.015 thick rubber bonded alumina abrasive disc. Examination on a toolmaker's microscope indicated parallelism of sides within 0-25 μ in. and squareness of sides and ends between 0 and 0.007 and 0 and 0.0002 degrees respectively. The surface roughness was better than 25 μ in. Flatness was seen to be $\approx$ 187 μ in. These latter two measurements were made utilizing a Proficorder (TM) device.

The slotting of the DLT specimens represents a very critical operation. Consequently, a series of dummy slots were prepared utilizing the Charpy bar material referred to above. Previous experience in producing DLT bar slots had employed both high speed steel saws and abrasive discs. Clearly, with the current hardness levels abrasive wheel, EDM or ECM type techniques would appear necessary.

Preliminary tests were undertaken by slotting the above bar using the AL_2O_3 rubber bonded 0.015 inch thick wheel with heavy constraining flanges. Slots were produced as follows:

Slot #1	3450 rpm,	feed 12 ft/min.,	no coolant
Slot #2	3450 rpm,	feed 6 ft/min.,	no coolant
Slot #3	3450 rpm,	feed 6 ft/min.,	with coolant
Slot #4	3450 rpm,	feed 12 ft/min.,	with coolant

Taper sections were then taken of each ligament-like section produced between the above slots. Careful polishing and etching indicated that no burning was present. Microhardness traverses later confirmed this:

TABLE III
Microhardness Survey of Ligaments ESR 4340

<u>Location</u>	<u>Average Microhardness</u>	
	H_V	H_{RC}^*
Near Surface of Slot 1	580	54
Near Surface of Slot 2	575	53
Midway Between 1 & 2	535	51
Near Surface of Slot 3	585	54
Near Surface of Slot 4	560	53
Midway Between 3 & 4	525	51

*Equivalent, nearest whole number value.

Tests upon an unslotted Charpy bar section indicated a range of values between 49.8 and 54.1 H_{RC} .

From the above tests it was deemed that the structure of the ligament was not significantly damaged upon slotting. All subsequent bars were produced in this manner.

Fabrication of the DT and CT specimens and of the tensile bars from heat treated material followed normally accepted procedures which are well established. It should be noted the slotting, grooving and notching of the DT and CT specimens, although less critical than parallel operations on the small DLT bars, were conducted with utmost care to ensure that no grinding damage occurred.

III. PRELIMINARY TESTING

Certain preliminary tests were undertaken with the DLT and miniature DT specimens, since the applications of these techniques to a high hardness material represented a new departure.

The results of DL tests on specimens cut from broken Charpy bars drawn from previous heats of ESR 4340 and supplied to GIT by AMMRC indicated that specimen rotation within the clamping arrangement [1] might be a problem in testing. Consequently, all DLT bars fabricated from S-I, II and III were cut to a 1.00 inch length as opposed to the 0.75 in. length used previously (Fig. 1). Clamping bolts of a high strength steel were also utilized in the rig, along with

redesigned and specially fabricated clamps hardened to a level slightly above that of the specimens involved.

Turning to the preliminary tests with the miniature DT specimens, several methods were examined for pre-cracking [2] the specimens concerned. The most convenient technique was considered to be that of initiating a pre-crack by fatigue (as in CT testing) rather than by simple bending [2]. All subsequent DT tests had their initial pre-cracks formed this way, although K_Q values are reported for both fatigue pre-cracking and non-fatigue pre-cracking. In the latter case K_Q values were obtained by re-initiating an established crack which itself had been initiated by fatigue. Subsequently, the crack was again stopped and re-sharpened by fatiguing. In this way sequences of fatigue--non-fatigue initiated cracks could be propagated and the associated K_Q values reported on separately [2]. All subsequent DT tests both full scale and miniature were conducted in this fashion.

IV. SPECIMEN LOCATION

The small size of the DLT specimen permits location of the specimen at different depths below the surface of material of the thicknesses currently involved. Consequently, specimens were sampled near the surface and at the center of the sections concerned, as well as in all of the orientations agreed upon in the original proposal:

<u>Ligament Orientation</u>	<u>Code</u>
•Short transverse	TZ & LZ
•Transverse	LY
•Longitudinal	TX

The orientation codes utilized above correspond to those described in the ASME paper referred to previously [1] (Fig. 2).

The location of DT and CT tests followed a similar course; where possible both surface and center material being sampled, together with the various orientations which in this case followed the standard ASTM nomenclature [3].

<u>Applied Stress Orientation</u>	<u>Crack Plane Orientation</u>	<u>Code</u>
Long transverse	Longitudinal plane	T-L
Longitudinal	Transverse plane	L-T
Short transverse	Plane of plate	S-T

Figures 2 and 3 illustrate the orientations involved in DLT specimens and DT/CT specimens respectively.

V. RESULTS

The results of the mechanical property tests performed under the present contract are contained in Tables IV - XV. The tests were performed in conformance with existing ASTM codes where applicable or with practice established previously and described elsewhere [1,2]. (Note: The samples received from AMMRC were numbered SI, SII-1, SII-2, SIII-1 and SIII-2. The subdivision of SII and SIII arises only because two separate samples from each step were received at Georgia Tech.)

The results of the SEM examinations are also described in summary in the following section. (Detailed information is available in references 4 and 5).

VI. DISCUSSION AND CONCLUSIONS

Careful scrutiny of the summary tables describing both DLT and tensile bar data on one hand (Tables VII, VIII, and XV) and fracture toughness data on the other (Tables XI A and B, XII and XIV) indicates, not unexpectedly, that the differences between the longitudinal and transverse properties of heat 9060 (step forging) at various reductions are at best minor in nature. A similar restatement can be made with respect to the 0.4 in. thick cross rolled plate material drawn from heat 2780. It would appear from results of the SEM fractographic work as well as LM examination that the colonization of the relatively small volume fraction of non-metallic inclusions and the subsequent probability of locating such colonies within a particular testbar cross section should lead to a scatter of results (especially elongation and K_Q and in some cases UTS) within a particular orientation (X or Y) for a given forging reduction applied to a given ingot, of the same magnitude as the range of averages indicated. Referring to the DLT data this would appear to be substantiated on comparing the summary data (Table VII) with the ranges which may be seen in Tables IV to VI.

Regarding differences existing between center and surface properties, locations where only one set of DLT data is present* have to be ignored and only sets of data compared. When this is done the breadths of the individual ranges

*This situation arose because of limitation in the size of the portions of S-II and S-III supplied by AMMRC.

concerned again come in line with the above remarks regarding effects of orientation (X versus Y). [See Figures 4 (a) and (b)].

The strongest trend which may be discovered when examining the results in toto appears to be the marked difference existing between the X and Y direction ductility related properties on one hand and those of the through thickness (Z) direction on the other. This appears to be present with both the DLT results, and the K_Q data (plate S-III) generated using the miniature DT test. (Refer to Tables VII and XI B.)* When the AMMRC tensile and Charpy data (Tables VIII and IX) are also examined in this respect, it would appear that the expected sensitivity to forging reduction--that is, decreasing ductility with increasing reduction--is clearly present.

The results of the SEM fractography on the DLT bars reported upon by Stotz [4] were to be compared with those obtained on a selection of large scale and miniature DT and limited number of CT specimens, as reported on by Ganatra [5]. All of the specimens examined which were concerned with the fracture toughness testing showed mixtures of the principal types of fracture appearance seen in the DLT specimens sharing 'flat' or normal areas of rupture:

- equiaxed dimple rupture
- quasi-cleavage fracture
- markedly intergranular fracture (with respect to prior austenite grains).

Once again indications of inclusion colonization were present.

No trend could be established regarding the inter-relation of 'local' K_Q values in the DT test with approximate area fractions of a particular type of fracture appearance, possibly due to the 'averaging' effect of the long curved crack front present in this test. (Further test work in this area under rigidly controlled humidity conditions is desirable in the light of recent unpublished work at AMMRC [6].

It may be concluded then from the present results, that while the general scatter in ductility related properties (especially elongation and to some extent UTS) which is related to a particular orientation in a particular forging reduction is of the same general order of the ranges associated with orientation differences in the X and Y plane, a more marked difference exists upon comparing appropriate properties in those directions on one hand with those in the short transverse or Z direction on the other. These differences are more apparent at heavier reductions.

*See also Figure 5.

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1. Oppenheimer, E.D., R. G. Kumble and J. T. Berry, "The Double Ligament Tensile Test: Its Development and Application", Trans. ASME, Journal of Engineering Materials and Technology, April 1975, pp. 107-112.
2. Outwater, J.O., M. C. Murphy, R. G. Kumble and J. T. Berry, "Double Torsion Technique as a Universal Fracture Toughness Test Method", ASTM STP 559, 1974, pp. 127-138.
3. ASTM (1974) Standard Method of Test for Plane Strain Fracture Toughness of Metallic Materials. E 399-74, Part 10, ASTM Annual Standards, Reissued on ANSI/ASTM E 399-78.
4. Stotz, R. MS Project Report 1980, Georgia Institute of Technology, School of Mechanical Engineering.
5. Ganatra, R. MS Project Report 1980, Georgia Institute of Technology, School of Mechanical Engineering.
6. Private Communication from AMMRC via Mr. A. A. Anctil describing unpublished work (1980).

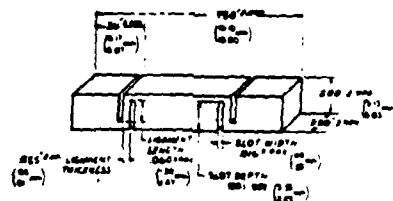


Fig. 1 Detail of double tensile ligament specimen

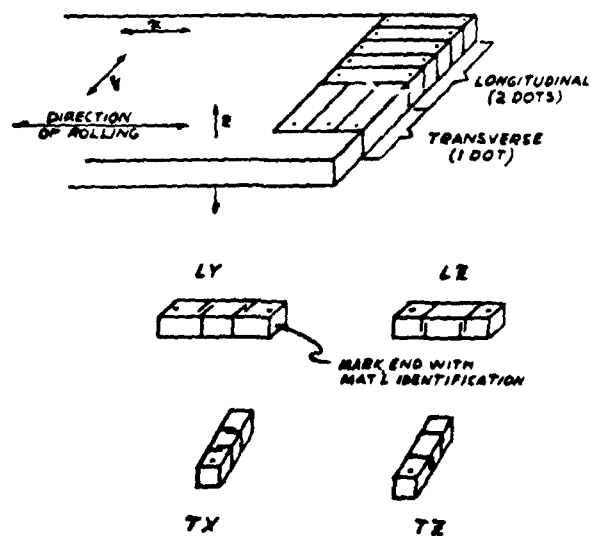


Fig. 2 Specimen identification and nomenclature (DLT specimen)

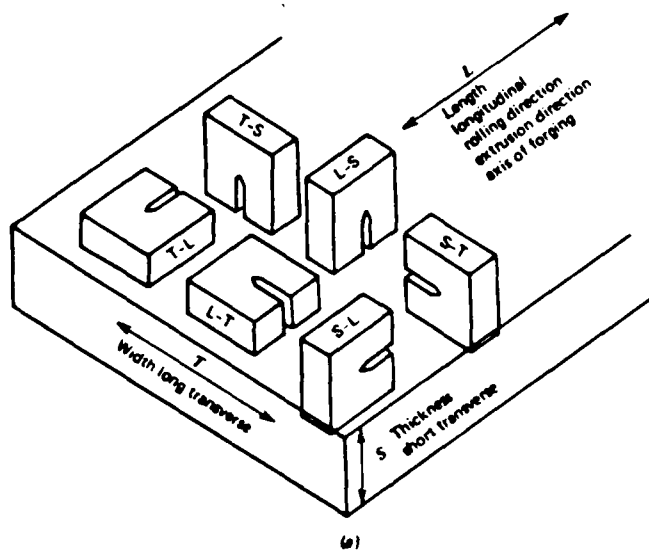
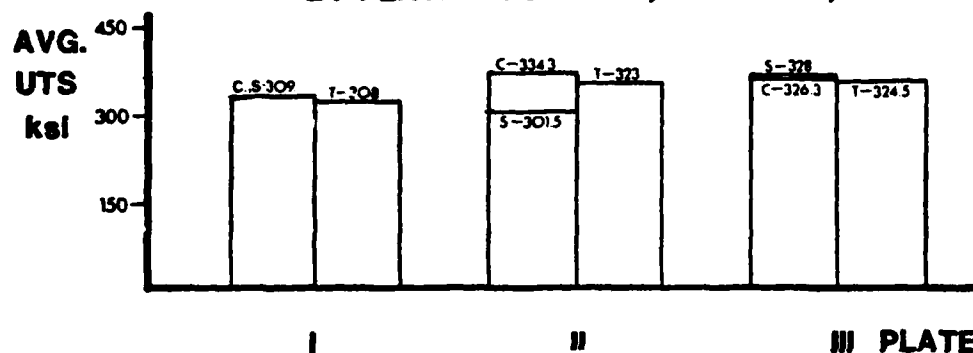
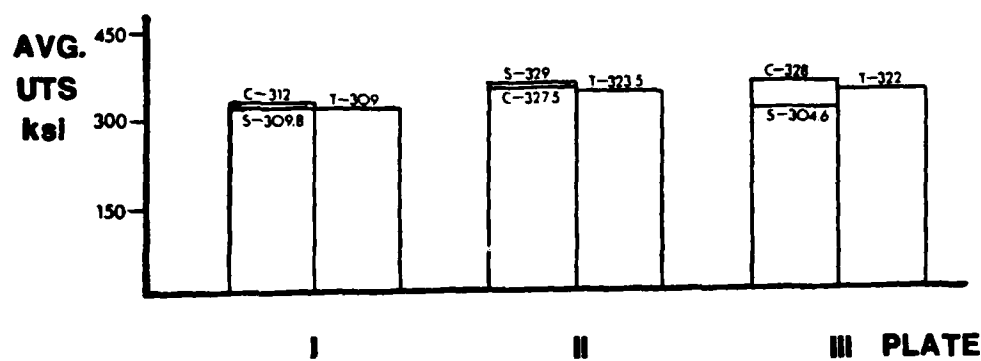


Fig. 3--Specimen orientation
CT and DT specimens.

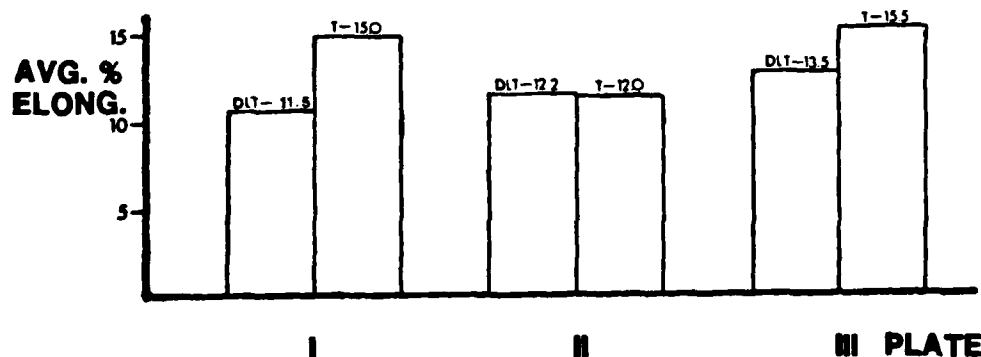
Fig. 4 (a) **AVG. VALUES FOR UTS AND AVG.% ELONGATION
BY PLATE THICKNESS, LOCATION, AND ORIENTATION**



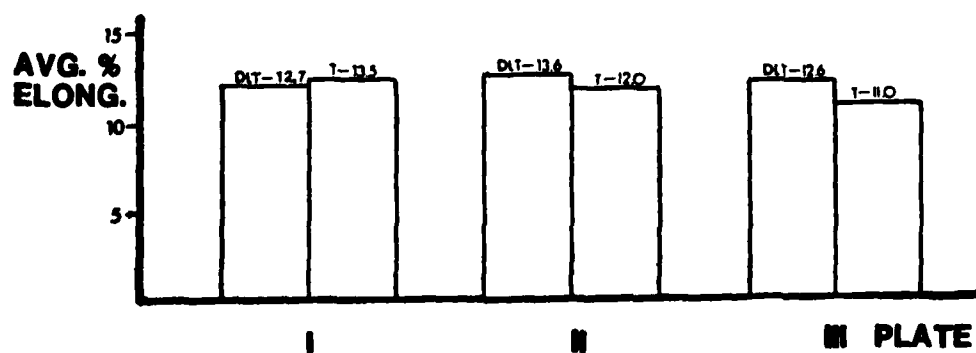
LONGITUDINAL



TRANSVERSE



LONGITUDINAL



TRANSVERSE

KEY

C - CENTRAL DLT SPECIMENS

S - SURFACE DLT SPECIMENS

T - TENSION SPECIMENS

I - 0.4 in. PLATE THICKNESS

II - 1.0 in. PLATE THICKNESS

III - 1.875 in. PLATE THICKNESS

Fig. 4 (b)

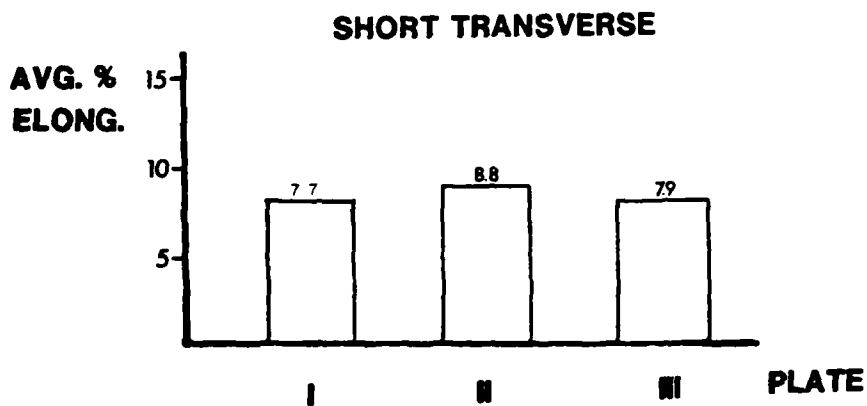
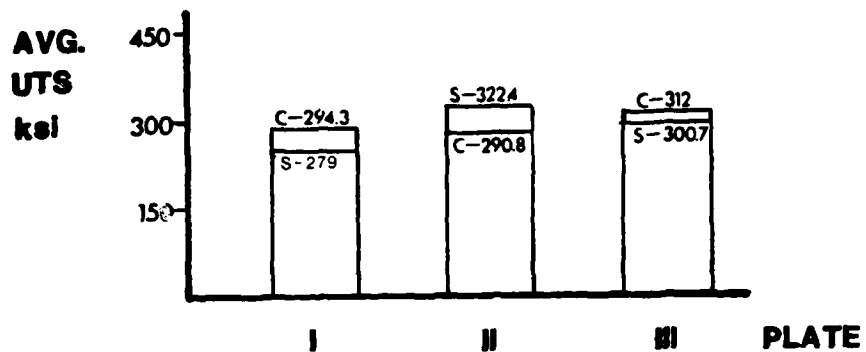
SHORT - TRANSVERSE PROPERTIES**SHORT TRANSVERSE****KEY****S - SURFACE DLT SPECIMENS****C - CENTER DLT SPECIMENS****I - 0.4 in. PLATE THICKNESS****II - 1.0 in. PLATE THICKNESS****III - 1.875 in. PLATE THICKNESS**

Fig. 5

FRACURE TOUGHNESS OF (ESP) AISI-52100 STEEL USING
DOUBLE TOESION & COMPACT TENSION TEST METHODS

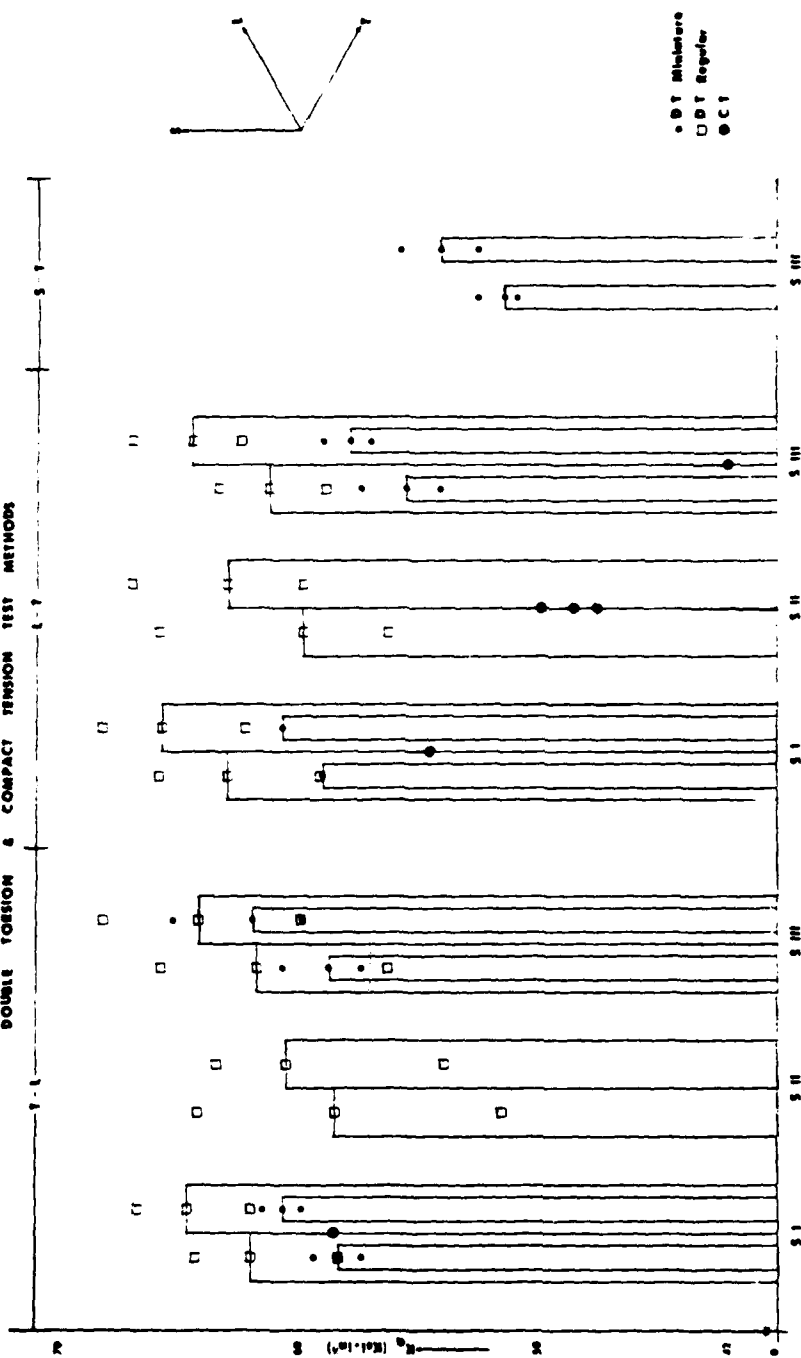


TABLE I

Chemical Composition and Mechanical Processing Details
 Plate S-I ESR AISI 4340 Steel (Heat 2780)

Chemical Composition

C	Mn	Si	P	S	Ni	Cr	Mo	V*
0.40	0.77	0.20	0.010	0.003	1.69	0.85	0.24	0.003
Al*	As*	Sb*	Sn*	O+	H+	N°		
0.008	0.006	0.004	0.016	0.0011	0.00005	0.0130		

Processing

- 20 inch diameter ingot reduced to 12 inch round cross section at 2030 F.
- Pressed to 12 x 5 inch, cross rolled to 0.4 inch thick plate, annealed.

Notes

- * Spectrochemical method
- + Vacuum fusion technique
- ° Semi-micro Kjeldahl distillation

TABLE II

Chemical Composition and Mechanical Processing Details
 Plates S-II and -III
 ESR AISI 4340 Steel (Heat 9060)

Chemical Composition

C	Mn	Si	P	S	Ni	Cr	Mo	V
0.40	0.82	0.25	0.007	0.002	1.76	0.84	0.26	<0.02
Cu	Sn*	Sb*	As*	O*	H*	N*		
0.11	0.004	0.004	0.010	0.001	0.0003	0.008		

Processing

- 20 inch diameter ingot forged to 9½ inch diameter cross section, machined to 8½ inch diameter by 16 inch
- Soaked at 2350 F, upset to 10 inch long and forged to 8 x 7 inches. Step forged (S-III = 1.9 inch step)
- Annealed 1600 F--8 hrs., FC to 1200 F over 12 hrs. followed by AC to ambient

Part of above step (1.9 inch) forged at 2050 F to 7 x 9½ x 1 inch plate (S-II = 1.0 inch)

Notes

- * Spectrochemical method
- + Vacuum fusion technique
- Semi-micro Kjeldahl distillation

TABLE IV

MECHANICAL PROPERTIES DETERMINED BY DLT TEST FROM
PLATE (S-I) OF AISI 4340 STEEL ($H_{RC}=57$) W.R.T. TO LOCATION AND ORIENTATION

PLATE #	S-I								
	SPECIMEN #	LOCATION	ORIENTATION	YIELD STRENGTH σ_{ys} (ksi)		ULTIMATE STRENGTH σ_{UTS} (ksi)		ELONGATION % e	
				RANGE MAX.-MIN.	AVERAGE σ_{ys}	RANGE MAX.-MIN.	AVERAGE σ_{UTS}	RANGE MAX.-MIN.	AVERAGE %
	3; 5; 15; 16; 18.	C	TX	216 → 204	208.75	314 → 298	309.2	11.12 → 9.58	10.58
	2; 6; 14; 20; 22.	C	LY	201 → 197	195.5	322 → 299	312	14.93 → 11.54	13.54
	1; 7; 17; 21.	C	TZ	209 → 195	200.67	308 → 271	294	12.52 → 4.26	8.58
	B; 4; 19; F.	C	LZ	216 → 195	204	311 → 262	294.5	10.82 → 6.01	9.04

11; 13; 25; 26; 29; J.	S	TX	245 → 182	212	334 → 283	309	16.74 → 7.79	12.6
9°; 23; 27; 28; 32.	S	LY	223 → 194	206.67	315 → 302	309.75	13.38 → 10.82	12.21
C; 8; 10; 24; 31; G.	S	TZ	217 → 176	196.4	321 → 255	283	11.23 → 4.59	6.72
12; 30; H; D.	S	LZ	233 → 195	219.67	306 → 255	274.75	15.47 → 3.39	7.1

° Invalid test.

TABLE V A

TABLE V A

PLATE #	S-II 1								
	SPECIMEN #	LOCATION	ORIENTATION	YIELD STRENGTH σ_{ys} (ksi)		ULTIMATE STRENGTH σ_{UTS} (ksi)		ELONGATION % ϵ	
				RANGE MAX.-MIN.	AVERAGE σ_{ys}	RANGE MAX.-MIN.	AVERAGE σ_{UTS}	RANGE MAX.-MIN.	AVERAGE %
	44; 46.	C	TX	216 + 211	213.5	334 + 329	331.5	13.94 + 12.47	13.205
	33; 43; 48.	C	LY	216 + 204	208.67	331 + 322	326.67	14.40 + 12.58	13.69
	45.	C	TZ	199	199	331	331	12.50	12.50
	47.	C	LZ	198	198	332	332	10.37	10.37

36; 38; 39.	S	TX	202 + 201	201.5	332 + 324	329	14.75 + 12.70	13.91
34°; 40.	S	LY	202	202	325	325	12.81	12.81
35; 37; 41.	S	TZ	212 + 206	208.67	334 + 332	333	12.34 + 9.90	11.29
42.	S	LZ	190	190	333	333	13.47	13.47

° Invalid test.

TABLE V B

TABLE V B

S-II 2									
PLATE #	SPECIMEN #	LOCATION	ORIENTATION	YIELD STRENGTH σ_{ys} (ksi)		ULTIMATE STRENGTH σ_{UTS} (ksi)		ELONGATION % ϵ	
				RANGE MAX.-MIN.	AVERAGE σ_{ys}	RANGE MAX.-MIN.	AVERAGE σ_{UTS}	RANGE MAX.-MIN.	AVERAGE % ϵ
	79; 81°; 84°.	C	TX	207	207	340	340	15.04	15.04
	82; 86°.	C	LY	202	202	330	330	13.65	13.65
	80; 83; 85.	C	TZ	220 → 178	197	268 → 214	249.67	5.50 → 2.60	4.10
	No specimen	C	LZ	-----	---	-----	-----	-----	----

87°; 92.	S	TX	182	182	219	219	219	1.88	1.88
89°; 91.	S	LY	210	210	333	333	333	13.89	13.89
88.	S	TZ	210	210	288	288	288	7.89	7.89
90; 93.	S	LZ	225 + 198	211.5	337 + 300	318.5	318.5	8.84 + 5.73	7.29

*Invalid test.

TABLE VI A

TABLE VI A

S-III 1									
PLATE #	SPECIMEN #	LOCATION	ORIENTATION	YIELD STRENGTH σ_{ys} (ksi)		ULTIMATE STRENGTH σ_{UTS} (ksi)		ELONGATION % e	
				RANGE MAX. - MIN.	AVERAGE σ_{ys}	RANGE MAX. - MIN.	AVERAGE σ_{UTS}	RANGE MAX. - MIN.	AVERAGE % e
	51; 52; 53.	C	TX	212 + 200	205.33	327 + 323	325.33	13.68 + 11.40	12.85
	50; 54.	C	LY	203 + 200	201.5	331 + 322	326.5	13.68 + 13.24	13.46
	55; 56.	C	TZ	214 + 199	206.5	334 + 333	333.5	13.48 + 12.12	12.8
	57.	C	LZ	211	211	325	325	7.25	7.25

	59; 61.	S	TX	218 + 206	212	330 + 326	328	14.40 + 10.88	12.64
	49; 58; 63.	S	LY	216 + 186	206	337 + 204	290.33	13.27 + 11.92	12.60
	60.	S	TZ	214	214	339	339	11.36	11.36
	62.	S	LZ	212	212	307	307	5.28	5.28

TABLE VI B

TABLE VI B

PLATE #	S-III 2								
	SPECIMEN #	LOCATION	ORIENTATION	YIELD STRENGTH σ_{ys} (ksi)		ULTIMATE STRENGTH σ_{UTS} (ksi)		ELONGATION % ϵ	
				RANGE MAX.-MIN.	AVERAGE σ_{ys}	RANGE MAX.-MIN.	AVERAGE σ_{UTS}	RANGE MAX.-MIN.	AVERAGE % ϵ
	74°; 77.	C	TX	212	212	329	329	17.24	17.24
	73°; 78.	C	LY	221	221	331	331	12.28	12.28
	75.	C	TZ	194	194	262	262	5.01	5.01
	76.	C	LZ	226	226	327	327	5.04	5.04

65°; 66°; 68.	S	TX	N/A	N/A	302	302	302		8.4
64; 70.	S	LY	225 + 207	216	328 + 324	326	326	11.93 + 11.82	11.88
67; 69; 71.	S	TZ	213 + 201	205	334 + 257	288.67	288.67	12.42 + 5.22	7.69
72.	S	LZ	216	216	292	292	292	4.52	4.52

°Invalid test.

N/A - Not Available.

TABLE VII		SUMMARY OF THE MECHANICAL PROPERTY AVERAGES DETERMINED BY DLT TEST FOR SPECIMENS FROM DIFFERENT PLATES OF ESR AISI 4340 STEEL ($H_{RC} \approx 57$) W.R.T. ORIENTATION									
ORIENTATION	PLATES	T-X				L-Y				T-Z AND L-Z	
		YIELD STRENGTH σ_{ys} (ksi)	ULTIMATE TENSILE STRENGTH σ_{UTS} (ksi)	% ELONGATION ϵ_e (in)	YIELD STRENGTH σ_{ys} (ksi)	ULTIMATE TENSILE STRENGTH σ_{UTS} (ksi)	% ELONGATION ϵ_e (in)	YIELD STRENGTH σ_{ys} (ksi)	ULTIMATE TENSILE STRENGTH σ_{UTS} (ksi)	% ELONGATION ϵ_e (in)	
	SI	210	309	11.63	200.29	311	12.95	203.45	286.16	7.73	
	SI1-1	207.50	330	13.63	207	326.25	13.47	202.17	332.5	11.70	
	SI1-2	194.50	279.50	8.46	206	331.50	13.77	204	279	5.79	
	Average of SI1 -1,2	203.17	315.57	12.15	206.67	328	13.57	203.10	305.75	8.75	
	SI11-1	208	326.4	12.76	204.20	304.80	13.03	210	335.33	9.90	
	SI11-2	212	329	17.24	217.67	327.67	12.01	208.5	288.17	6.27	
	Average of SI11 -1,2	208.67	326.83	13.51	209.25	313.38	12.59	209.18	307.73	7.92	

TABLE VIII

COMPARISON OF MECHANICAL PROPERTIES OF
ESR 4340 STEEL STEP FORGING AT VARIOUS FORGING REDUCTIONS*

SECTION (in.)	ORIENTATION	0.2% YS, ksi		UTS, ksi		%EL		%RA	
		RANGE	AVG	RANGE	AVG	RANGE	AVG	RANGE	AVG
8.0 in. (A)	LONG.								
	LT	204-212	209	314-319	317	11.6-13.2	12.3	41.0-47.5	42.9
	ST	207-220	214	317-319	318	9.9-11.4	10.8	29.3-37.7	34.6
4-3/4 in. (B)	LONG.								
	LT	204-219	213	316-321	319	10-11.7	10.8	30.7-41.1	35.5
	ST								
2-3/4 in. (C)	LONG.								
	LT	214-217	215	315-319	318	11.3-12.8	12.0	40.1-44.2	42.0
	ST	207-216	212	317-319	318	9.8-11	10.2	29.3-35.1	32.3
1.9 in. (SIII)	LONG.								
	LT	208-220	213	313-322	317	7-10.2	9.3	21-34.6	27.4
	ST								
1.0 in. (SII)	LONG.								
	LT	210-216	213	317-320	319	11.6-13.4	12.7	41-44.8	43.6
	ST	208-216	213	317-319	318	10.2-12.8	11.0	28.7-38.3	33.2
0.4 in. (SI)+	LONG.								
	LT	206-222	216	316-322	319	5.4-9	7.3	12.3-25.9	20.0
	ST								
1.9 in. (SIII)	TX		209						
	LY		209						
	TZ/LZ		209						
1.0 in. (SII)	TX		203						
	LY		207						
	TZ/LZ		203						
0.4 in. (SI)+	TX		206						
	LY		200						
	TZ/LZ		202						

[] Indicates range of averages w.r.t. orientation.

+ Cross rolled ESR 4340 plate from separate heat.

* Incorporates data supplied by AMMRC (Mr. A. Anctil).

TABLE IX

HARDNESS AND IMPACT ENERGY OF
ESR 4340 STEEL STEP FORGING*

SECTION IN.	ORIENTATION	HRC	RANGE ft-lbs	IMPACT ft-lbs	
8	A	LONG.	56	14.2-16.8	15.6
		LT	56	9.5-15.8	12.8
		ST	56	11.5-16.8	15.1
4-3/4	B	LONG.	56	16.3-19.0	18.0
		LT	56	13.9-16.0	15.1
		ST	56	11.5-17.1	14.4
2-3/4	C	LONG.	56	13.6-19.0	16.5
		LT	56	11.8-17.7	14.8
		ST	56	7.6-12.6	10.2

*Data supplied by AMRC (Mr. A. Anctil).

TABLE X

DOUBLE TORSION TEST RESULTS FOR BOTH REGULAR & MINIATURE SIZE
SPECIMENS OF ESR-AISI 4340 STEEL ($H_{RC} \approx 54$)

Specimen #	Plate	Crack Plane Orientation	Minimum K_Q Ksi/ $\sqrt{in}$		Maximum K_Q Ksi/ $\sqrt{in}$		Average K_Q Ksi/ $\sqrt{in}$	
			(f)	(Nf)	(f)	(Nf)	(f)	(Nf)
REGULAR SIZE DT								
1	S-I	T - L	° --		--		° --	
2	S-I	T - L	58.40	61.98	64.36	66.75	62.00 ^{5*}	64.72 ⁵
3	S-I	L - T	58.65	62.24	60.44	68.22	60.80 ⁵	64.78 ⁴
4	S-I	L - T	65.83	67.02	65.83	67.02	65.83 ⁴	67.02 ³
5	S-II	T - L	51.46	53.86	62.24	62.83	56.97 ⁵	59.50 ⁵
6	S-II	L - T	58.65	59.84	65.83	67.02	62.00 ⁵	63.20 ⁵
7	S-III	T - L	58.25	59.85	61.00	61.00	58.00 ⁴	60.25 ³
8	S-III	L - T	58.88	62.48	63.43	67.02	61.25 ⁴	64.51 ⁴
9	S-III	T - L	63.43	64.63	65.82	68.22	64.75 ⁵	66.54 ⁵
10	S-II	T - L	59.84	60.80	64.24	63.43	61.04 ³	62.15 ³
11	S-II	L - T	56.25	61.34	59.84	61.34	57.15 ⁴	61.34 ¹
MINIATURE								
A	S-III	S - T	+ --		--		--	
B @	III	L - T	44.3	47.56	50.8	53.3	48.48 ³	51.12 ³
C @	III	L - T	47.56	50.84	47.88	50.84	47.66 ³	50.84 ²
D	III	L - T	54.12	57.07	57.40	59.04	55.50 ³	57.80 ³
E	III	T - L	+ --		--		--	
F	III	T - L	57.40	59.86	60.68	65.27	58.75 ³	61.95 ³
G e	III	L - T	49.20	53.80	50.02	54.12	49.47 ³	54.00 ³
H	S-I	T - L	57.40	59.86	59.04	61.50	58.40 ³	60.70 ³
I	S-I	L - T	59.04	60.70	59.04	60.70	59.04 ³	60.70 ³
J	S-III	S - T	50.84	52.48	52.48	55.76	51.38 ³	54.12 ³

° Results disregarded as method of observation was changed.

* Average taken from given number of observations.

(f) Fatigue precracked

(nf) Non fatigue precracked

+ Specimens failed during testing.

@ Different method of fatigue precracking was used.

TABLE XI A

SUMMARY OF DT TEST RESULTS FOR REGULAR SIZE SPECIMENS
 WITH RESPECT TO PLATE AND CRACK PLANE ORIENTATION.
 MATERIAL--ESR-AISI 4340 STEEL ($H_{RC} \approx 54$)

PLATE \ CPO*	L - T		T - L	
	K_Q Ksi $\sqrt{\text{in}}$		K_Q Ksi $\sqrt{\text{in}}$	
	Fatigue Precracked	Non-fatigue Precracked	F	NF
S-I	63.03	65.74	62.00	64.72
S-II	59.80	62.90	58.50	60.50
S-III	61.25	64.51	61.75	64.18

*CPO - Crack Plane Orientation

TABLE XI B

SUMMARY OF DT TEST RESULTS FOR MINIATURE SIZE SPECIMENS
 WITH RESPECT TO PLATE AND CRACK PLANE ORIENTATION.
 MATERIAL--ESR-AISI 4340 STEEL ($H_{RC} \approx 54$)

PLATE \ CPO*	L - T		T - L		S - T	
	K_Q Ksi $\sqrt{\text{in}}$		K_Q Ksi $\sqrt{\text{in}}$		K_Q Ksi $\sqrt{\text{in}}$	
	F	NF	F	NF	F	NF
S-I	59.04	60.70	58.40	60.70	--	--
S-II	--	--	--	--	--	--
S-III	57.80	55.5	58.70	61.90	51.40	54.10

*CPO - Crack Plane Orientation

TABLE XII

CT TEST RESULT FOR ALL SPECIMENS WITH DIMENSIONAL DETAILS.

MATERIAL--ESR 4340 STEEL ($H_{RC} \approx 54$)

Specimen Number	Plate	CPO	Measured Crack Length a in.	Thickness of the Specimen B in.	Specimen Width W in.	$\frac{a}{W}$	$f\left(\frac{a}{W}\right)$	P_Q lbf	$K_Q = \frac{P_Q}{BW^{3/2}} f\left(\frac{a}{W}\right)$ Ksi $\sqrt{\text{in}}$
1	S-I	L-T	0.4275	0.4	1.2125	0.35	6.297	3828	54.5
2	S-I	T-L	0.4125	0.4	1.2125	0.34	6.233	4136	58.5
3	S-II	L-T	1.0625	0.875	1.75	0.607	14.03	3872	47.05
4	S-II	L-T	1.0375	0.875	1.75	0.593	13.28	4290	49.32
5	S-III	L-T	1.325	1.5	3.00	0.44	8.15	13,420	42.08

Notes: (i) $\frac{a}{W}$ ratios in the above table do not satisfy the limits ($0.45 < \frac{a}{W} < 0.55$) imposed by ASTM-E 399-78 standard.

(ii) Results are for single tests.

TABLE XIII

RESULTS OF TESTS USING MINIATURE DT SPECIMENS WITH
 CHEVRON & ELLIPTICAL PRECRACKS--PLATE S-III
 WITH CPO AS L-T, MATERIAL--ESR-AISI 4340 STEEL ($H_{RC} \approx 54$)

SPECIMEN	FATIGUE PRECRACK GEOMETRY	MINIMUM K_Q $Ksi\sqrt{in}^Q$		MAX. K_Q $Ksi\sqrt{in}^Q$		AVE. K_Q $Ksi\sqrt{in}^Q$	
		F	NF	F	NF	F	NF
B, C, G	CHEVRON	44.3	47.56	50.8	54.12	48.5 ^{9*}	51.98 ⁹
D	ELLIPTICAL	54.12	57.07	57.40	59.04	55.5 ³	57.8 ³

* Average of so many observations.

TABLE XIV

COMPARISON OF K_Q RESULTS OBTAINED USING DIFFERENT
TEST METHODS FOR PLATE S-I.

MATERIAL ESR-AISI 4340 STEEL ($H_{RC} = 54$)

METHOD	NUMBER OF VALUES	CPO	K_Q $Ksi\sqrt{in}$	REMARKS
DT	9	L-T	63.0	--
	5	T-L	62.0	--
mDT	3	L-T	59.0	--
	3	T-L	58.4	--
CT	1	L-T	54.5	$a/w = 0.35$
	1	T-L	58.5	$a/w = 0.34$
IC	5	L-T	51.4	results of tests conducted at AMMRC
	5	T-L	52.7	

All specimens experienced fatigue precracking prior to testing.

TABLE XV

RESULTS OF TENSILE TESTS ESR 4340

BAR NO.	ORIENTATION	FROM PLATE	ORIGINAL DIA. (in)	ORIGINAL AREA (in ²)	YIELD STRENGTH (ksi)	ULT. STRENGTH (ksi)	FRACT. STRENGTH (ksi)	ELONGATION (%)
A	Longitudinal	SI	0.2497	0.0490	202	306	235	15
B	Longitudinal	SI	0.2497	0.0490	201	310	224	15
D	Long Transverse	SI	0.2503	0.0492	202	309	254	13
C	Long Transverse	SI	0.2496	0.0489	204	309	245	14
U	Longitudinal	SIII-2	0.2490	0.0487	197	326	253	16
V	Long Transverse	SII-2	0.2492	0.0488	193	322	277	12
W	Long Transverse	SIII-2	0.2490	0.0487	200	322	271	11
X	Longitudinal	SIII-1	0.2496	0.0489	198	323	252	15
Y	Long Transverse	SII-1	0.2488	0.0486	199	325	273	12
Z	Longitudinal	SII-1	0.2488	0.0486	197	323	257	12

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