NISTIR 4501
Report No. 21

Crack Arrest Fracture Toughness Measurements of Normalized and Inclusion Shape Controlled AAR TC128 Grade B Steel, and Micro-Alloyed, Control-Rolled, and Inclusion Shape Controlled A 8XX Grade B Steel

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INTRODUCTION

The Association of American Railroads (AAR) Tank Car Committee recently asked the Research Progress Institute (RPI)-AAR Tank Car Safety Project to investigate the properties of micro-alloyed steels and the potential for using them as replacements for conventional tank car steels. An extensive test program was conducted by the RPI-AAR to identify candidate new steels. It was concluded that the control-rolled steels of the niobium vanadium (Nb-V) type showed superior weldability and improved toughness at low temperatures. Hence, specifications were developed for these micro-alloyed steels, and material was prepared and tested by members of the RPI-AAR Tank Car Committee.

In conjunction with the RPI-AAR research, the Mechanical Properties and Performance Group of the National Institute of Standards and Technology (NIST), formerly the National Bureau of Standards, was asked by Ms. Claire Orth, Chief of the Safety Research Division of the Federal Railroad Administration (FRA), to develop, in addition to the AAR's Tank Car Committee, a mechanical property and fracture toughness data base for the newly developed, control-rolled, micro-alloyed Nb-V steel, A 8XX grade B. A similar data base was requested for normalized AAR TC128 grade B steel which is currently used in the manufacture of all new tank cars.

These two steels were ordered and, upon receipt metallographic examinations revealed that they were similar to, but not the same as, the steels mentioned above because both steels had been made using inclusion shape control practice (ISCP). This process spheroidizes the inclusions which is reported to enhance the upper shelf impact properties of the steel. After consultation with the project manager, Ms. Claire Orth, it was decided to continue evaluating these steels and subsequently two reports were prepared and delivered. The first report, NISTIR 90-4289, was entitled "Mechanical Properties and Fracture Toughness of AAR TC128 Grade B Steel, and a Micro-Alloyed, Control-Rolled Steel, A 8XX Grade B, From -80°F to +73°F," and the second, NISTIR 4300, "Determination of the NDT Temperature and Charpy V-Notch Impact Properties of

AAR TC128 Grade B Steel and A 8XX Grade B Steel." The first report presented mechanical test data including ultimate tensile and yield strengths, reduction-in-area, and elongation as a function of temperature. In addition, the Charpy V-notch impact strength as a function of temperature, and the NDT, or nil-ductility temperature, were determined for each steel. The NDT is the highest temperature at which cleavage, or brittle fracture occurs in these steels. Fracture toughness tests were also conducted in order to determine each steel's resistance to crack initiation. The second report, Number 20, consisted of the redetermination of both the NDT and impact properties of these two steels.

In assessing failures of steel structures, there often is evidence that prior to failure an undetected crack existed in the structure. In the study of cracks, there is often a "history" consisting of three stages. Stage one is crack initiation, which can occur under static or dynamic loading conditions. Stage two is crack growth, and this occurs under dynamic loading. The final stage is crack arrest. Sometimes crack arrest does not occur and a failure ensues, such as the unstable fracture observed during the separation of a tank car into two sections. Static fracture toughness data in Reports 19 and 20 showed that the normalized and inclusion shaped controlled AAR TC128 grade B steel was more resistant to crack <u>initiation</u> than the new experimental micro-alloyed, control-rolled, and inclusion shape controlled A 8XX grade B steel. Data such as these results are often considered conservative in fracture mechanics analysis, because they represent the fracture toughness under static loading conditions. More characteristic of the true or lower bound fracture toughness is the crack arrest value. This value is a dynamic fracture toughness value; that is, it is a measure of the steel's ability to arrest a <u>propagating</u> crack. It was, therefore, of interest to determine the crack arrest fracture toughness of both of these steels and ascertain whether or not the new A 8XX steel possessed a arrest fracture toughness comparable to normalized and inclusion shape controlled AAR TC128 grade B steel.

<u>EXPERIMENTAL PROCEDURE</u>

In order to test comparable material, Mr. T. H. Dalrymple, Chief Engineer of the Union Tank Car Company (UTC) and a member of the Tank Car Safety Committee, obtained for NIST from the Bethlehem Steel Corporation four plates of the micro-alloyed, control-rolled A 8XX grade B steel similar to that used in their research program. UTC also furnished NIST four plates of the normalized AAR TC128 grade B steel similar to that which was required for tank car construction as of January 1, 1989. These plates were also supplied by the Bethlehem Steel Corporation. Of the eight plates of steel received at NIST, four were AAR TC128 grade B steel taken from heat number 803A66600, and four plates A 8XX grade B steel taken from heat number 803A71430. A representative specimen used for the determination of chemical composition of each heat of steel was sectioned from the as-received plates. Microscopic examinations were conducted on all of the as-received plates in order to determine the as-polished and etched microstructures. These same samples were used to determine each steel's ferrite/pearlite grain size and the primary rolling direction of each plate.

For identification purposes, the control-rolled A 8XX grade B steel plates with Bethlehem heat number 803A71430 stenciled on them were labeled A, B, C, and D, and the normalized AAR TC128 grade B steel plates with Bethlehem heat number 803A66600 stenciled on them were labeled E, F, G, and H. The heat and check chemical analyses for each heat of steel, plates A and E, as determined by NIST and the Bethlehem Steel Corporation, along with the AAR chemical composition requirements for each steel, are shown in Table 1.

The chemical composition determinations, in particular the low sulfur contents and the presence of calcium, revealed that both of these steels were made using inclusion shape control practice. In conventionally processed steels, the sulfide inclusions are elongated in shape. However, if the final sulfur is 0.010 weight percent or less, the steel was probably desulfurized either in the hot-metal stage or by using steel-ladle metallurgy techniques. The desulfurization by Ca-Si injection usually leads to low sulfur and round inclusions. These round inclusions have a significant effect on the isotropy of the impact properties of the steel. The presence of the low sulfur and the calcium suggested that the AAR TC128 grade B steel was made using inclusion shape control practice and may have better notch toughness than AAR TC188 grade B steel without inclusion shape control.

Coupons used for the preparation of fracture toughness specimens in both the ASTM LT and TL orientations (see Appendix I for test specimen orientation diagram) were sectioned from both steels. In the ASTM LT orientation (conventionally referred to as "longitudinal" specimens), the plane of crack propagation in the specimen is perpendicular to the rolling direction, and in the TL orientation (conventionally referred to as "transverse" specimens), the plane of crack propagation in the specimen is parallel to the rolling direction. There were a total of 30 crack arrest specimens, 16 TL and 14 LT, tested from the normalized and inclusion shape controlled AAR TC128 grade B steel. A total of 30 crack arrest specimens, 13 TL and 17 LT, were tested from the micro-alloyed, control rolled, and inclusion shape controlled A 8XX grade B steel. The test temperatures for both steels ranged from -46°C (-50°F) to -18°C (0°F).

The crack arrest specimens were prepared and tested according to ASTM Designation E 1221-88, Standard Method for Determining Plane-Strain Crack-Arrest Fracture Toughness, K_{Ia}, for Ferritic Steels. This test method estimates the minimum value of the stress intensity factor, K, at which a fast running (i.e., unstable crack) will arrest. The test is made by forcing a wedge into a split pin which applies an opening force across the crack starter notch in a modified compact specimen, causing a run-arrest action. A schematic draw of this arrangement is shown in Figure 1.

The crack starter notch used was a hard, brittle weld into which a notch was machined. The distance from the edge of the specimen to the root of the notch was taken as the initial crack length. This value was used to calculate K_0, the stress intensity at crack initiation. A clip gage was attached near the edge of the specimen in order to measure the crack-mouth opening displacement (CMOD) one inch from the load line. The testing was performed in an insulated chamber, and both the specimen and chamber temperatures were monitored with thermocouples. After the system equilibrated, the load was applied to the wedge and both load and CMOD were recorded on an X-Y recorder. The ASTM method requires that the entire system initially be preloaded to a predetermined CMOD value, significantly lower than the initial CMOD value, in order to "seat" both the apparatus and specimen, and then unloaded. Following preloading, the specimen is loaded to a predetermined displacement. If the crack does not propagate and arrest, indicated by a load drop on the X-Y recorder, the specimen was unloaded and then reloaded to a higher displacement value. This sequence is repeated until either the crack propagates and arrests, or until the test record indicates that the crack is growing in a stable manner. Once crack arrest occurs, the specimen is removed from the test apparatus and heated in an air furnace at 371°C (700°F) for about one hour. The heating tints or darkens the crack that grew and arrested in the specimen. The specimen, upon cooling, is inserted into liquid nitrogen and then pulled apart. Visible to the naked eye is the crack growth that occurred in the specimen. The crack growth is measured, and this value is used to calculate the arrest fracture toughness, K_{Ia}.

RESULTS

The crack arrest fracture toughness values, as a function of temperature and specimen orientation, obtained for specimens taken from the normalized and inclusion shape controlled AAR TC128 grade B steel are shown in Tables 2 and 3. The K_o, calculated using ASTM method E 1221-88, reported in these tables is called the stress intensity factor at crack initiation since there was not an initial crack present in the material. The crack arrest toughness, K_a, was found to be essentially the same from -46°C (-50°F) to -26°C (-15°F) for the TL and LT test specimens. The average crack arrest fracture toughness for AAR TC128 grade B steel specimens was 67 ± 11 MPa*m^{½} (61 ± 10 Ksi*in^{½}) over this temperature range. The crack arrest fracture toughness, Tables 4 and 5, for specimens tested from A 8XX grade B steel, over the same temperature range, was 56 ± 9 MPa*m^{½} (51 ± 8 Ksi*in^{½}).

Tables 6 and 7 show comparisons of crack initiation and crack arrest fracture toughness values for both steels. The crack initiation values identified as K_I^1 in Tables 6 and 7 were those calculated according to the ASTM method E 813-89 and reported in FRA Report 19. The crack initiation fracture toughness, (these specimen were fatigued cracked), was computed using the measured "J" value and the following equation:

$$K = (JE)^{½}, \text{ where E is the elastic modulus}$$

It should be noted from these tables that the crack <u>initiation</u> toughness, or the ability of the AAR TC128 grade steel to resist crack initiation was significantly higher than that for the A 8XX grade B steel. The average crack initiation fracture toughness for the AAR TC128 grade B steel, for both LT and TL orientations, was 303 MPa*m^{½} (275 Ksi*in^{½}), whereas for the A 8XX grade B steel it was 75 MPa*^{½} (68 Ksi*in^{½}). Crack initiation values comparable to those measured for the AAR TC128 grade B steel were obtained when the A 8XX steel was tested at a temperature of -17.8°C (0°F) and above.

DISCUSSION AND CONCLUSIONS

A basic premise of fracture analyses is that there is a pre-existing crack, and that the stresses in the body and in particular near the crack tip exhibit elastic behavior. The stress magnitude at this crack tip depend on the stress intensity factor K. In cases where the specimens are pulled axially, such as those reported in Report 19, the stress intensity needed to initiate a crack is identified as K_I. An equation has been developed that relates the applied load, and various crack sizes and shapes, takes on the form:

$$K_I = \sigma*(\pi a)^{½}*f(a/W)$$

where a is the crack length, W the width of the specimen, and σ is the remote tensile stress perpendicular to the plane of the crack. In linear elastic fracture mechanics, unstable propagation of the existing flaw will occur when the stress intensity K_I attains a critical value called K_{Ic}. This fracture toughness value is both temperature dependent and is a property of the material. Having determined the value of K_{Ic}, and then substituting values of the anticipated flaw size into the above equation, the tensile stress which will propagate the crack could be determined. By comparing this value with the yield strength, or design strength, the ability of the structure to sustain this size crack and not fail in an unstable manner could be determined. The reader should be reminded that this is a static fracture toughness, since we are discussing the energy needed to initiate crack growth.

In addition to the K_{Ic} there are two additional fracture toughness properties, K_{Id} and K_{Ia} that are also dependent upon temperature and loading rate. The fracture toughness property K_{Id} is defined as the dynamic fracture toughness that is determined using fast loading rates. K_{Ia} is defined as the crack arrest fracture toughness determined when a fast propagating crack is arrested. It has been shown that K_{Id} and K_{Ia} are in most cases less than K_{Ic}, and that all three of these show a sharp increase with temperature.

In analyzing most failures involving tank cars, the scenario is often a derailment, followed by the puncturing of the shell or head of the car, and the tearing of the steel, i.e., a crack propagating in an unstable manner. We have shown in FRA Reports 19 and 20 that the normalized and inclusion shape controlled AAR TC128 Grade B steel was more resistant to crack initiation. Hence we concluded that if derailment and puncturing occurred, and no fire is present, the normalized and inclusion shaped controlled AAR TC128 grade B steel would be more resistant to crack initiation than the control rolled and inclusion shape controlled A 8XX grade B steel.

However, in a situation where impact produces a crack propagating in the steel, then the appropriate measure of the ability of the steel to arrest this propagating crack is the crack arrest fracture toughness. Tables 2, 3, 4, and 5 show the crack arrest fracture toughness for the AAR TC128 grade B steel to be slightly better than that for the A 8XX grade B steel.

Table 1. Chemical Composition (Wt%), the AAR Specifications, and Heat Analyses for both Steels.

AAR TC128 grade B			A 8XX grade B		
Specification[1]	Heat[2] Analysis	Check[3] Analysis	Specification[4]	Heat[2] Analysis	Check[3] Analysis
Carbon					
0.25 max	.22	.19	0.16 max	.15	.15
Manganese					
1.0-1.50	1.25	1.15	1.0-1.75	1.49	1.44
Phosphorus					
0.035 max	.024	.015	0.035 max	.016	.018
Sulfur					
0.040 max	.007	.009	0.010 max	.006	.007
Silicon					
0.15-0.50	.213	.21	0.10-0.55	.277	.30
Nickel					
0.25 max	.03	.01	NS[5]	.03	.01
Chromium					
0.25 max	.19	.21	NS	.04	.04
Molybdenum					
0.08 max	.074	.07	NS	.011	.01
Copper					
0.35 max	.017	.02	NS	.023	.03
Aluminum	.045	.059	NS	.054	.060
Niobium (Nb)	NS	<.005	0.06 max[6]	.035	.039
Vanadium					
0.08 max	.033	.032	0.11 max[6]	.075	.076
Nitrogen	NS	.009	NS	NS	.014
Calcium	NS	.005	NS	NS	.006
Titanium	NS	<.005	NS	NS	<.005
C.E.[7]					
0.62 max	.49	.45	.47 max	.43	.42

1. AAR Specification for Tank Cars: Specification M-1002, M128.
2. Bethlehem Steel Corp.
3. NIST
4. Preliminary draft specification: A 8XX, Pressure vessel plates, high-strength, low alloy.
5. NS: Not specified
6. Niobium plus vanadium: 0.16 max
7. C.E. = Carbon Equivalent = C + Mn/6 + (Cr + Mo + V)/5 + (Cu + Ni)/15

Table 2. Crack Arrest Toughness for TL Specimens Taken from Normalized and Inclusion Shape Controlled AAR TC128 Grade B Steel

Specimen Number	Test Temperature °C	(°F)	Crack Initiation Stress Intensity Factor K_o MPa*m$^{1/2}$	Ksi*in$^{1/2}$	Crack Arrest Toughness K_a MPa*m$^{1/2}$	Ksi*in$^{1/2}$	K_a* ± SD MPa*m$^{1/2}$	Ksi*in$^{1/2}$
H6	-46	-50	119	108	46	42		
H7	"	"	111	101	70	64		
H8	"	"	125	114	59	54	56 ± 10	51 ± 9
H10	"	"	99	90	56	51		
H11	"	"	108	98	49	45		
H3	-40	-40	113	103	66	60		
H4	"	"	111	101	67	61	66 ± 3	60 ± 2
H5	"	"	108	98	64	58		
H12	-34	-30	99	90	47	43		
H13	"	"	119	108	59	54	55 ± 7	50 ± 6
H14	"	"	116	106	58	53		
H15	-26	-15	108	98	59	54	58 ± NA	53 ± NA
H16	"	"	111	107	57	52		
H17	-17.8	0	---	STABLE CRACK GROWTH				
H1	"	"	124	113	76	69	76	69

* Average at indicated temperature.

Table 3. Crack Arrest Toughness for LT Specimens Taken from Normalized and Inclusion Shape Controlled AAR TC128 Grade B Steel.

Specimen Number	Test Temperature °C	(°F)	Crack Initiation Stress Intensity Factor K_o MPa*m$^{1/2}$	Ksi*in$^{1/2}$	K_a MPa*m$^{1/2}$	Ksi*in$^{1/2}$	Crack Arrest Toughness K_a* ± SD MPa*m$^{1/2}$	Ksi*in$^{1/2}$
H23	-46	-50	104	95	56	51		
H24	"	"	112	102	74	67	66 ± 10	60 ± 9
H25	"	"	109	99	60	55		
H26	"	"	116	106	75	68		
H27	-40	-40	112	102	55	50		
H28	"	"	135	123	77	70	67 ± 11	61 ± 10
H29	"	"	137	125	70	64		
H30	-34	-30	125	114	54	49		
H31	"	"	112	102	53	48	56 ± 4	51 ± 4
H32	"	"	105	96	60	55		
H33	-26	-15	121	110	86	78		
H34	"	"	151	137	89	81	88 ± NA	80 ± NA
H36	-17.8	0	---	CRACK DID NOT RUN				
H37	"	"	171	156	69	63	69 ± NA	63 ± NA

* Average at indicated temperature.

Table 4. Crack Arrest Toughness for TL Specimens Taken from Micro-Alloyed, Control-Rolled, and Inclusion Shape Controlled A 8XX Grade B Steel.

Specimen Number	Test Temperature °C	(°F)	Crack Initiation Stress Intensity Factor K_o MPa*m^{½}	Ksi*in^{½}	Crack Arrest Toughness K_a MPa*m^{½}	Ksi*in^{½}	K_a* ± SD MPa*m^{½}	Ksi*in^{½}
D14	-46	-50	90	82	41	37	46 ± NA	42 ± NA
D15	"	"	107	97	52	47		
D11	-40	-40	103	94	45	41		
D12	"	"	116	106	53	48	51 ± 4	46 ± 4
D13	"	"	144	131	53	48		
D8	-34	-30	112	102	68	62		
D9	"	"	123	112	65	59	64 ± 5	58 ± 5
D10	"	"	119	108	58	53		
D5	-26	-15	119	108	67	61	69 ± NA	63 ± NA
D6	"	"	---	CRACK DID NOT RUN				
D7	"	"	155	141	71	65		
D2	-17.8	0	---	CRACK DID NOT RUN				
D3	"	0	---	CRACK DID NOT RUN				

*Average at indicated temperature.

Table 5. Crack Arrest Toughness for LT Specimens Taken from Micro-Alloyed, Control-Rolled, and Inclusion Shape Controlled A 8XX Grade B Steel.

Specimen Number	Test Temperature °C	(°F)	Crack Initiation Stress Intensity Factor K_o MPa*m^{½}	K_o Ksi*in^{½}	Crack Arrest Toughness K_a MPa*m^{½}	K_a Ksi*in^{½}	K_a* ± SD MPa*m^{½}	K_a* ± SD Ksi*in^{½}
D37	-46	-50	102	93	58	53	55 ± NA	50 ± NA
D38	"	"	125	114	52	47		
D33	-40	-40	110	100	51	46		
D34	"	"	124	158	66	60	54 ± 9	49 ± 10
D35	"	"	---	CRACK DID NOT RUN				
D36	"	"	112	102	45	41		
D28	-34	-30	---	CRACK DID NOT RUN				
D29	"	"	---	CRACK DID NOT RUN				
D30	"	"	125	114	54	49	56 ± 9	51 ± 8
D31	"	"	112	102	66	60		
D32	"	"	97	88	49	45		
D25	-26	-15	---	INVALID, CRACK GREW OUT OF SIDE GROOVES				
D26	"	"	---	INVALID, CRACK GREW OUT OF SIDE GROOVES				

* Average at indicated temperature.

Table 6. Crack Initiation and Crack Arrest Fracture Toughness for Normalized and Inclusion Shape Controlled AAR TC128 Grade B Steel.

Specimen Number	Specimen Orientation	Test Temperature °C	Test Temperature (°F)	Fracture Toughness K_I^1 MPa*m$^{1/2}$	Fracture Toughness K_I^1 Ksi*in$^{1/2}$	Fracture Toughness K_a^2 MPa*m$^{1/2}$	Fracture Toughness K_a^2 Ksi*in$^{1/2}$
F1[3]	LT	-53	-63	319	290		
F2	LT	"	"	319	290		
F15	TL	"	"	266	242		
F16	TL	"	"	245	223		
H234	LT	-46	-50			56	51
H24	LT	"	"			74	67
H25	LT	"	"			60	55
H26	LT	"	"			75	68
F3	LT	-40	-40	265	241		
F17	TL	"	"	284	258		
H27	LT	"	"			55	50
H28	LT	"	"			77	70
H29	LT	"	"			70	64
H33	LT	-26	-15			86	78
H15	TL	"	"			57	52

1. Crack initiation fracture toughness, plane stress, ASTM E 813-89.
2. Crack arrest fracture toughness, plane stress, ASTM E 1221-88.
3. "F" specimens are compact tension type.
4. "H" specimens are modified compact tension type.

Table 7. Crack Initiation and Crack Arrest Fracture Toughness for Micro-Alloyed, Control-Rolled, and Inclusion Shape Controlled A 8XX Grade B Steel.

Specimen Number	Specimen Orientation	Test Temperature °C	(°F)	Fracture Toughness K_I^1 MPa*m$^{1/2}$	Ksi*in$^{1/2}$	K_a^2 MPa*m$^{1/2}$	Ksi*in$^{1/2}$
B3[3]	LT	-51	-60	71	65		
D37[4]	LT	-46	-50			58	53
D38	LT	"	"			52	47
D14	TL	"	"			41	37
D14	TL	"	"			51	46
B1	LT	-40	-40	76	69		
D33	LT	"	"			51	46
D34	LT	"	"			65	59
D36	LT	"	"			45	41
D11	TL	"	"			45	41
D12	TL	"	"			53	48
D13	TL	"	"			53	48
D30	LT	-34	-30			54	49
D31	LT	"	"			66	60
D32	LT	"	"			49	45
D8	TL	"	"			68	62
D9	TL	"	"			65	59
B2	LT	-29	-20			-76	69
D5	TL	-26	-15	67	61		
D25	LT	"	"		CRACK DID NOT RUN		
D26	LT	"	"		CRACK DID NOT RUN		
B4	LT	-17.8	0	248	226		
B5	LT	-6.7	+20	306	279		
B14	LT	+22.8	+73	363	330		

1. Crack initiation fracture toughness, plane stress, ASTM E 813-89.
2. Crack arrest fracture toughness, ASTM E 1221-88.
3. "B" specimens are compact tension type.
4. "D" specimens are modified compact tension type.

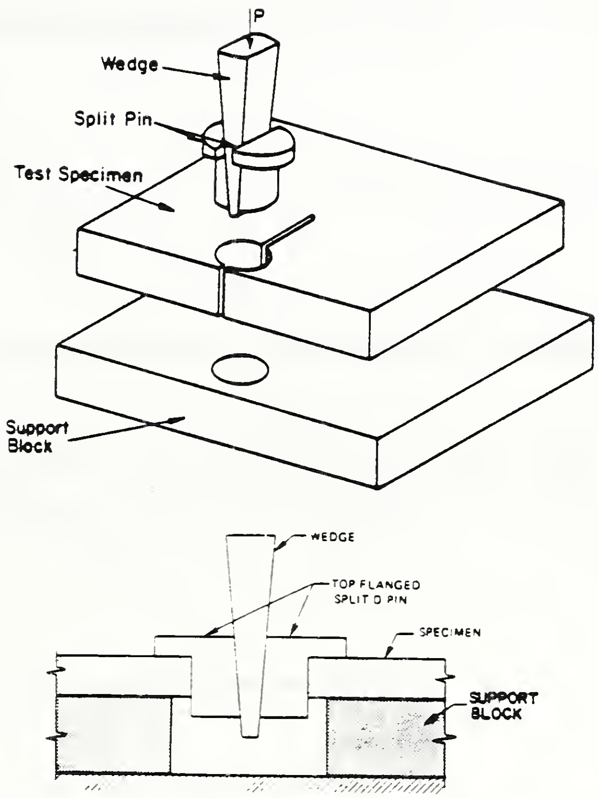
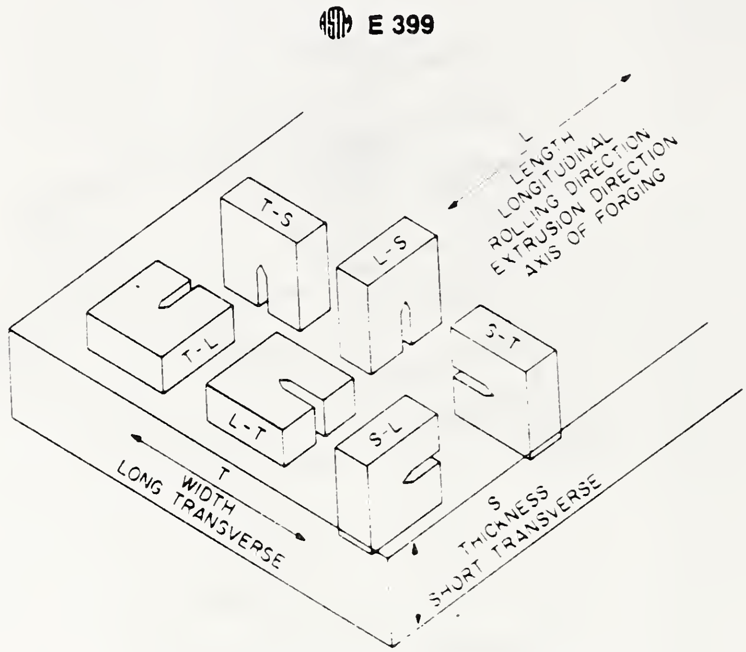


FIG. 1 Schematic Pictorial and Sectional Views Showing the Standard Arrangement of the Wedge and Split-Pin Assembly, the Test Specimen, and the Support Block.

Figure 1. Schematic drawing showing the standard arrangement of the wedge and split-pin assembly, the test specimen, and the support block. (ASTM drawing).

Appendix I

Test Specimen Orientation According to ASTM.



Crack Plane Orientation Code for Rectangular Sections

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The crack arrest fracture toughness was determined for normalized AAR TC 128 grade B steel and control rolled A 8XX grade B steel. Both steels were made using inclusion shape control practice. The crack arrest fracture toughness of the AAR TC 128 steel was slightly better than that for the A 8XX steel.

12. KEY WORDS (6 TO 12 ENTRIES; ALPHABETICAL ORDER; CAPITALIZE ONLY PROPER NAMES; AND SEPARATE KEY WORDS BY SEMICOLONS)
control-rolled steel; crack arrest; crack initiation; fracture toughness; inclusion shape control; normalized steel

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