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AMMRC TR 81-19

DETERMINATION OF THE TRANSVERSE PROPERTIES OF TEXTURED ESR 4340 STEEL

MAY 1981

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Final Report

Contract Number DAAG46-80-C-0043

Prepared for

ARMY MATERIALS AND MECHANICS RESEARCH CENTER
Watertown, Massachusetts 02172

UNCLASSIFIED

SECURITY CLASSIFICATION OF THIS PAGE (When Data Entered)

REPORT DOCUMENTATION PAGE

READ INSTRUCTIONS BEFORE COMPLETING FORM

1. REPORT NUMBER: AMMRC TR-81-19

2. GOVT ACCESSION NO.:

3. RECIPIENT'S CATALOG NUMBER:

4. TITLE (and Subtitle): DETERMINATION OF THE TRANSVERSE PROPERTIES OF TEXTURED ESR 4340 STEEL

5. TYPE OF REPORT & PERIOD COVERED: Final Report - 13 May 80 - 24 Feb 81

6. PERFORMING ORG. REPORT NUMBER:

7. AUTHOR(s): John T. Berry

8. CONTRACT OR GRANT NUMBER(s): DAAG46-80-C-0043

9. PERFORMING ORGANIZATION NAME AND ADDRESS:
Georgia Institute of Technology
School of Mechanical Engineering
Atlanta, Georgia 30332

10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS:
D/A Project: 1L162105AH84
AMCMS Code: 612105.H840011

11. CONTROLLING OFFICE NAME AND ADDRESS:
Army Materials and Mechanics Research Center
ATTN: DRXMR-AP
Watertown, Massachusetts 02172

12. REPORT DATE: May 1981

13. NUMBER OF PAGES: 36

14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office):

15. SECURITY CLASS. (of this report): Unclassified

15a. DECLASSIFICATION/DOWNGRADING SCHEDULE:

16. DISTRIBUTION STATEMENT (of this Report):
Approved for public release; distribution unlimited.

17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report):

18. SUPPLEMENTARY NOTES:

19. KEY WORDS (Continue on reverse side if necessary and identify by block number):
- 4340 Steel
- Electroslag remelting (ESR)
- Texture
- Mechanical properties
- Anisotropy
- Tensile properties
- Ductility

20. ABSTRACT (Continue on reverse side if necessary and identify by block number):

The objective of the current investigation was to determine the transverse properties of electroslag remelted AISI 4340 which had been processed to produce an intense (112) + (111) type texture. The material was processed from 10 inch (250 mm) x 5.0 inch (125 mm) x 5.0 inch (125 mm) thick slabs to approximately 0.5 inch (12.5 mm) thick plate in a two high rolling mill to produce the above texture. Utilizing the double ligament test; long transverse, short transverse, longitudinal and diagonal mechanical properties were determined. (over)

DD FORM 1 JAN 73 1473 EDITION OF 1 NOV 65 IS OBSOLETE

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Block No. 20

The results of the tests indicate that some anisotropy does exist in the plane of the plate. The associated levels of longitudinal yield stress and ultimate stress are considerably higher than those of a non-textured material of corresponding longitudinal ductility and hardness level (~ H_{RC} 57). The long transverse and short transverse ductilities are, however, lower than those of the non-textured material. In the case of the short transverse properties, both inferior strength and ductility were observed.

The associated scanning electron microscopy showed the presence of minute flattened strip-like MnS inclusions on the macroscopically flat or terrace type fracture surfaces associated with the low ductility short transverse specimens. All of the specimens concerned with this orientation broke at stresses below the level of general yielding.

GEORGIA INSTITUTE OF TECHNOLOGY

School of Mechanical Engineering

FINAL REPORT

TO: Director
Army Materials and Mechanics Research Center
ATTN: DRXMR-AP, Contracting Administration
Watertown, Massachusetts 02172

Technical Supervisor: Mr. Albert Anctil

FROM: Professor John T. Berry
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SUBJECT: Final Report
Contract No. DAAG46-80-C-0043
Research Project No. E-25-634
Determination of the Transverse Properties of Textured ESR 4340 Steel
Covering period from May 13, 1980 to February 24, 1981

DATED: August 12, 1981

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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.

The entire bulk of the mechanical testing associated with the present project was undertaken by Mr. Issam Fadel, masters student in the School of Mechanical Engineering. Without Mr. Fadel's diligent work and careful scrutiny this work could not have been performed. Together with Mr. Y. Shimazaki, Mr. Fadel undertook the preliminary SEM study. The final SEM study was performed by Mr. J. Hubbard of the Georgia Tech Engineering Experimental Station, for whom we have special commendation. Special thanks should also be conveyed to Mr. Ed Oppenheimer for his counsel on testing aspects, to Messrs. Harry Vaughan and Virgil McCollum for their part in the exacting task of producing the DLT specimens from pre-hardened plate and finally to Mrs. Rosie Atkins for her incredible care in generating clear accurate manuscripts with the very minimal guidance from the author.

ABSTRACT

The objective of the current investigation was to determine the transverse properties of electroslag remelted AISI 4340 which had been processed to produce an intense (112) + (111) type texture. The material was processed from 10 inch (250 mm) x 5.0 inch (125 mm) x 5.0 inch (125 mm) thick slabs to approximately 0.5 inch (12.5 mm) thick plate in a two high rolling mill to produce the above texture. Utilizing the double ligament test; long transverse, short transverse, longitudinal and diagonal mechanical properties were determined.

The results of the tests indicate that some anisotropy does exist in the plane of the plate. The associated levels of longitudinal yield stress and ultimate stress are considerably higher than those of a non-textured material of corresponding longitudinal ductility and hardness level (~ H_{RC} 57). The long transverse and short transverse ductilites are, however, lower than those of the non-textured material. In the case of the short transverse properties, both inferior strength and ductility were observed.

The associated scanning electron microscopy showed the presence of minute flattened strip-like MnS inclusions on the macroscopically flat or terrace type fracture surfaces associated with the low ductility short transverse specimens. All of the specimens concerned with this orientation broke at stresses below the level of general yielding.

1. INTRODUCTION

The present investigation was concerned with the determination of the transverse properties of electroslag remelted AISI 4340* which had been processed to produce a crystallographic perferred orientation/texture or fibering.

The processing of the two plates received from AMMRC involved the rolling of two ESR 4340 slabs approximately 10.0 inch (250 mm) x 5.0 inch (125 mm) wide x 5.0 inch (125 mm) thick, using a thermomechanical process which results in an intense (112) + (111) type texture [1]. The processing was accomplished on a two-high rolling mill using a ninety percent reduction. The treatment involved was undertaken at the United States Steel Corporation. The hardness of the material (as received) was ~ H_{RC} 57. Prior to delivery to Georgia Tech the plates (~ 0.5 inch or 12.5 mm thick) were surface ground at AMMRC to approximately 15/64 inch (~ 6 mm) thick such that the central section of the plate would be tested using the DLT bars (0.2 inch, ~ 5 mm in thickness). The DLT specimen blanks were cut from the plate so that longitudinal, transverse, and both diagonal blank orientations were obtained. Slots were then cut so that properties in the longitudinal, transverse, diagonal or short transverse directions could be determined. In this way the following type DLT bar designations arise:

TX
TZ
LY
LZ
45X
45Z
315X
315Z

*Chemical analyses are given in Tables I and II.

In the first four of the designations, the first letter indicates the bar orientation (T = transverse, L = longitudinal) whilst the letter indicates the direction in which the ligaments are cut and ultimately tested (X, Y or Z). The last four orientations represent bars which are oriented in what might be termed a diagonal (45°) manner, the 45 and 315 designated bars are mutually orthogonal. The slots were then cut and the bars subsequently tested so that 45X and 315X type bars provided information on the in-plane diagonal properties, whilst the 45Z and 315Z provided information on short transverse properties as are obtained from diagonally oriented specimens (see Figure 1).

The techniques used for specimen fabrication were essentially those described in an earlier work [2] excepting that the rough machining phase involved slitting and facing with abrasive wheel type tooling in view of the hardness of the as-received plate.

The DL testing technique has also been described elsewhere [3,4]. The tests were conducted upon a calibrated 10,000 lb Instron testing machine using a crosshead speed of 0.02 in/min (~ 0.5 mm/min).

II. RESULTS

The results of the present tests are summarized in Tables III and IV with respect to individual orientations. Both averages (four specimens per individual orientation) and ranges are shown.

A more compact alternative summary of properties is exhibited in Tables V and VI, wherein further averaging of groups, for example averages of both diagonal orientations combined, are presented (see also Figures 2 and 3).

The raw data from which these tables (III to VI) are constructed is shown in the appendix in Tables A-I and A-II. The bar locations are also detailed in the appendix (Figures A1 and 2).

The results of scanning electron microscopy are included in the accompanying discussion.

III. DISCUSSION AND CONCLUSIONS

It is interesting to compare the data collected in Tables III through VI with those reported upon previously [1] for a non-textured plate (S-I) of ESR 4340 of equivalent hardness level.

It will be seen that the levels of longitudinal yield and ultimate stresses are considerably higher than those of the non-textured material, which as well as being of equivalent hardness, is of roughly equivalent longitudinal ductility.

A further significant difference exists between the short transverse properties exhibited by the non-textured plate of ESR 4340 S-I previously investigated and those exhibited by the textured plates C and S, inspite of the fact that all three plates received roughly similar total amounts of reduction during processing to plate.

Two interesting differences do surface however on comparing chemical analyses and actual rolling/forging schedules. In the first instance sulphur levels for one of the textured plates is somewhat higher than that of the non-textured material (although none of the sulphur levels can be considered high in terms of ESR practice [5,6]). In the second instance there is a profound difference in the way in which the final reduction to size was brought about. The textured plates experienced a severe final reduction of the order of 90%. Such a continuous reduction would promote pronounced flattening of plastic inclusions (MnS) and would not permit any readjustment of inclusion shape which could conceivably take place where there was a forging/rolling schedule with numerous interstage reheatings. (Although it should be mentioned that such adjustment of shape would be limited unless heating extended into the homogenization range. Nonetheless the effect should not be overlooked, since the plate S-I did obviously receive intermediate reheats in pressing and cross-rolling [2]). It should also be noted that the cross-rolling experienced by the plate of non-textured material would also promote a differently shaped inclusion to that expected with material reduced without rotation in the X-Y plane.

Some interesting pointers do emerge when the SEM studies of each set of fractures are examined. The somewhat flat short-transverse direction fracture appearance in plate C of the textured material frequently exhibited the presence of terraces bearing strip-like streaks (Figure 4a). The streaks could be differentiated from the dimpled but highly oriented prior austenite grain envelopes by their smooth but sometimes perforated appearance (Figures 4b and c). Plate S showed fewer examples of flattened inclusions than did plate C. It will be recalled that although the short-transverse direction fractures of the non-textured plate S-I showed flat spots, sometimes quite extensive, closer examination of those areas revealed a larger local volume fraction of globular rather than the plate shaped inclusions (Figures 5a and b).

In view of the significant part thought to be played by the terraces and flattened streaks seen in the textured material, further electron microscopy was undertaken using more versatile instrument (Cambridge Steroscan as opposed to bench type ISI) which also had available an analysis system (Envirotech attachment) which could examine and characterize X-radiation excited by the electron-beam (Figures 6 and 7).

Reference to the scanning electron micrography in the region of the perforations suggested that the strip-like streaks, if they were in fact inclusions, were extremely thin. The x-ray analysis of the steaks themselves, the underlying regions (areas of perforation) and the regular machined surface (plate C) revealed the presence of manganese and sulphur within the streaks themselves, suggesting very strongly that the streaks were in fact highly elongated very thin manganese sulphide type inclusions. (The outputs of the respective analyses are shown in Figures 8 to 10.)

The thin nature of the subject inclusions in the Z or short-transverse direction can also be appreciated from the color ordinary light photomicrography of Figure 11 which would seem to indicate a typical thickness of ~ 1μ. Reference to the literature [7] suggests that ribbon like MnS inclusions of this morphology may be of the harmful so-called type II variety promoted by low oxygen contents.

Consequently, it is concluded that the presence of these film like MnS lamellae contributes significantly to the low elongations witnessed in the through thickness DLT tests. At this point, however, the role played by the remaining features of the highly oriented microstructure cannot be elucidated. Possibly TEM work upon this aspect would prove valuable if further development is desired. Furthermore, additional SEM study of the sulphides prior to and after the texturing treatment would be valuable to determine their exact type and origin. Similiarly study of rare-earth treated--or alternatively ultra low sulphur--feed stock heats used in conjunction with the ESR and texture inducing process would also be valuable, especially in view of the extremely encouraging strength, ductility combinations seen in the X and Y direction property evaluations of the textured material.

Turning to the in-plane aspects of the mechanical properties determined for the plates C and S, it will be seen that the averaged ultimate stresses showed the diagonal (45X + 315X) direction values to lie intermediate between the longitudinal and transverse values (Figures 2 and 3). This was also true for the yield stress values to plate C. In the case of plate S averaged values were all within 4 Ksi, that is within 1-1/2 percent of each other.

The significant contrast is undoubtedly that seen on comparing the in-plane elongation values, where the transverse (LY) values show a fairly marked inferiority to those of the longitudinal and diagonal orientations. It will also be seen again that plate C shows inferior ductility values overall to those of plate S within the plane of the plate.

It is concluded that:

1. The texturing treatment applied to the subject material results in yield and ultimate stress values in the longitudinal direction of the plate, substantially greater than those of non-textured material of similar hardness level ($H_{RC} \sim 57$) examined previously.
2. The ductility of the textured material in the longitudinal direction is of a similar level to that of the non-textured material, in spite of its superior strength levels.

3. The averaged yield and ultimate stresses of the in-plane samples indicate some degree of anisotropy for plate C at least, where the averaged UTS values for the diagonal orientations (45X + 315X) are intermediate with respect to those of the longitudinal and transverse direction values.
4. In-plane ductility values measured indicate that the transverse (LY) ductility is inferior to those of the longitudinal and diagonal orientations.
5. The significant findings of the present investigation, however, hinge upon the poor ductility and inferior tensile strength witnessed in the short-transverse direction. This is apparent not only on comparison with mechanical properties observed within the plane of the plate but on comparison with the short transverse properties of the non-textured material investigated previously.
6. The macrosopically flat or facetted fractures associated with this behavior, show extensive indications of terracing. Upon undertaking higher-power scanning electron microscopy of the terraced areas of the fracture, strip- or ribbon-like streaks become apparent. These features appear to be minute flattened MnS inclusions, which may be responsible, at least in part, for the low ductility concerned in the short transverse orientations.

TABLE I

Chemical Composition
Plate C ESR AISI 4340 Steel (H_{RC} ≈ 57)

Chemical Composition:

C	Mn	Si	Ni	Cr	Mo
0.43	0.72	0.35	1.83	0.90	0.31
P	S	N	O*	H*	
0.012	0.007	0.012	26	0.3	

*ppm

TABLE II

Chemical Composition
Plate S ESR AISI 4340 Steel (H_{RC} ≈ 56)

Chemical Composition:

C	Mn	Si	Ni	Cr	Mo
0.40	0.77	0.22	1.78	0.80	0.24
P	S	N	O*	H*	
0.008	0.003	0.01	15	0.6	

*ppm

TABLE III

Mechanical Properties Determined by DL Test from Plate C of Textured ESR AISI 4340 Steel ($H_{RC} \approx 57$) with Respect to Orientation (Averages and Ranges)

PLATE I.D.		C					
		YIELD STRENGTH σ_{ys} (Ksi)		ULTIMATE STRENGTH σ_{UTS} (Ksi)		ELONGATION %	
SPECIMEN #	ORIENTATION	RANGE MAX.-MIN.	AVERAGE σ_{ys}	RANGE MAX.-MIN.	AVERAGE σ_{UTS}	RANGE MAX.-MIN	AVERAGE %
1; 3; 6; 8	TX	268 → 239	258	366 → 334	350	12.5 → 8.88	10.7
21; 25; 31; 19	45X	302 → 280	291	391 → 345	370	10.9 → 8.5	10.0
24; 30; 18; 28	315X	307 → 251	278	393 → 366	380	10.54 → 7.70	9.52
9; 13; 15; 11	LY	325 → 304	314.5	391 → 362	382	8.85 → 5.75	7.68
4; 5; 7; 2	TZ	--- ---†	----†	178 → 108	146	1.0 → 0.023	0.6
17; 23; 29; 27	45Z	--- ---†	----†	162 → 147	152	1.45 → 0.41	0.74
22; 32; 20; 26	315Z	--- ---†	----†	202 → 147	170	1.3 → 0.49	0.74
10; 16; 12; 14	LZ	--- ---†	----†	218 → 148	178	1.3 → 0.50	0.86

†Appeared to break within elastic range, that is below stress for general yielding.

TABLE IV

Mechanical Properties Determined by DL Test from Plate S of Textured ESR AISI 4340 Steel ($H_{RC} \approx 56$) With Respect to Orientation (Averages and Ranges)

PLATE I.D.		S					
		YIELD STRENGTH σ_{ys} (Ksi)		ULTIMATE STRENGTH σ_{UTS} (Ksi)		ELONGATION %	
SPECIMEN #.	ORIENTATION	RANGE MAX.-MIN.	AVERAGE σ_{ys}	RANGE MAX.-MIN.	AVERAGE σ_{UTS}	RANGE MAX.-MIN.	AVERAGE %
33; 38; 40; 35	TX	307 → 267	287	384 → 363	375	12.9 → 10.5	11.95
53; 63; 51; 57	45X	289 → 269	277	378 → 366	372	12.4 → 11.74	12.16
56; 62; 50; 60	315X	308 → 265	289	376 → 358	367	12.96 → 11.17	12.09
41; 45; 47; 43	LY	298 → 284	289	388 → 322	357	10.77 → 5.93	8.68
34; 36°; 37; 39	TZ	--- ---†	---†	281 → 231	264	2.63 → 1.41	2.21
49; 55; 59; 61	45Z	--- ---†	---†	230 → 181	210	1.80 → 1.04	1.34
54; 64; 58; 52	315Z	--- ---†	---†	385 → 184	245	2.10 → 0.81	1.28
42; 48; 44; 46	LZ	--- ---†	---†	257 → 223	244	2.41 → 1.33	1.89

° Invalid Test. † See footnote, Table III.

TABLE V

Summary of the Mechanical Property Averages and Ranges Determined by DL Test for Specimens from Plate C of the Textured ESR AISI 4340 Steel With Respect to Orientations

PLATE I.D.	C					
	ULTIMATE STRENGTH σ_{UTS} (Ksi)		YIELD STRENGTH σ_{ys} (Ksi)		ELONGATION %	
ORIENTATION	RANGE MAX.–MIN.	AVERAGE σ_{UTS}	RANGE MAX.–MIN.	AVERAGE σ_{ys}	RANGE MAX.–MIN.	AVERAGE
TX	366 → 334	350	268 → 239	258	12.5 → 8.88	10.7
45X; 315X	393 → 345	375	307 → 251	284	10.9 → 7.70	9.76
LY	391 → 362	382	325 → 304	314.5	8.85 → 5.75	7.68
TZ	178 → 108	146	––– –––	–––	1.0 → 0.23	0.6
45Z; 315Z	202 → 147	161	––– –––	–––	1.45 → 0.41	0.74
LZ	218 → 148	178	––– –––	–––	1.3 → 0.50	0.86

TABLE VI

Summary of the Mechanical Property Averages and Ranges Determined by DL Test for Specimens from Plate S of the Textured ESR AISI 4340 Steel With Respect to Orientations

PLATE I.D.	S					
	ULTIMATE STRENGTH σ_{UTS} (Ksi)		YIELD STRENGTH σ_{ys} (Ksi)		ELONGATION %	
ORIENTATION	RANGE MAX.-MIN.	AVERAGE σ_{UTS}	RANGE MAX.-MIN.	AVERAGE σ_{ys}	RANGE MAX.-MIN.	AVERAGE
TX	384 → 363	375	307 → 267	287	12.9 → 10.5	11.95
45X; 315X	378 → 358	370	308 → 265	283	12.96 → 11.17	12.12
LY	388 → 322	357	298 → 284	289	10.77 → 5.93	8.68
TZ	281 → 231	284	--- ---	---	2.63 → 1.41	2.21
45Z; 315Z	385 → 181	227	--- ---	---	2.10 → 0.81	1.31
LZ	257 → 223	244	--- ---	---	2.41 → 1.33	1.89

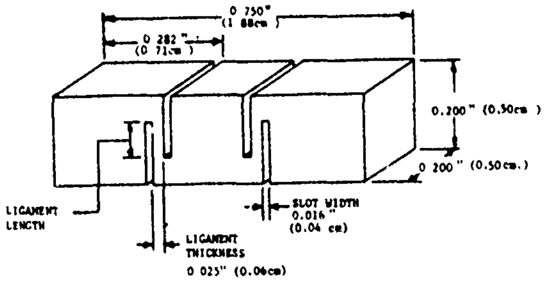
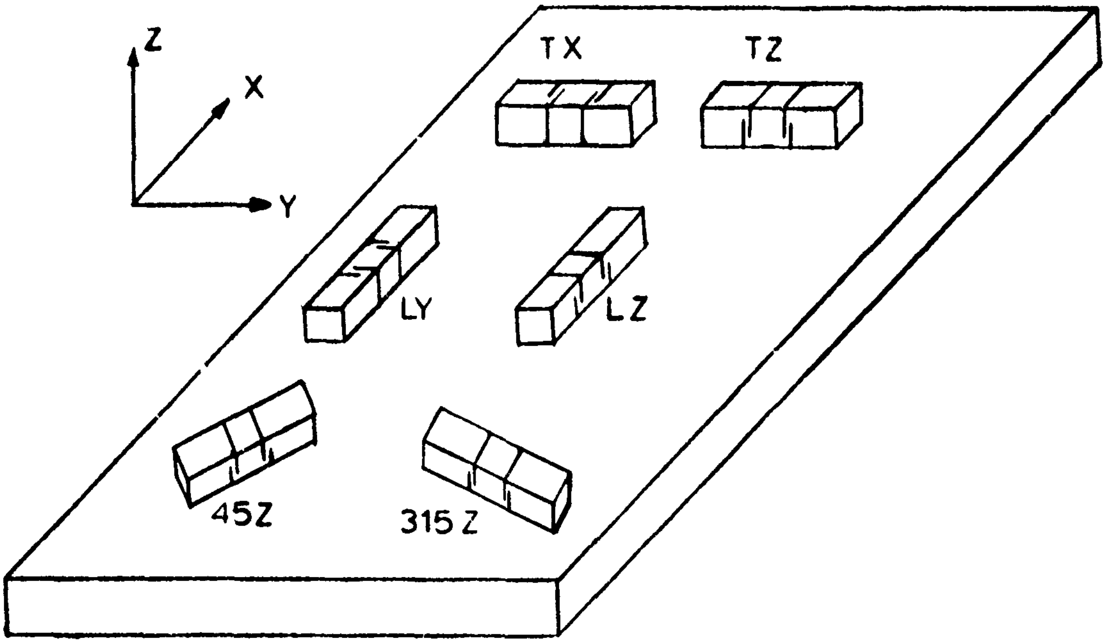


Figure 1(a). Showing double ligament test (DLT) specimen.



(b) Showing nomenclature for various orientations of DLT bar specimens.

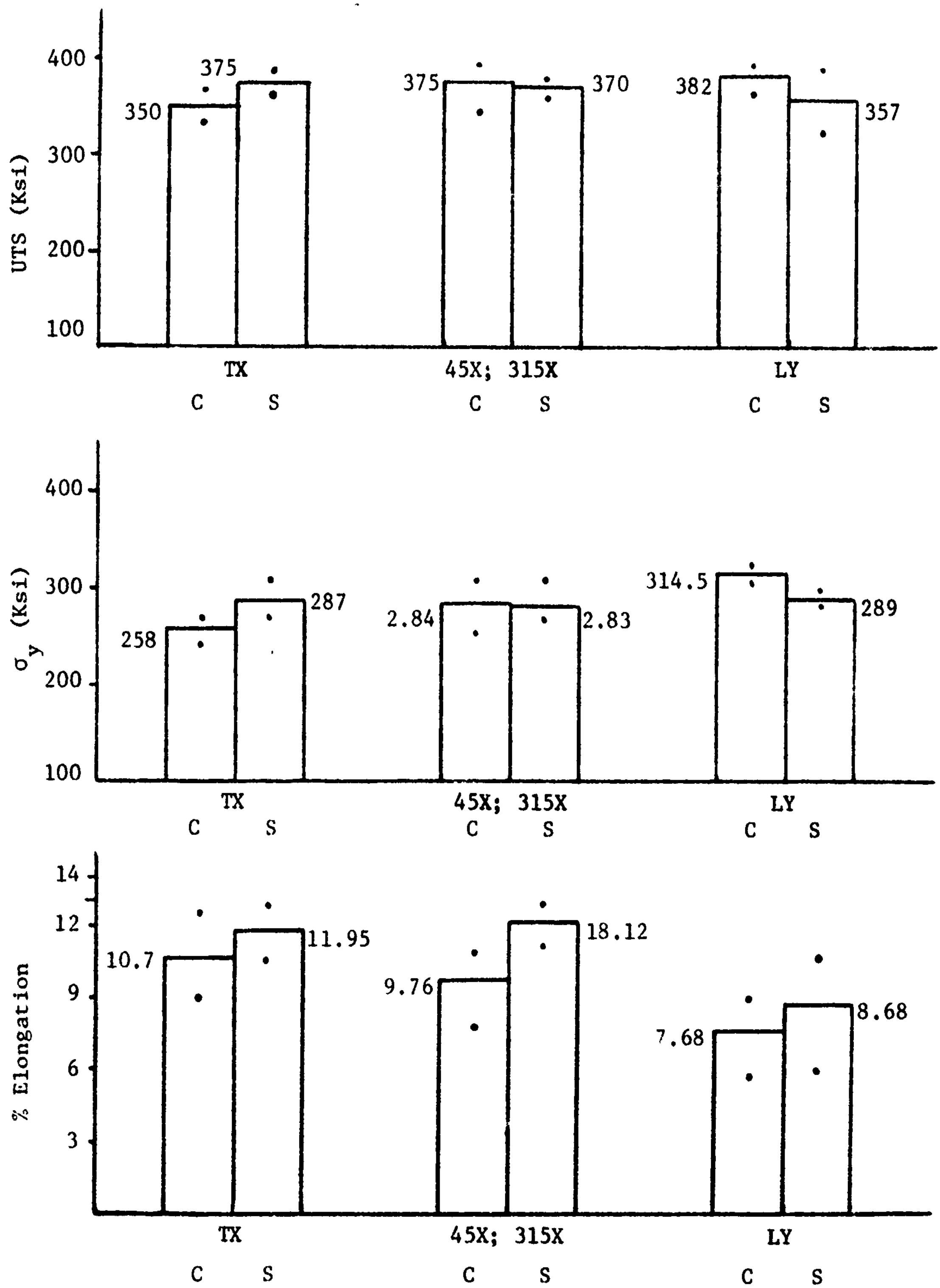


Figure 2. In-plane variation of the mechanical properties of textured ESR AISI 4340 steel plates C and S (H_{RC} ~ 57). (Averaged values--dots indicate ranges)

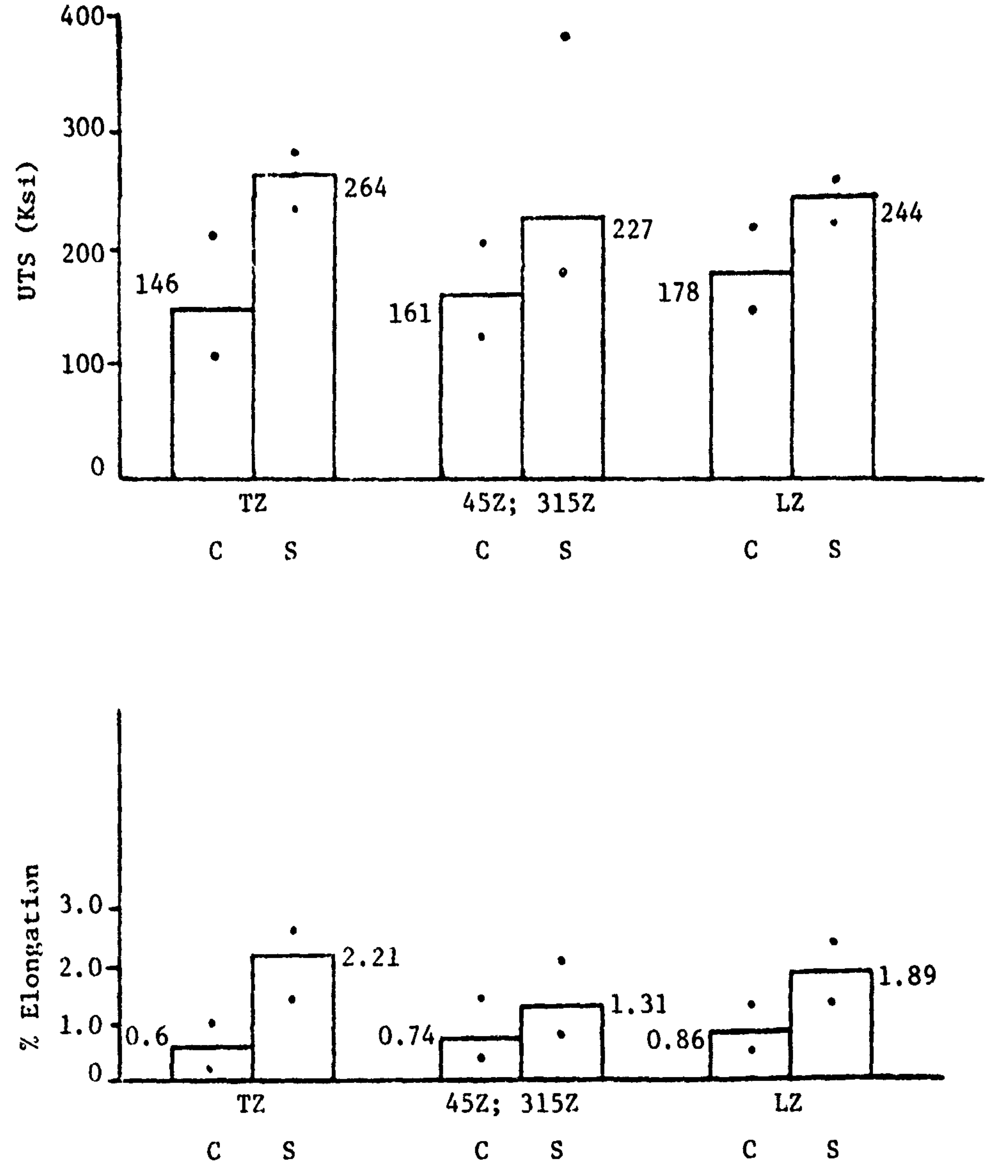
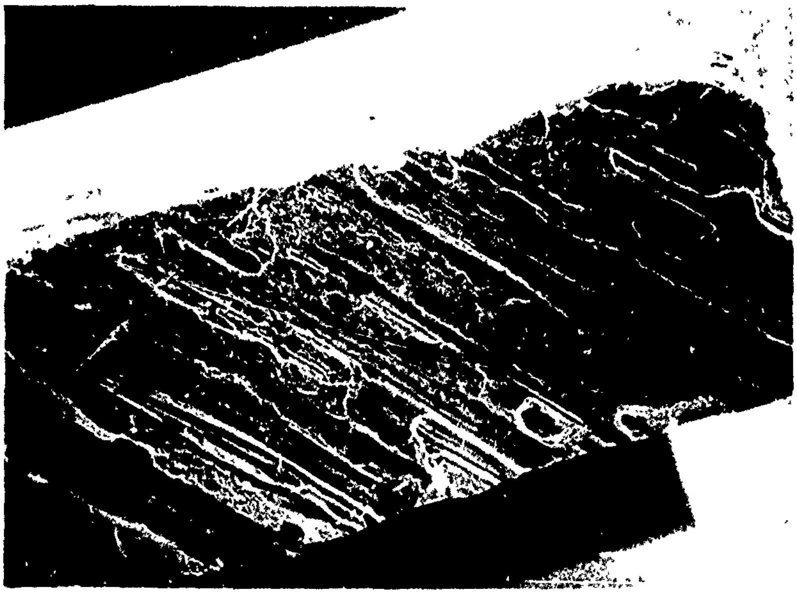


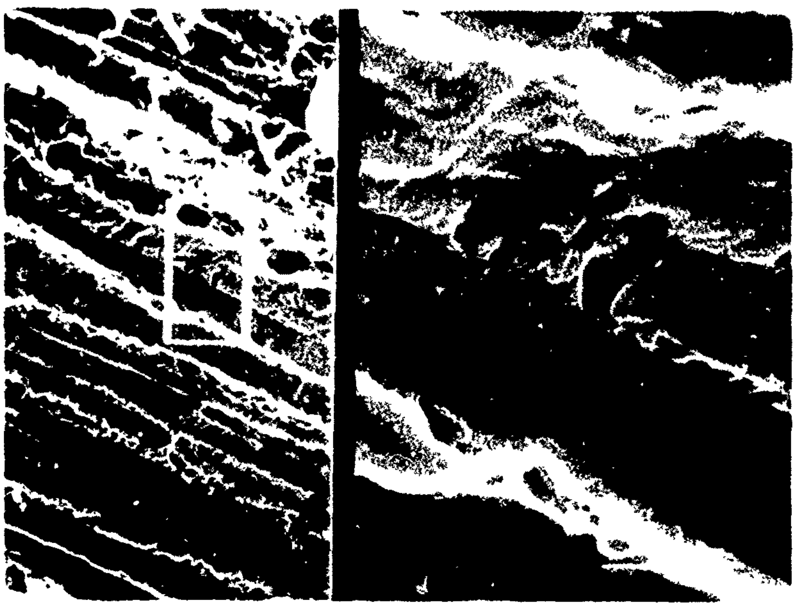
Figure 3. Short transverse mechanical properties of textured ESR AISI 4340 steel plates C and S (H_{RC} ~ 57). (Averaged values--dots indicate ranges)



x 60

Figure 4(a). Scanning electron microscope (SEM) shot of macroscopically flat area of fractured ligament of 45Z specimen #23 (plate C) showing terracing effect.

(b)



(c)

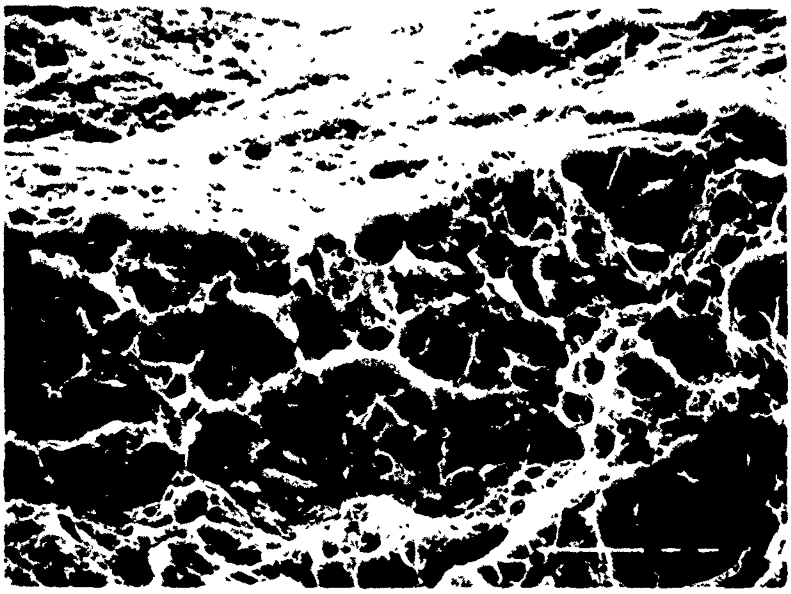
x 850

x 4200

(b) & (c). Successively higher magnifications of terraced areas of fracture examined above (#23, plate C). Ribbon-like areas appear as inclusions elongated in rolling. Note perforations.

x 60

Figure 5(a). Showing low-magnification SEM view of flat areas on TZ bar ligament in non-textured material (specimen #10, plate S-I).

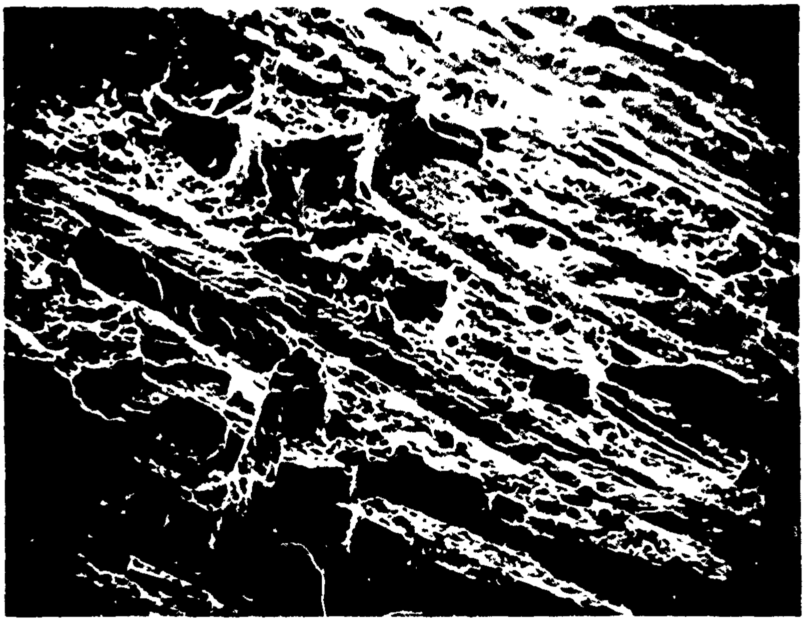


x 1500

(b). Higher magnification view of flat area of specimen #10 plate S-I above. Note: large inclusion population related to equiaxed dimples.

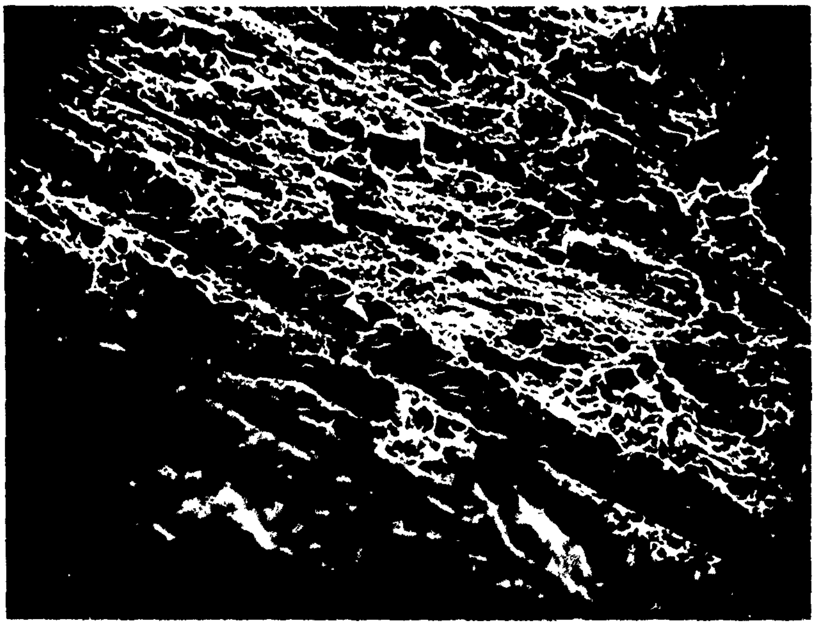
x 140

Figure 6(a). View of terraced area of ligament of 45Z specimen #29 (plate C). Beam of SEM is inclined at 45° to fracture plane.



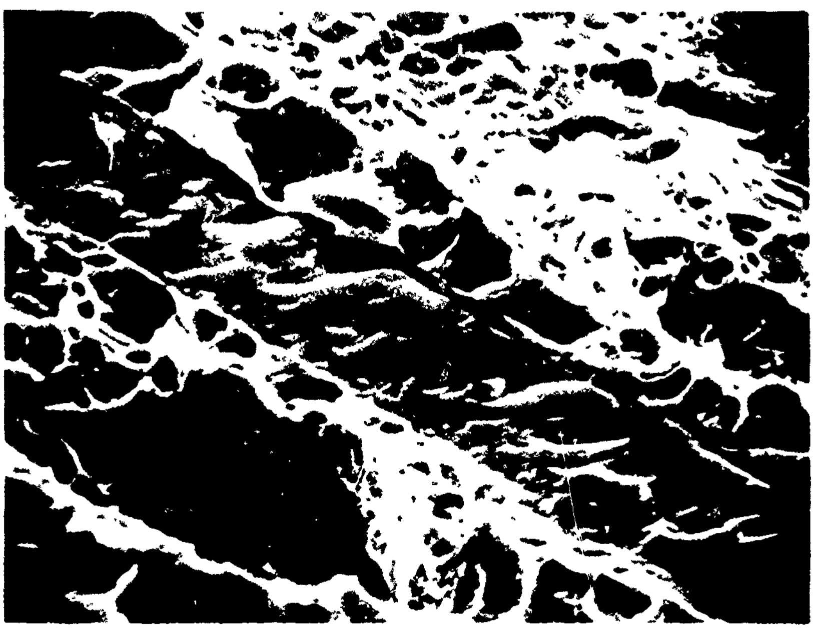
x 700

(b). Higher magnification view of (a) above showing ribbon-like areas and neighboring dimpled zone.



x 700

Figure 7(a). Alternate view of ribbon-like area on sample #29, perforations are visible.



x 3000

(b). High magnification view of (a) above, perforations fully in evidence.

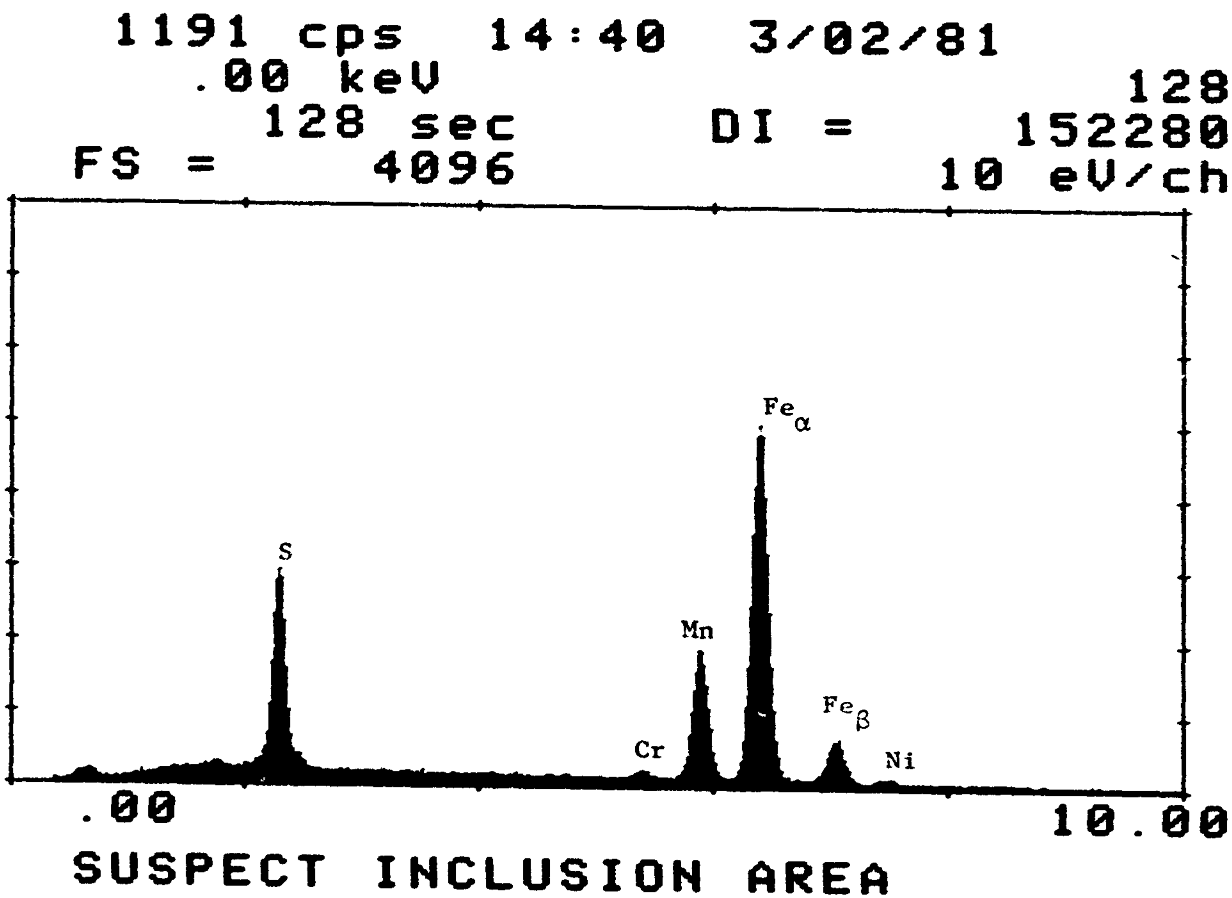


Figure 8. Energy dispersive X-ray analysis output for suspected inclusion area shown in Figure 7(b). Units of abscissa are KeV. Note presence of sulfur peak.

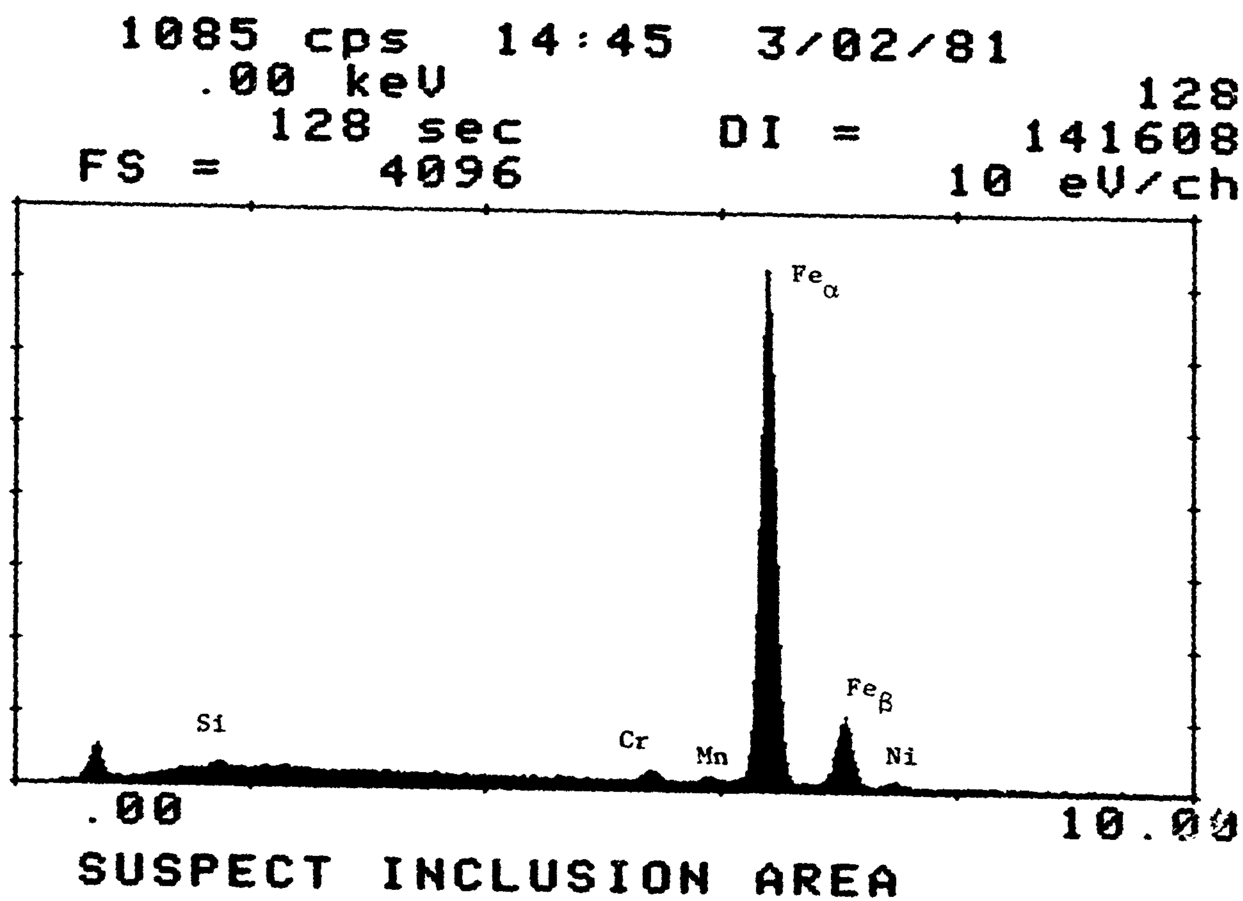


Figure 9. Energy dispersive X-ray analysis output for area associated with perforation in inclusion shown in Figure 7(b). Note absence of sulfur peak.

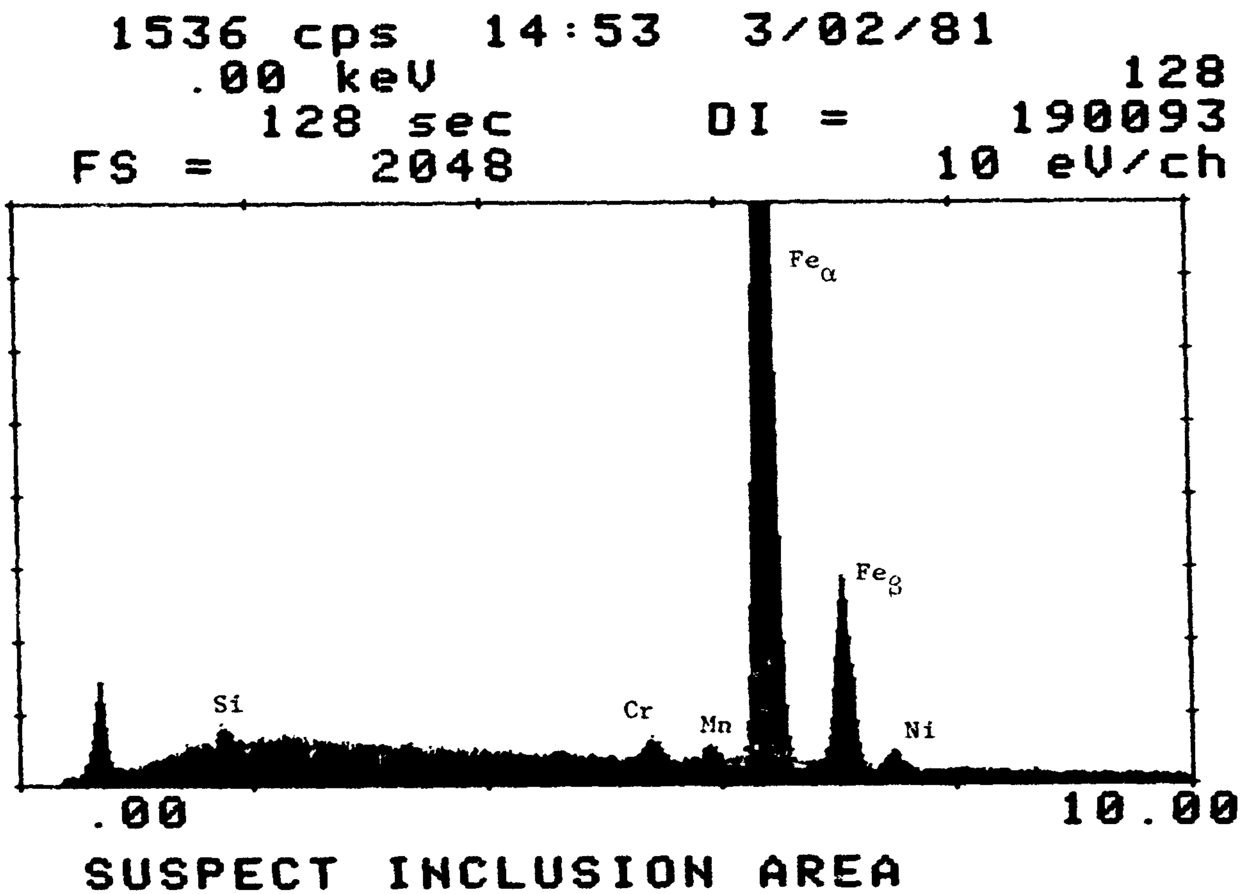


Figure 10. Energy dispersive X-ray analysis output for machined surface of DLT specimen #29.

x 992

Figure 11. View of MnS inclusion as seen in ZX plane of typical DLT bar sample. Note also highly directional nature of prior austenite grain structure.

APPENDIX

In the accompanying tables and sketches are included raw data on mechanical properties as determined, range information, as well as bar location information.

Note: When ligaments did not break simultaneously, the data reported is that for the first ligament to break. This principally involves short transverse samples only, but is an important point of procedure, since these values were then entered into the subsequent computations of ranges and averages. The tables attached to previous progress reports on this project generally reported average values of UTS, etc. where separate ligament fracture occurred. Tables included in the final report on the non-textured material, (reference two) dealt with such occurrences on the bases used in the attached tables, that is reporting data on the ligament breaking first only. Data on the second ligament breaking is available if required for further computation for both investigations.

Table A-I. Mechanical Properties of Textured ESR 4340, Plate S (DL Test Results)$^{\phi}$ (Raw Data)

Specimen Number	Specimen Orientation	Ultimate Tensile Strength σ_{UTS}	Stress at Fracture σ_f	Yield Strength σ_{ys}	Ligaments Break Together?	Ligament Percent Elongation		
						Left Ligament	Right Ligament	Average
33	TX	363	360	307	Yes	10.49	10.49	10.49
38	"	383	380	267	Yes	12.90	12.90	12.90
40	"	384	381	287	Yes	12.77	12.77	12.77
35	"	371	371	287	Yes	11.67	11.67	11.67
53	45X	366	360	269	Yes	12.25	12.25	12.25
63	"	377	374	289	Yes	11.74	11.74	11.74
51	"	378	375	275	Yes	12.25	12.25	12.25
57	"	366	360	276	Yes	12.40	12.40	12.40
56	315X	376	371	306	Yes	12.44	12.44	12.44
62	"	374	369	308	Yes	11.79	11.79	11.79
50	"	361	361	277	Yes	11.17	11.17	11.17
60	"	358	352	265	Yes	12.96	12.96	12.96
41	LY	388	385	284	Yes	10.77	10.77	10.77
45	"	344	341	286	Yes	8.28	8.28	8.28
47	"	375	375	298	Yes	9.72	9.72	9.72
43	"	322	322	---	Yes	5.93	5.93	5.93

Table A-1. (continued)

Specimen Number	Specimen Orientation	Tensile Strength σ_{UTS}	Stress at Fracture σ_f	Yield Strength σ_{ys}	Ligaments Break Together?	Ligament Percent Elongation: Left Ligament	Right Ligament	Average
34	TZ	281	281	---*	Yes	2.60	2.60	2.60
36	"		Not Valid					
37	"	231	231	---*	No	1.41	9.68	5.55
39	"	281	281	---*	Yes	2.63	2.63	2.63
49	45Z	181	181	---*	No	1.04	6.13	3.59
55	"	202	198	---*	No	1.8	11.54	6.67
59	"	230	230	---*	No	1.45	12.16	6.80
61	"	227	227	---*	Yes	1.07	1.07	1.07
54	315Z	210	210	---*	No	1.39	5.77	3.58
64	"	184	184	---*	No	0.81	7.05	3.93
58	"	199	199	---*	Yes	0.83	0.83	0.83
52	"	385	385	---*	No	2.1	12.33	7.22
42	LZ	249	249	---*	No	2.41	8.06	5.24
48	"	248	248	---*	No	1.55	9.60	5.57
44	"	223	223	---*	Yes	1.33	1.33	1.33
46	"	257	257	---*	No	2.3	12.2	7.25

*Appeared to break within the elastic range.

$^{\phi}$Stresses in Ksi.

Table A-II. Mechanical Properties of Textured ESR 4340, Plate C (DL Test Results)$^{\phi}$ (Raw Data)

Specimen Number	Specimen Orientation	Ultimate Tensile Strength σ_{UTS}	Stress at Fracture σ_f	Yield Strength σ_{ys}	Ligaments Break Together?	Ligament Percent Elongation: Left Ligament	Right Ligament	Average
1	TX	366	362	268	Yes	12.08	12.08	12.08
3	"	335	297	239	Yes	12.50	12.50	12.50
6	"	363	360	268	No	8.88	22.81	15.85
8	"	334	334	---	Yes	9.34	9.34	9.34
21	45X	385	381	290	Yes	10.71	10.71	10.71
25	"	345	342	302	Yes	9.90	9.90	9.90
31	"	391	391	290	Yes	8.5	8.5	8.5
19	"	359	358	280	Yes	10.9	10.9	10.9
24	315X	393	393	307	Yes	9.43	9.43	9.43
30	"	384	377	294	Yes	10.41	10.41	10.41
18	"	376	373	259	Yes	10.54	10.54	10.54
28	"	366	366	251	No	7.70	23.0	15.35
9	LY	387	387	313	Yes	8.34	8.34	8.34
13	"	391	391	325	Yes	7.79	7.79	7.79
15	"	362	359	304	Yes	8.85	8.85	8.85
11	"	389	389	316	Yes	5.75	5.75	5.75

Table A-II. (continued)

Specimen Number	Specimen Orientation	Ultimate Tensile Strength σ_{UTS}	Stress at Fracture σ_f	Yield Strength σ_{ys}	Ligaments Break Together?	Ligament Percent Elongation: Left Ligament	Right Ligament	Average
4	TZ	150	150	---*	Yes	0.42	0.42	0.42
5	"	178	178	---*	No	0.75	5.67	3.21
7	"	148	146	---*	No	1.0	5.79	3.40
2	"	108	108	---*	Yes	0.23	0.23	0.23
17	45Z	147	147	---*	No	0.41	5.74	3.08
23	"	162	162	---*	No	1.45	5.68	3.57
29	"	149	149	---*	No	0.57	4.59	2.58
27	"	148	148	---*	Yes	0.53	0.53	0.53
22	315Z	147	147	---*	No	0.49	4.18	2.34
32	"	162	162	---*	No	0.58	5.25	2.92
20	"	168	168	---	Yes	0.60	0.60	0.62
26	"	202	202	---	No	1.3	7.58	4.44
10	LZ	148	148	---*	No	0.50	5.25	2.87
16	"	190	190	---*	No	0.83	6.18	3.51
12	"	155	155	---	Yes	0.80	0.80	0.80
14	"	218	218	---*	Yes	1.3	1.3	1.3

*Appeared to break within the elastic range.

$^{\phi}$Stresses in Ksi.

Table A-III. Ranges of Mechanical Properties Obtained Using DLT Test on Textured Plates of VAR 4340†

Orientation of Specimens	Plate	Ultimate Tensile Strength σ_{UTS}	Yield Strength σ_{ys}	Percent Elongation
TX	S	363-384	267-307	10.49-12.9
TX	C	334-366	239-268	8.88-12.5
45X	S	366-378	269-289	11.74-12.40
45X	C	363-393	280-302	8.5-10.90
315X	S	358-376	265-308	11.17-12.96
315X	C	365-393	251-307	7.7-10.54
LY	S	322-388	284-298	5.93-10.77
LY	C	362-391	304-325	5.75-8.85
TZ	S	231-281	------*	1.41-2.63
TZ	C	108-178	------*	0.23-1.00
LZ	S	257-223	------*	1.33-2.41
LZ	C	148-218	------*	0.50-1.3
45Z	S	181-230	------*	1.04-1.8
45Z	C	147-162	------*	0.41-1.45
315Z	S	184-385	------*	0.81-2.1
315Z	C	147-202	------*	0.49-1.3

*Appeared to break at stress below that of general yielding.

†Stresses in Ksi.

DIRECTIONS:

X LONGITUDINAL

Y LONG TRANSVERSE

Z SHORT TRANSVERSE

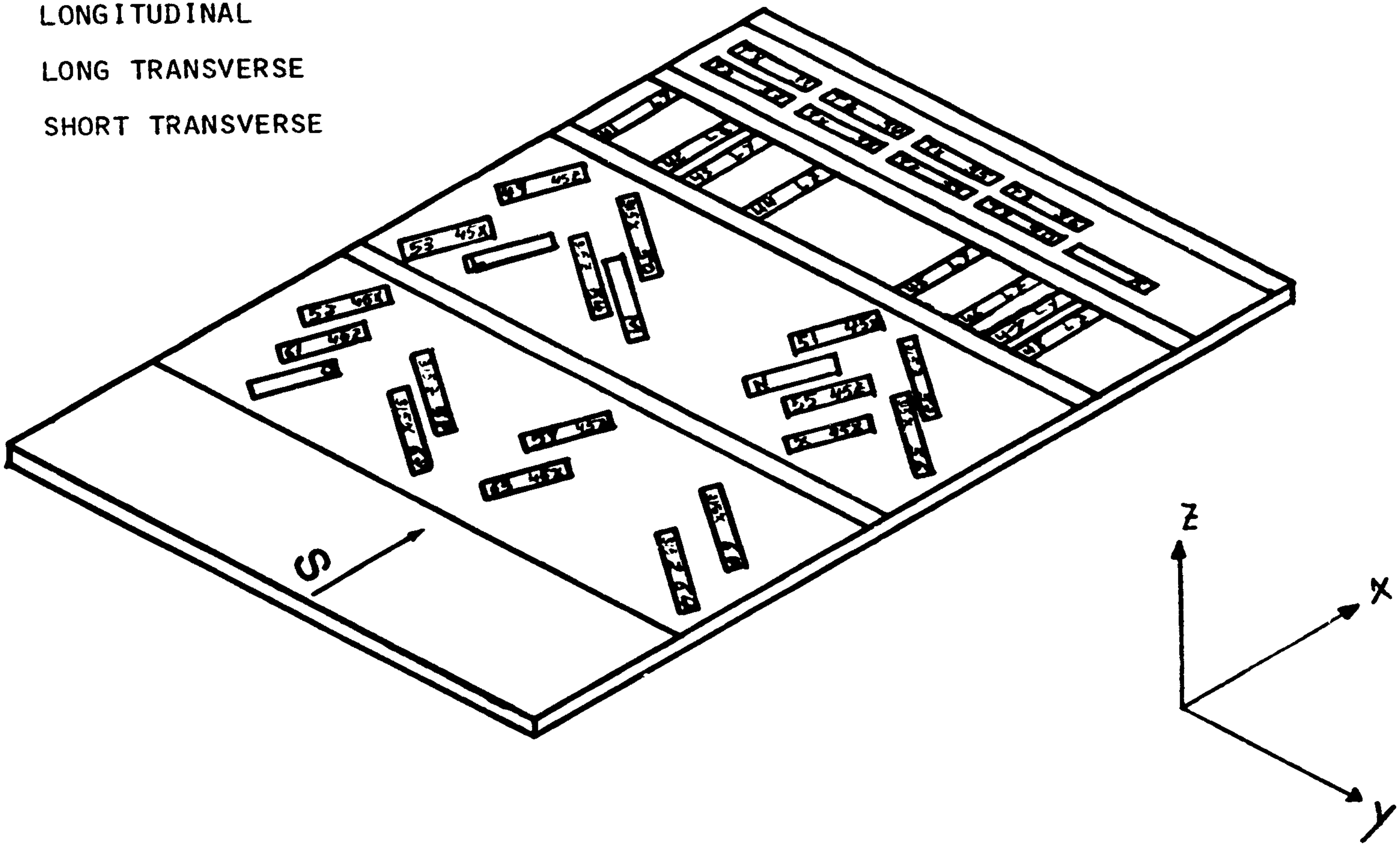


Figure A-1. Showing Specimen Location in 0.2 in Thick Material

DIRECTIONS:

X LONGITUDINAL

Y LONG TRANSVERSE

Z SHORT TRANSVERSE

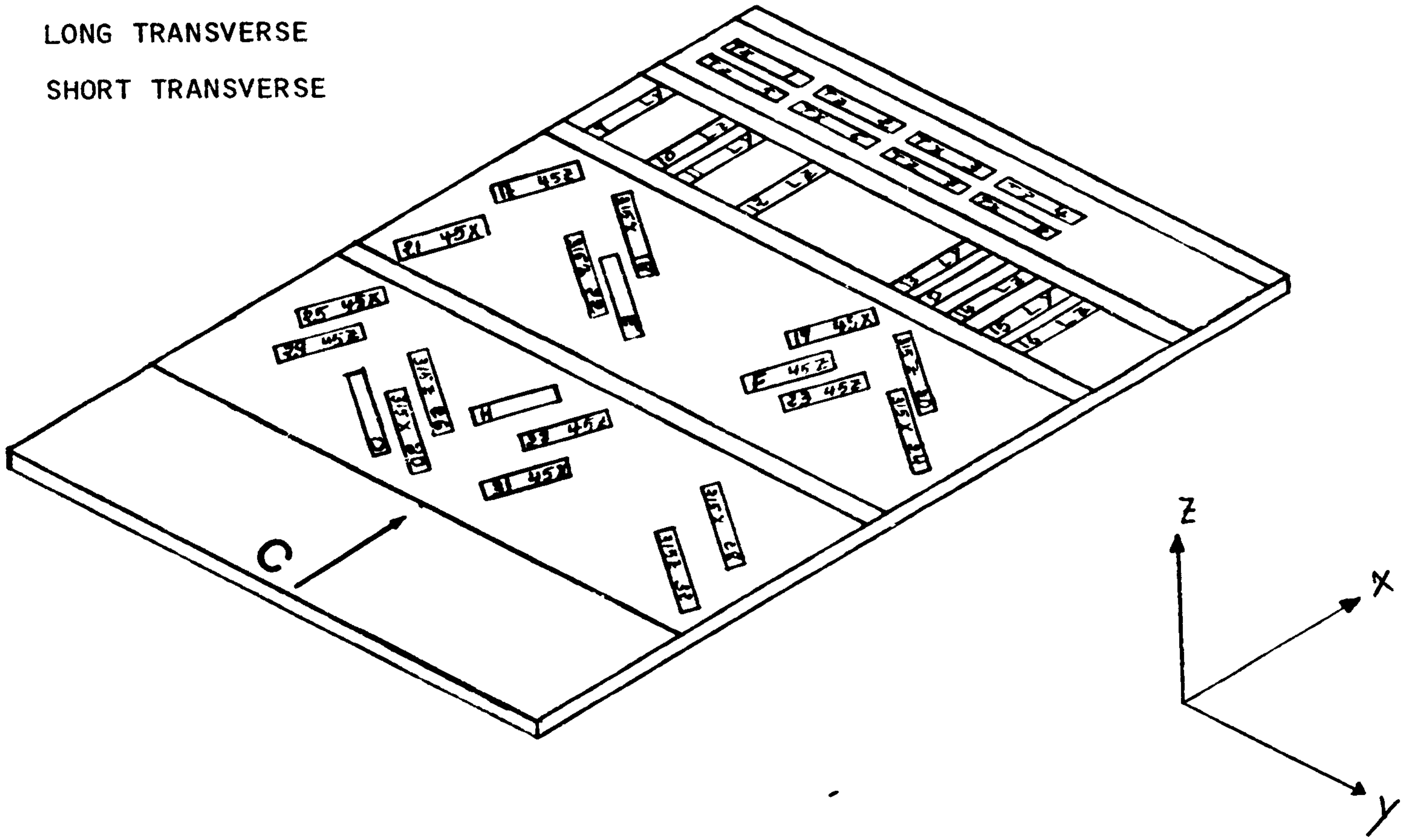


Figure A-2. Showing Specimen Location in 0.2 in Thick Material

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