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ESTABLISHMENT OF ULTRASONIC INCLUSION RATING METHOD FOR TORSION--ETC(U)
AUG 77 C J CARTER, R A CELLITTI DAAE07-75-C-0088

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TARADCOM LABORATORY TECHNICAL REPORT

NO. 12304

ESTABLISHMENT OF ULTRASONIC INCLUSION RATING METHOD FOR TORSION BAR SPRING

AUGUST, 1977

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by Clarence J. Carter &
Raymond A. Cellitti

International Harvester Co.
Manufacturing Research

Contract No. DAAE07-75-C-0088

U.S. ARMY TANK-AUTOMOTIVE
RESEARCH AND DEVELOPMENT COMMAND
Warren, Michigan 48090

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(9) Technical Report No. 12304

(6) Establishment of Ultrasonic Inclusion Rating Method for Torsion Bar Spring

By

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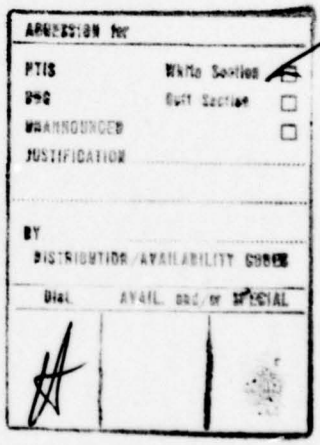
FOREWORD

This final technical report covers work performed under Contract DAAE07-75-C-0088 entitled "Establishment of Ultrasonic Inclusion Rating Method for Torsion Bar Spring."

The project was initiated under Materials Testing Technology Program and administered by Mr. Kazys Navasaitis of Material Application and Technology, U.S. Army Tank - Automotive Research and Development Command, Warren, Michigan.

Project activities were under the technical supervision of R. A. Cellitti, Manager, Metallurgical Research. Other areas of technical responsibility were provided by J. A. Harlan, Research Metallurgist and C. J. Carter, Research Associate.



ABSTRACT

Torsion spring material steel billets of 8660 and 51B60 were ultrasonically evaluated and graded for internal cleanliness. The billets were rolled to bar stock (2-5/8 inch diameter) reinspected ultrasonically and processed into torsion bars (P/N 7359890) for subsequent testing at TARADCOM. Standard test specimens were prepared and tested from bar and billet stock. Tension tests indicated that reduction (> 2:1) in ductility occurred with 8660 billets containing inclusion areas of ultrasonic signature No. 10. Inclusion area of 8660 bar stock (6.6:1 reduction from billet cross section) showed a 1.25:1 reduction in ductility for inclusion areas of category 10. Billet material of 51B60 indicated a 7:1 reduction in ductility for category 10 inclusion and bar stock indicated a 2:1 average reduction of ductility. Torsion test of specimens from billet stock for both alloy grades indicated susceptibility to crack occurrence from internal defects. Torsion yield strength of 51B60 showed a decline of 17.5% between extreme cleanliness grades. No difference in torsion yield strength was noted with 8660 bar stock which is attributed to a higher degree of ductility at high cleanliness severity levels. Fracture toughness (K_{IC}) was comparable for both alloy grades. Ultrasonic category 10 is equivalent to 2×10^{-5} in^2.

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INTRODUCTION

The classification of defects and acceptable quality level of straight, solid circular cross-section torsion bar springs and materials from which processed bars are inspected by visual methods include magnetic particle inspection. While visual inspection of surface and near surface discontinuities may afford suitable inspectional controls when applied to large defects and discontinuities, small indications which go undetected are crack initiation sources which may grow to critical sizes under service conditions resulting in premature fracture of the structure.

The ultrasonic inspection approach to evaluating and rating material quality has been successfully utilized as a supplemental method by steel producers and consumers for reliable quality assessment of raw material and end item structures. By coupling the ultrasonic detection unit with rapid electronic data processing equipment, an accurate and reliable quality rating system capable of detecting small defects is provided.

This program was concerned with a study in which (1) an automatic computerized ultrasonic rating system was utilized to inspect and rate internal cleanliness quality of semi-finished material (6" x 6", 15.24 cm x 15.24 cm cross-section billets) from which torsion bars were subsequently processed and (2) mechanical behavior of heat treated specimen bars representative of various material quality levels was ascertained.

I. OBJECTIVES

The primary objective of this study was to ultrasonically evaluate torsion bar material in the semi-finished condition (6" x 6", 15.24 cm x 15.24 cm billet) and rolled-formed bar size (2-5/8", 6.7 cm diameter) to assess and relate the influence of non-metallic inclusion size on engineering properties. A secondary objective was to evaluate a less expensive alloy steel (51B60) as an acceptable alternate in lieu of the alloy steel (8660) currently in use as torsion springs on the M-60 tank. Additionally, the project was concerned with fabrication of 70 torsion bars (P/N 7359890) representative of five cleanliness levels as determined ultrasonically. Thirty-five torsion bars were processed for each alloy and delivered for torsion testing at TARADCOM laboratories. Test specimen blanks (tension, torsion and fcsg Charpy) from bar and billet stock representative of various cleanliness levels were ultrasonically located, machined to a standard configuration and tested.

II. MATERIAL

Material for this study was procured in the form of 6" x 6" billets of 9.6 ft., 2.93 m lengths. The ladle analyses of the alloy steels were as follows:

Designation	C	Mn	P	S	Si	Ni	Cr	Mo	B
	.59	.88	.016	.028	.26	.43	.53	.18	-
51B60	.63	.91	.019	.020	.28	.04	.78	.01	.0005 Min

Jominy hardenability tests were also conducted. Jominy bars from both materials were normalized at 1600F (871C) and end-quenched

from an austenization temperature of 1550F (843C). The hardenability results are shown below:

Distance From Quenched End In 1/16"(1.6 mm)	Hardness, Rc 8660	51B60
1	62	62
2	62	62
3	61	61
4	61	61
5	61	61
6	60	61
7	60	61
8	59	60
10	59	60
12	56	59
14	49	51
16	46	43
20	39	41
24	36	37
28	34	33
32	34	31

Both alloys represented the product of three ingots which were selected (last poured ingots) to obtain a wide range of cleanliness grades.

Preparation

All billets were heat treated and surface conditioned (2 opposite and parallel ground surfaces) for optimizing ultrasonic acoustical response. Heat treatment consisted of normalizing at 1600F (871C) for six hours followed by air cooling. Two opposite surfaces were then ground to provide a surface finish of 15 to 84 RMS.

Each billet was identified with a numeric code and marked in preselect segments (mult lengths) of 13 inch (33 cm) lengths. This mult length corresponded to a subsequent rolled 2-5/8 inch (6.7 cm) diameter bar of 84 inch (2.13m) length. This procedure

was intended to provide a comparison of inclusion magnitude or cleanliness rating between the semi-finished product (billet) and final bar size as determined ultrasonically. Figure 1 illustrates the manner in which the billets were identified and marked for individual inspection of each mult length.

III. ULTRASONIC INSPECTION

Instrumentation

Ultrasonic inspection was carried out using an automatic computerized ultrasonic cleanliness rating system. The IH cleanliness rating system is not commercially available as an assembled inspection unit. However, the inspection procedure and instrumentation requirements are described in Method B of ASTM E-588. The automatic computerized ultrasonic cleanliness rating system is pictorially shown in Figure 8.

The system detects and counts various size inclusions and internal discontinuities by pulsing a high frequency sound wave through the material. The sound waves are reflected back to a search unit with an intensity level which is related to the inclusion area. The reflected sound waves are converted to electric energy in which voltage is monitored 750 times a second and categorized into 16 separate levels. The computer continuously stores the incoming signals and performs a calculation of cleanliness index rating upon scan termination. The method of computation is as follows:

Cleanliness Index Rating = $\sum_i F_i P_i$

where: F_i = Frequency of counts (expressed as percent) for Category i

P_i = Progression factor for Category i

The progression or weighting factor (Pi) for category i = $1.62^{(i-2)}$.

The search unit or transducer employed was a 5 mhz, lithium sulfate, focused crystal.

Calibration

Ultrasonic calibration standards were prepared from both alloy grades which contained 1/64 inch (.40mm) dia. flat-bottom holes. Instrument calibration was effected by positioning the transducer over a (3 inch, 7.6 cm metal travel) flat-bottom hole and adjusting the sensitivity control to obtain a 2 inch (5.1 cm) video amplitude on the cathode ray tube. The highest magnitude counter (category 16) was then adjusted with an interface sensitivity control to respond to a mid-range voltage of 9.70 volts. Each category corresponds to a voltage range of 0.625 volts. The voltage range of category 16 is 9.375 volts to 10.00 volts. The video amplitude is lineally related to the analog (pulser/receiver) output voltage for video amplitudes between 0.2 inch (.51 cm) and 2 inch (5.1 cm). The video amplitude is related to the magnitude of energy reflected from an inclusion and/or defect area.

Ultrasonic Inspection Procedure

Billets

The billets were scanned parallel to the rolling direction with

lateral indexing of 0.050" (1.3mm). Each mult length was rated separately with gated inspection zones of 2 inch (5.1 cm) depth 1 to 3 inches, (2.54 cm to 7.6 cm) from the top surface). Five separate and adjacent gate widths of 1 inch (2.54 cm) were rated for each mult length as depicted in Figure 1. Figure 2 shows a print-out of data obtained for individual inspection zones.

Rolled Bars (2-5/8 inch diameter (6.7 cm) Diameter

A special fixture was constructed to accommodate round bar stock for ultrasonic inspection. The fixture consisted of a drive sleeve which was bolted to one end of the bar diameter. The sleeve was connected by a rubber gear pulley belt to a variable speed drive motor. A similar gear sleeve was attached to the motor drive shaft. The bar was immersed in an ultrasonic tank and supported on roller bearings clamped to cross beams in the tank. The fixture is photographically illustrated in Figure 3. The bar was rotated in position while the transducer traversed the length via a mechanized carriage at a lineal speed of .5 inches/sec. (1.3 cm/sec.).

IV. ULTRASONIC TEST RESULTS

Billet

The inspected material was assigned a cleanliness grade which was cross-referenced with the weighted ultrasonic cleanliness rating index. The five cleanliness grades or levels and associate ultrasonic cleanliness indices are shown below:

Grade	Ultrasonic Cleanliness Index	Remarks
A	0.6 to 1.2	No inclusions were noted in excess of category 8. 80% of inclusions are less than category 2 level.
B	1.2 to 3.0	No inclusions were noted in excess of category 13 and at least 60% of counts were below category 2 level.
C	3.0 to 10.0	A small percentage (less than 1) of category 16* level inclusions noted.
D	10.0 to 70.0	1% to 5% of category 16 level present.
E	Greater than 70.0	Over 5% of the total number inclusions scanned occurred in category 16 or higher.

*Category 16 is equivalent to a 1/64 inch (.4mm) diameter flat bottom hole.

The ultrasonic inspection results obtained from billet mult lengths are shown in Table I through Table V.

Bar

The various ultrasonic grades obtained for the bar stock are shown in Table VI and VII. Figure 4 shows a long subsurface crack which was ultrasonically detected in a billet and subsequently machined to locate the defect near the surface.

V. MECHANICAL PROPERTIES

Although a quantity (70) of torsions bars (P/N 7359890) were processed from 8660 and 51B60 material representative of various

cleanliness grades, mechanical tests were conducted on specimens to ascertain tension, static torsion and fracture toughness properties.

Specimen blanks representative of various cleanliness levels were ultrasonically located and sectioned from billet and rolled bar stock. Specimen blanks were heat treated (quenched and tempered) to obtain a hardness of Rc50 in accord with specification requirements (MIL-S-45387A). The heat treat cycles for both material grades consisted of austenitizing at 1575°F (857C) for 1½ hours, oil quenching and tempering at 725°F (385C) 2 hours. The resultant hardness after temper was Rc 49 to Rc 50.

Tension Tests

Standard tension specimens (0.505 inch (1.28cm) diameter) were prepared and tested in accord with ASTM E-8. The test results obtained with specimens (8660) located from billet material are shown in Table VIII. Test results of specimens (8660) located from rolled bar stock are shown in Table IX. As can be noted, both materials show comparable ultimate and yield strengths with specimens sectioned from the billet stock. Specimens prepared from 8660 show a higher percent reduction of area for all cleanliness levels or grades. Tension properties for specimens sectioned from billet and bar stock are shown in Table IX and Table X. Again, it is noted that strength properties remain fairly consistent until large defects are encountered whereupon ductility is reduced to such a magnitude that specimen fracture

occurs prior to yielding. This condition is more prevalent with the 51B60 alloy.

Torsion Tests

Torsion yield strength of specimens prepared from 8660 billet stock is presented in Table XII. Results obtained from bar stock material are listed in Table XIII for the various cleanliness grades. The bar stock indicates a higher yield strength in contrast to the billet stock.

Torsion yield strength of 51B60 specimens prepared from billet stock are listed in Table XIV. Torsion yield strength data of bar stock is shown in Table XV. As can be noted, the 51B60 material shows higher torsional yield strength over 8660 material for the cleaner grades (A and B). At the lower ultrasonic cleanliness levels a deterioration of 51B60 material torsional strength is observed. A photograph which depicts several fractured torsion specimens is shown in Figure 5. Figures 6 and 7 show the sites and extent of surface cracks observed on torsion specimens examined by magnetic particle inspection prior to testing.

Fracture Toughness

Fracture toughness evaluations were conducted using fcsg Charpy specimens. The results obtained for 8660 material are listed in Table XVI. Fracture toughness results for 51B60 material are shown in Table XVII. The influence of material cleanliness on

fracture toughness is observed with both alloys. A lower fracture toughness with the 51B60 material would be anticipated and was observed. The results shown in Tables XVI and XVII were computed by mathematical formula developed under Contract No. DAAG46-69-C-0005 for calculating K_{IC} using a fatigue cracked side-grooved Charpy specimen.

The mathematical formula is:

$$(K_{IC}/YS)^2 = \frac{4.9\ (W + 4.3)}{YS \times 10^{-3}} - 0.05$$

Where: YS = Yield Strength

W = Impact Energy

All side grooves were 0.020 in. (.51mm) deep with an included angle of 45^{o}. Fatigue crack depths of 0.025 to 0.030 inches (.635 to .762mm) were sought. However, the fatigue crack depth ranged from 0.015 to 0.290 inches (.38 to 7.37 mm) due to the high hardness level coupled with low toughness encountered with the specimens of higher defect severity. Therefore, K_{IC} values were also calculated based on G_{IC} or W/A which corrects for the wide scatter in fatigue crack depth.

The formula for calculating K_{IC} by this procedure is

$$K_{IC} = (EW/.0841A)^{\frac{1}{2}}$$

Where E = Young's Modulus

A = Net cross-section area

W = Energy (in.-lbs.)

The average K_{IC} values for all cleanliness grades were as follows:

	Maximum Value	Minimum Value	Mean Value	Std. Dev.
8660 (Bar)	84.6	68.9	74.3	3.14
8660 (Billet)	80.2	62.0	71.8	5.41
51B60 (Bar)	74.0	59.5	66.3	4.36
51B60 (Billet)	71.5	61.4	66.0	3.16

(ksi - $in^{\frac{1}{2}}$)

In comparing mean values, the 8660 bar stock indicated a 12% increase in fracture toughness over 51B60 bar stock. The 8660 billet stock shows a 9% increase in fracture toughness strength over 51B60 billet stock.

CONCLUSIONS

Mechanical properties evaluation of 8660 and 51B60 which were ultrasonically inspected and rated for cleanliness in bar and billet condition indicated the following:

1. Tension specimens from bar and billet material of 8660 showed a reduction in ductility (% R.A.) of 30.7% and 82.4%, respectively. Ductility of 51B60 specimens (bar and billet) were reduced 100% between clean (Grade A) and severe levels (Grade E) of internal defects.

2. Torsion yield strength for 8660 bar material did not show any reduction for the various cleanliness grades. Ultimate torsion strength

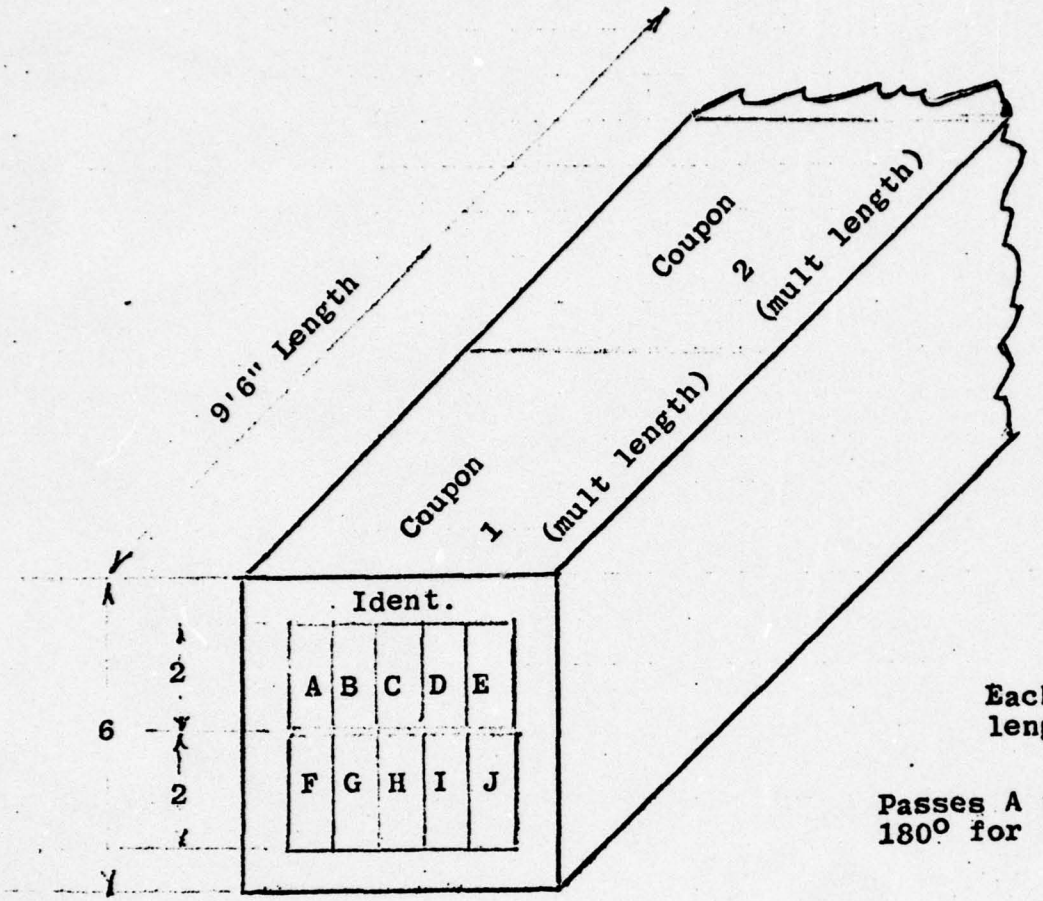
was reduced 6%. Torsion yield strength of 51B60 bar specimens was reduced 25% and a 13% reduction in ultimate torsion strength.

3. The 8660 bar material had a higher (12%) mean fracture toughness value than the 51B60 bar material.

4. In comparing very clean material (Grade A) for both steel alloys in bar form, 51B60 showed a 24% lower % R.A. for comparable ultimate and yield strength magnitudes, an 8% higher static torsion yield strength and a 5% lower static fracture toughness value.

RECOMMENDATIONS

Fatigue test results of the full size torsion bars for both steel chemistries at various cleanliness levels are needed before a complete recommendation can be made.



Pass Widths of 1"
(A, B, C, D,...J)

8 Coupons inspected/billet

Each coupon equivalent to torsion bar length of 85" when rolled to 2-5/8" dia.

Passes A through E inspected and billet rotated 180° for inspection of Passes F through J.

Figure 1 -- Zones and Method of Ultrasonic Inspection Coverage for 6" x 6" Billets

HEAT OPERATOR

BILLET 6 DATE

COUPON 1

PASS B (1")

GATE 1" to 3"

GAIN SETTING 120 P. FACT SET # 4.0

CATEG	COUNT	FREQ	P. FACT.	PROD
1				
2	63	.0008	1.0	.0008
3	10794	.1455	1.6	.2358
4	35186	.4744	2.6	1.2430
5	19824	.2673	4.2	1.1360
6	6025	.0812	6.9	.5597
7	1618	.0218	11.2	.2435
8	510	.0069	18.1	.1243
9	108	.0015	29.3	.0426
10	21	.0003	47.4	.0134
11	15	.0002	76.8	.0155
12				
13				
14				
15				
16				
TOTAL	74164			

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Figure 2 -- Computer Print-out of Defect Magnitude, Count and Calculated Cleanliness Index Rating

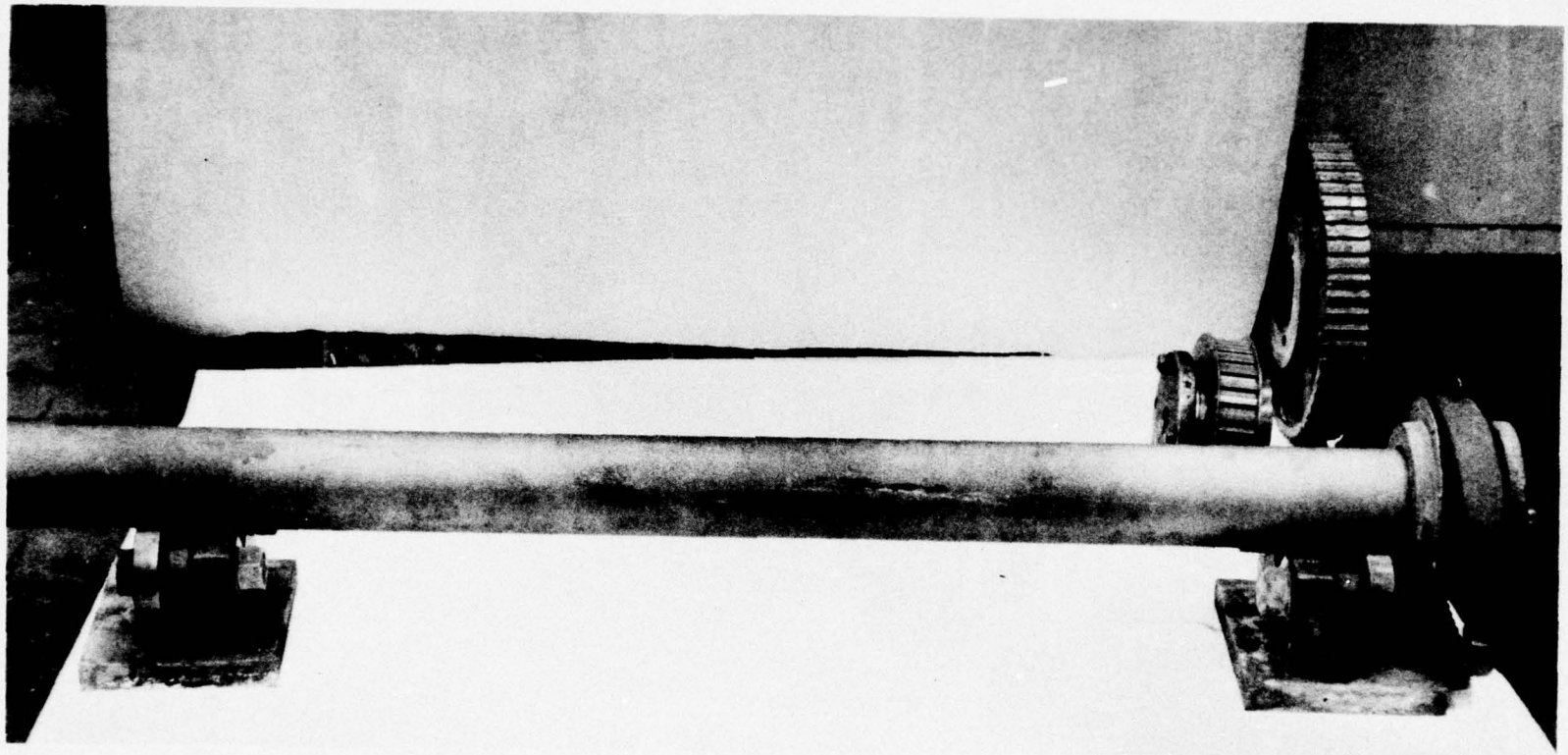

Figure 3 -- Support Fixture for Rotating Torsion Bar Stock
in Ultrasonic Immersion Tank

Figure 4 -- Internal Defect Located Ultrasonically in Billet and Subsequently Machined to Position Defect Near the Surface

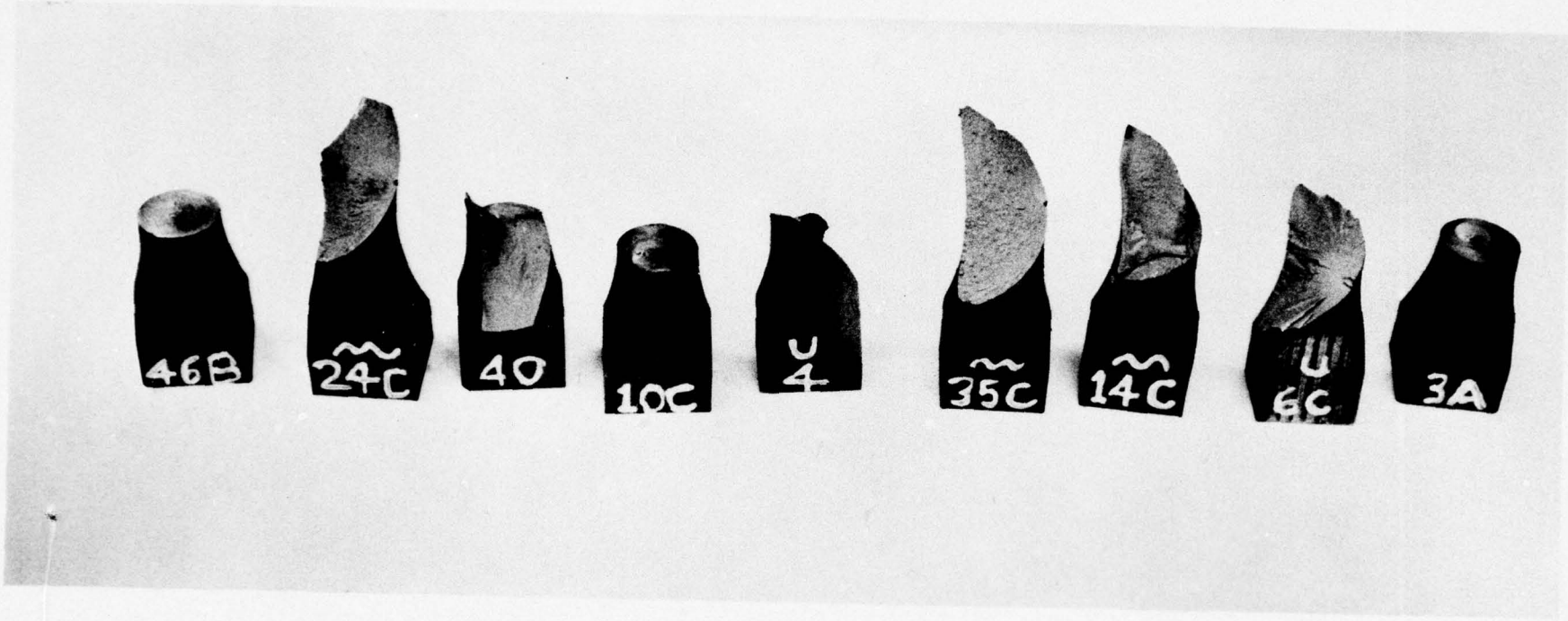

Figure 5 -- Fractured Torsion Bar Specimens

a. Spec. No. 3 8660, Cleanliness Grade A (bar)
b. Spec. No. 46 51B60, Cleanliness Grade A (bar)
c. Spec. No. 27 8660, Cleanliness Grade E (billet)
d. Spec. No. 35 51B60, Cleanliness Grade B (billet)

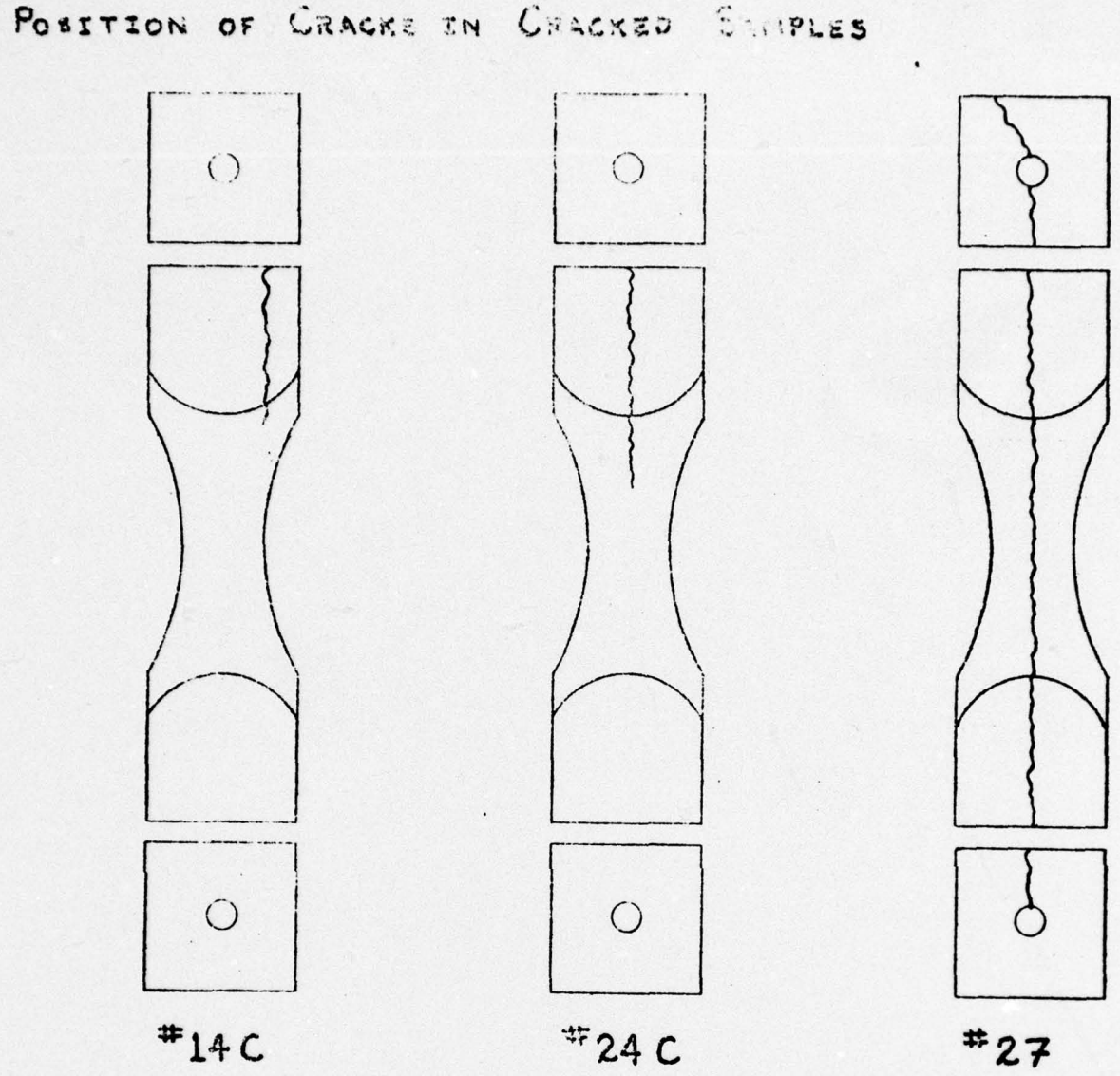

Figure 6 -- Sites of Surface Cracks which Propagated from Internal Defects Located Ultrasonically in Billet Stock

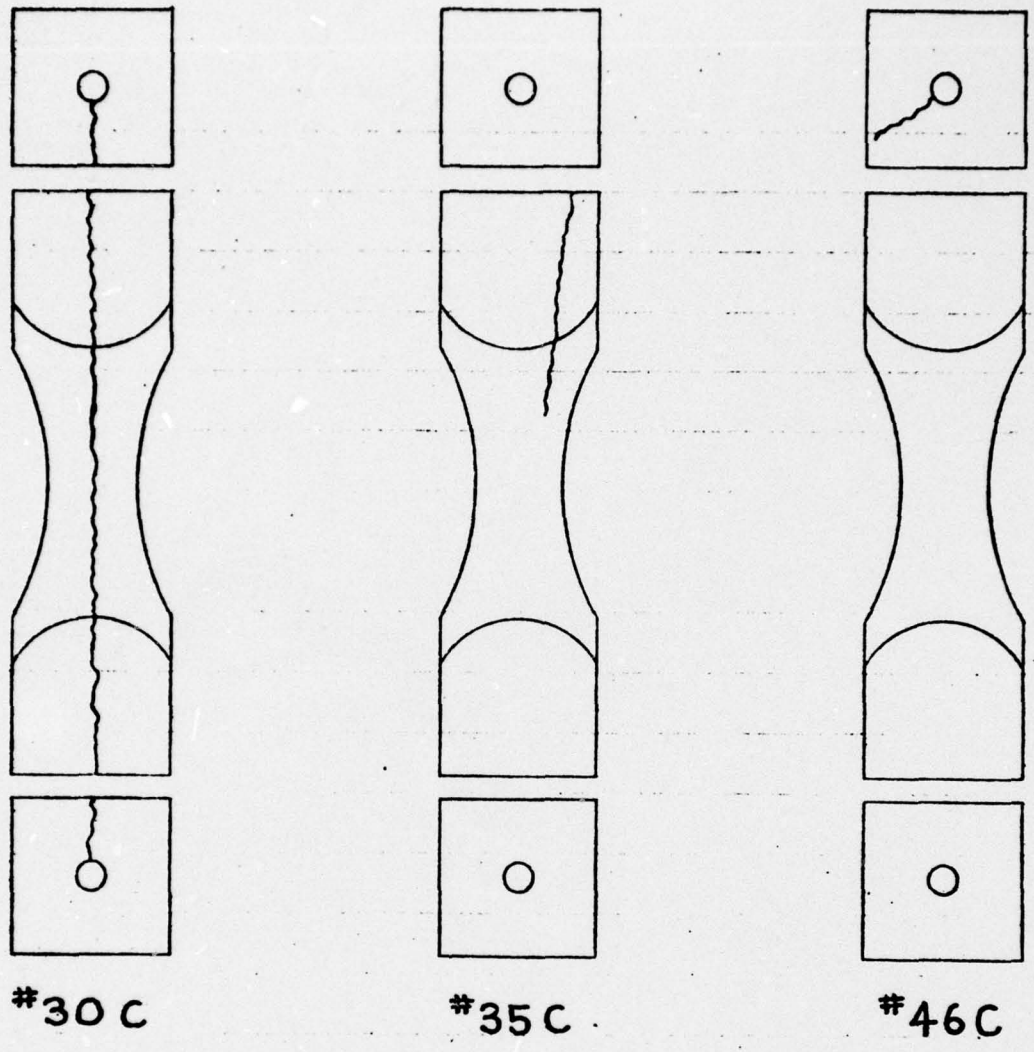

Figure 7 -- Sites of Surface Cracks which Propagated from Internal Defects Located Ultrasonically

(30C & 35C - Billet, 46C - Bar Stock)

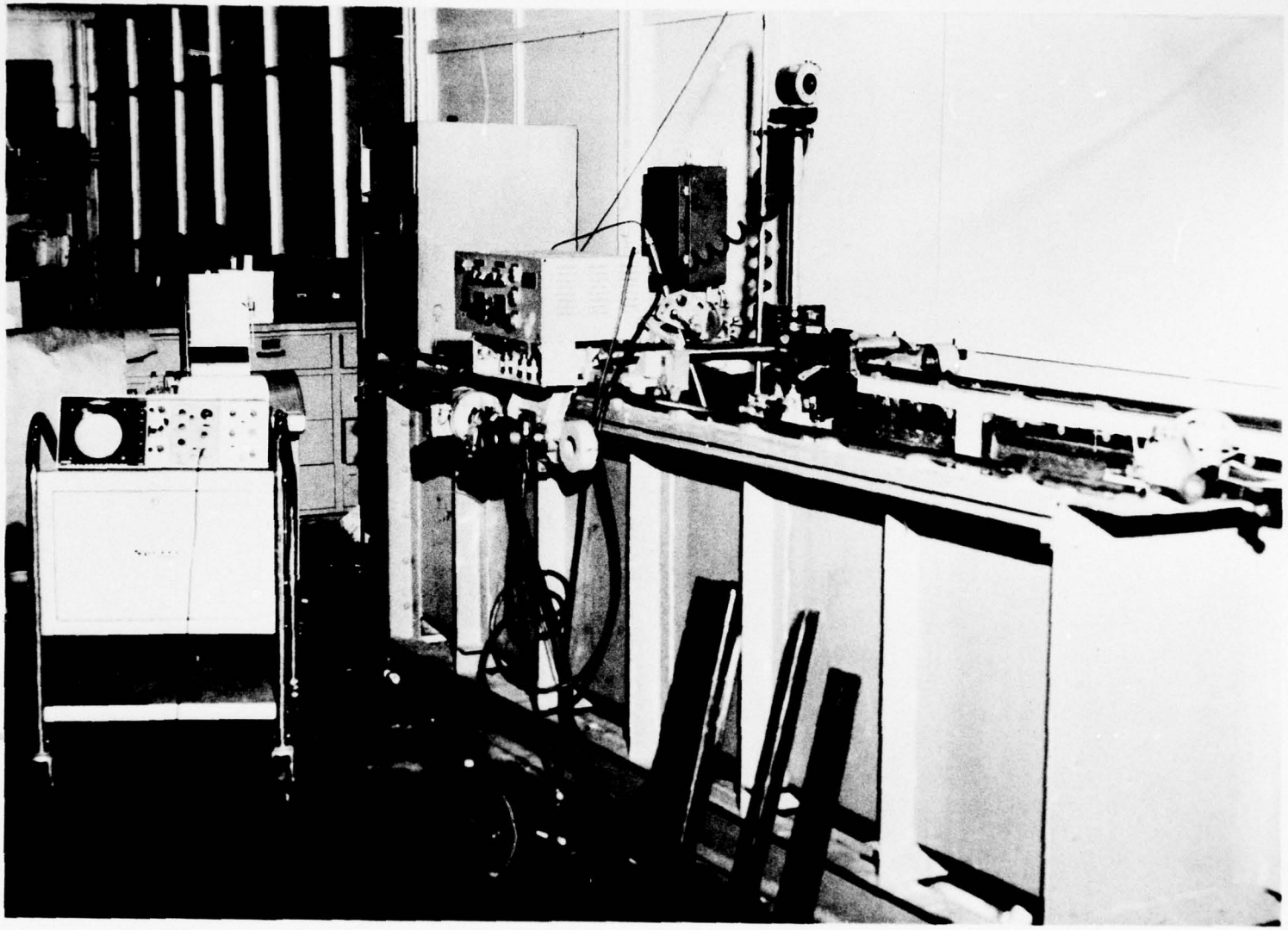

Figure 8 -- Automated Computerized Ultrasonic
Cleanliness Rating System

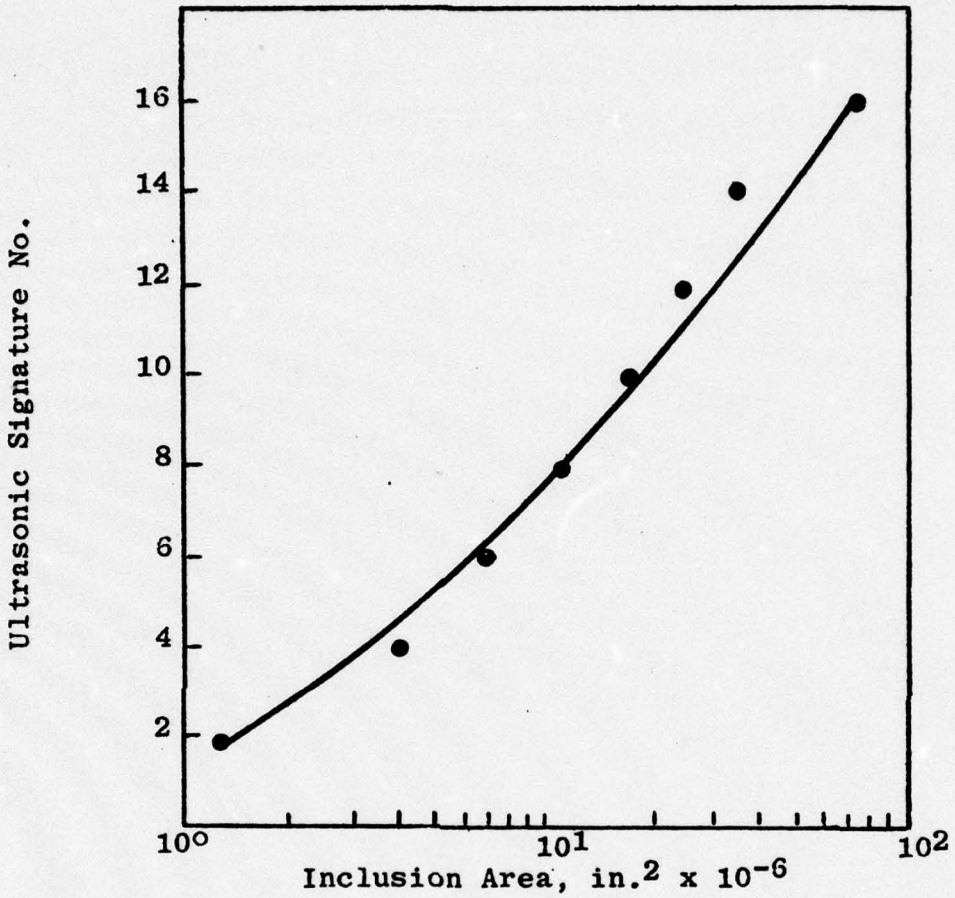

Figure 9 - Ultrasonic Inclusion Category Versus Inclusion Area as Measured by Light Microscopy

TABLE I

ULTRASONIC CLEANLINESS RATING (GRADE LEVEL) OF 6 IN X 6 IN BILLET MULT LENGTHS

8660

Billet #	Mult Length #	Grade	Billet #	Mult Length #	Grade
12	1	A	27	1	D
	2	C		2	C
	3	A		3	A
	4	A		4	A
	5	D		5	A
	6	D		6	E
	7	C		7	E
	8	D		8	E
8	1	D	7	1	A
	2	D		2	A
	3	B		3	A
	4	A		4	A
	5	B		5	B
	6	B		6	B
	7	A		7	B
	8	C		8	B
6	1	C	14	1	B
	2	B		2	B
	3	D		3	B
	4	D		4	B
	5	C		5	B
	6	C		6	B
	7	C		7	A
	8	D		8	B
9	1	D	11	1	A
	2	B		2	A
	3	B		3	A
	4	B		4	A
	5	B		5	A
	6	C		6	A
	7	B		7	C
	8	D		8	A
5	1	E	2	1	C
	2	E		2	C
	3	E		3	D
	4	E		4	A
	5	E		5	A
	6	E		6	A
	7	E		7	A
	8	E		8	D

TABLE II

ULTRASONIC CLEANLINESS RATING (GRADE LEVEL) OF 6 IN X 6 IN BILLET MULT LENGTHS

8660

Billet #	Mult Length #	Grade	Billet #	Mult Length #	Grade
22	1	C	10	1	A
	2	B		2	A
	3	B		3	A
	4	B		4	A
	5	D		5	A
	6	A		6	A
	7	A		7	A
	8	A		8	A
13	1	C	40	1	C
	2	A		2	A
	3	A		3	A
	4	A		4	A
	5	A		5	A
	6	B		6	C
	7	B		7	B
	8	C		8	A
37	1	B	33	1	D
	2	D		2	D
	3	D		3	D
	4	C		4	D
	5	C		5	D
	6	B		6	E
	7	C		7	D
	8	B		8	C
31	1	B	30	1	B
	2	D		2	B
	3	B		3	B
	4	B		4	B
	5	D		5	B
	6	B		6	B
	7	A		7	B
	8	B		8	B
14	1	C			
	2	B			
	3	C			
	4	C			
	5	D			
	6	B			
	7	B			
	8	A			

TABLE III

ULTRASONIC CLEANLINESS RATING (GRADE LEVEL) OF 6 IN X 6 IN BILLET MULT LENGTHS

51B60

Billet #	Mult Length #	Grade	Billet #	Mult Length #	Grade
15	1	A	34	1	D
	2	B		2	C
	3	B		3	C
	4	A		4	B
	5	A		5	C
	6	A		6	C
	7	A		7	D
	8	B		8	C
26	1	A	20	1	A
	2	B		2	A
	3	A		3	B
	4	C		4	B
	5	A		5	C
	6	A		6	A
	7	A		7	B
	8	B		8	A
32	1	A	36	1	C
	2	A		2	C
	3	A		3	C
	4	A		4	D
	5	A		5	E
	6	A		6	E
	7	B		7	B
	8	B		8	B
38	1	A	21	1	B
	2	A		2	D
	3	A		3	B
	4	A		4	D
	5	B		5	B
	6	A		6	D
	7	A		7	A
	8	A		8	A

TABLE IV

ULTRASONIC CLEANLINESS RATING (GRADE LEVEL) OF 6 IN X 6 IN BILLET MULT LENGTHS

51B60

Billet #	Mult Length #	Grade	Billet #	Mult Length #	Grade
23	1	A	4	1	A
	2	A		2	A
	3	A		3	B
	4	A		4	A
	5	A		5	B
	6	A		6	A
	7	A		7	A
	8	A		8	A
24	1	A	29	1	C
	2	A		2	C
	3	A		3	B
	4	A		4	B
	5	A		5	B
	6	A		6	A
	7	A		7	A
	8	A		8	B
35	1	A	16	1	A
	2	A		2	C
	3	A		3	C
	4	A		4	C
	5	B		5	C
	6	B		6	A
	7	B		7	A
	8	B		8	A
28	1	A	25	1	B
	2	A		2	B
	3	A		3	B
	4	C		4	B
	5	C		5	B
	6	A		6	B
	7	A		7	E
	8	A		8	E
18	1	B	3	1	A
	2	B		2	B
	3	B		3	C
	4	B		4	C
	5	C		5	B
	6	B		6	C
	7	C		7	C
	8	C		8	B

TABLE V

ULTRASONIC CLEANLINESS RATING (GRADE LEVEL) OF 6 IN X 6 IN BILLET MULT LENGTHS

51B60

Billet #	Mult Length #	Grade	Billet #	Mult Length #	Grade
39	1	B			
	2	B			
	3	C			
	4	A			
	5	A			
	5	C			
	7	A			
	8	A			

TABLE VI

BAR STOCK (2-5/8 INCH DIA.) MACHINED FROM 6 INCH X 6 INCH BILLETS

8660

Grade	Identification
I	A
II	F
III	B
IV	J
V	E

51B60

Grade	Identification
I	G
II	H
III	D
IV	K
V	C

TABLE VII

ULTRASONIC RATING (GRADE LEVEL) OF 2-5/8 INCH DIAMETER ROLLED BARS

8660

Grade	Bar Identification
A	9, 1, 20, 23, 18, 19
B	5, 2, 24, 12, 25, 13
C	11, 7, 14, 16, 17, 10, 26
D	21, 32, 39, 34, 37, 36
E	30, 31, 33, 29, 35, 38

51B60

Grade	Bar Identification
A	84, 56, 47, 77, 80, 82
B	62, 71, 83, 55, 69, 78
C	67, 87, 81, 68, 49, 72
D	61, 85, 86, 79, 41, 50
E	70, 53, 88, 63, 43, 73, 42

TABLE VIII

TENSION PROPERTIES (0.505 INCH DIA. SPECIMEN) SECTIONED FROM 6 IN. X 6 IN. BILLETS

8660

Ultrasonic Grade	Inclusion Category	UTS, Ksi	Ys Ksi	% Elong. (2 in.)	% R.A.
A	3	256.8	230.5	9.0	32.4
	3	256.4	228.1	8.5	29.6
B	5	256.7	229.4	8.5	32.5
	6	256.8	231.0	8.5	31.4
C	8	255.8	229.7	9.0	29.1
	10	264.7	233.3	8.5	29.7
D	13	257.8	229.6	6.0	15.4
	14	264.5	236.0	3.5	7.4
E	16	260.5	235.3	1.5	4.9
	16	248.6	235.5	1.5	3.7

TABLE IX

TENSION PROPERTIES (0.505 INCH DIA. SPECIMEN) SECTIONED FROM 2-5/8 INCH DIA. BAR

8660

Ultrasonic Grade	UTS, Ksi	YS, Ksi	% Elong. (in 2 Inch)	% R.A.
A	257.8	231.0	9.0	35.9
	261.6	235.6	9.0	35.0
B	258.6	230.1	8.5	30.5
	258.0	230.4	8.0	28.5
C	259.9	232.8	8.5	28.2
	259.1	232.6	8.5	27.9
D	256.8	230.9	8.0	27.5
	259.9	234.4	6.5	23.7
E	258.1	232.0	5.0	13.0
	259.4	230.2	5.5	11.9
	259.9	232.8	3.0	7.8

TABLE X

TENSION PROPERTIES (0.505 INCH. DIA. SPECIMEN) SECTIONED FROM 6 IN. X 6 IN. BILLETS

51B60

A	3	257.1	234.3	8.5	29.2
	4	255.7	232.0	8.0	27.0
B	5	265.3	236.7	8.0	24.4
	8	258.6	235.3	1.0	2.4
C	9	263.8	236.4	2.0	3.9
	10	245.4	238.9	1.0	4.0
D	12	256.0	236.2	5.5	7.4
	14	257.1	234.8	1.0	2.5
E	16	228.2	--	0	0
	16	233.0	--	0	0

TABLE XI

TENSION PROPERTIES (0.505 INCH DIA. SPECIMEN)
SECTIONED FROM 2-5/8 INCH DIA. BAR

51B60

Ultrasonic Grade	UTS, Ksi	YS, Ksi	% Elong. (In 2 Inch)	% R.A.
A	264.6	238.2	8.5	28.8
	264.3	235.7	7.5	28.3
B	260.2	233.5	8.5	27.2
	264.5	238.9	7.0	24.0
C	277.4	246.4	6.5	22.5
	256.6	221.0	2.0	5.1
D	259.8	233.7	2.5	3.1
	208.8	--	0 (cracked from inclusion)	0
E	200.2	--	0 (cracked from inclusion)	0
	224.7	--	0 (cracked from inclusion)	0

TABLE XII

STATIC TORSION STRENGTH OF
BILLET STOCK (6" x 6")

8660

Ultrasonic Grade	Torsion Yield Strength, In.Lbs.	Torsion Ultimate Strength, In.Lbs.
A	101,200	135,300
B	61,600*	61,600
C	107,800	138,600
D	110,000	135,300
E	77,000*	78,100

*Ruptured prior to yield

TABLE XIII

STATIC TORSION STRENGTH OF
BAR STOCK (2-5/8 INCH DIA.)

8660

Ultrasonic Grade	Torsion Yield Strength, In.Lbs.	Torsion Ultimate Strength, In.Lbs.
A	116,600	149,600
B	116,600	144,100
C	116,600	147,400
D	116,600	141,900
E	116,600	140,800

TABLE XIV

STATIC TORSION STRENGTH OF BILLET STOCK (6" x 6")

51B60

Ultrasonic Grade	Torsion Yield Strength, In.Lbs.	Torsion Ultimate Strength, In.Lbs.
A	119,700	146,000
B	112,200	137,500
C	102,300	119,900
D	93,500*	93,500
E	66,000*	66,000

*Ruptured prior to yield

TABLE XV

STATIC TORSION STRENGTH OF BAR STOCK (2-5/8 IN.DIA.)

51B60

Ultrasonic Grade	Torsion Yield Strength, In.Lbs.	Torsion Ultimate Strength, In.Lbs.
A	119,900	149,000
B	126,500	151,800
C	114,400	145,200
D	102,300	148,500
E	101,000	134,200

TABLE XVI

ROOM TEMPERATURE FRACTURE TOUGHNESS (K_{IC}) AS MEASURED BY FCSG CHARPY SPECIMENS

8660 (Billet)

Ultrasonic Grade	K_{IC}, Ksi $In^{\frac{1}{2}}$
A	76.5, 85.2, 80.4, 82.4
B	78.4, 81.3, 79.7, 80.2
C	74.7, 83.6, 81.9, 78.8
D	88.6, 71.5, 69.7, 80.1
E	62.4, 48.9, 70.4, 66.0

8660 (Bar)

Ultrasonic Grade	K_{IC}, Ksi $-In^{\frac{1}{2}}$
A	82.4, 83.5, 87.4, 79.2
B	78.3, 80.5, 79.3, 83.1
C	76.2, 81.3, 82.5, 79.1
D	80.3, 75.6, 77.8, 73.6
E	68.3, 74.5, 66.7, 76.5

TABLE XVII

ROOM TEMPERATURE FRACTURE TOUGHNESS AS MEASURED BY FCSG CHARPY SPECIMENS

51B60 (Billet)

Ultrasonic Grade	K_{IC}, Ksi, $In^{\frac{1}{2}}$
A	68.3, 66.4, 62.8, 64.9
B	68.7, 72.3, 76.6, 65.1
C	58.2, 55.1, 61.7, 63.4
D	60.5, 52.3, 58.7, 48.2
E	44.3, 49.2, 34.8, 46.5

51B60 (Bar)

A	72.4, 69.8, 81.4, 84.2
B	73.1, 62.9, 67.3, 73.6
C	80.3, 71.4, 60.9, 58.3
D	63.7, 66.4, 69.1, 52.8
E	59.2, 54.6, 57.3, 41.8

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Torsion spring material - Ultrasonic evaluation
Variable steel cleanliness - Torsion properties
Tension properties

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

Torsion spring material steel billets of 8660 and 51B60 were ultrasonically evaluated and graded for internal cleanliness. The billets were rolled to bar stock (2-5/8 inch dia.) reinspected ultrasonically and processed into torsion bars (P/N 7359890) forsubsequent testing at TARADCOM. Standard test specimens were prepared and tested from bar and billet stock. Tension tests indicated that reduction (>2:1) in
(continued on reverse)

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Abstract Cont'd.

billets containing inclusion areas of ultrasonic signature No. 10. Inclusion area of 8660 bar stock (6.6:1 reduction from billet cross section) showed a 1.25:1 reduction in ductility for inclusion areas of category 10. Billet material of 51B60 indicated a 7:1 reduction in ductility for category 10 inclusion and bar stock indicated a 2:1 average reduction of ductility. Torsion test of specimens from billet stock for both alloy grades indicated susceptibility to crack occurrence from internal defects. Torsion yield strength of 51B60 showed a decline of 17.5% between extreme cleanliness grades. No difference in torsion yield strength was noted with 8660 which is attributed to a higher degree of ductility at high cleanliness severity levels. Fracture toughness (K_{IC}) was comparable for both alloy grades. Ultrasonic category 10 is equivalent to 2×10^{-5} in^2.