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THE EFFECT OF MICROSTRUCTURE AND AGING CONDITION ON THE FATIGUE CHARACTERISTICS OF THE 18% Ni MARAGING STEELS

TECHNICAL REPORT

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ABSTRACT

Smooth and notched rotating beam fatigue characteristics at various strength levels are presented over the range of 10^3 - 10^5 cycles-to-failure for 250 and 300 grade 18% Ni maraging steels and a modified 4330 alloy. Two different heats of each of the maraging steels having large differences in ductility and toughness due to microsegregation are examined. In addition, the effects of under- and over-aging on fatigue properties are also studied.

The microstructural segregation in the maraging steel showed no detrimental effect on the smooth or notched fatigue properties even though the ductility and toughness values were greatly reduced. Underaging the maraging steels was found to drastically impair the notched fatigue behavior. No correlation was found between notched fatigue behavior, as expressed by notch strength reduction factor, and the standard engineering mechanical properties of ductility and toughness.

Cross-Reference Data

Aging (metallurgical)

Banded microstructure

Alloy steel

Mechanical properties

Nickel chromium molybdenum steel

Nickel maraging steel

Rotating-beam notched-fatigue properties

Tempering

Foreword

The authors express appreciation to C. C. DeLaMater and J. J. Genthner for help connected with the heat treatment and mechanical testing of the specimens. Mr. W. Shorkey helped with the drawings. Miss C. D. Szymanski and Mrs. M. Rogers typed the manuscript.

TABLE OF CONTENTS

Tables

Figures

TABLE OF CONTENTS (Continued)

INTRODUCTION

During recent years, considerable emphasis has been placed upon the development and application of higher strength materials. One of the most promising of the variety of materials developed in the past few years is the 18% Ni-Mo-Co maraging series of steels which has attained usable strength levels approaching 300,000 psi in large sections. Considerable data have been developed [1] concerning the mechanical properties of this alloy. However, as compared to the wealth of data available for quenched and tempered type low and intermediate strength steels[2,3,4], knowledge of the fatigue characteristics of this alloy is quite limited. North American[5] has reported rotating beam fatigue data for a 250 and 300 type steel with primary emphasis being placed upon establishment of the endurance limit. Similar data are available from the International Nickel Company[6] and Vanadium Alloy Steel Company[7]. Very low cycle fatigue properties of maraging steel have been studied by Manson[8] and Carman[9].

In this current investigation, the fatigue characteristics of the 250 and 300 type maraging steels as compared to an intermediate strength quenched and tempered 4330 alloy is examined in the range of 10^3 - 10^5 cycles to failure. The effects of primary structure, strength level and aging conditions on fatigue properties is examined and the results compared to measured ductility and toughness characteristics for possible correlation.

EXPERIMENTAL PROCEDURE

Materials

The specimens of 250 and 300 grade maraging steel were obtained from transverse sections of 6 inch square forgings. Two different heats of each material were used. All material was consumable vacuum melted. The chemical analyses of the four heats are given in Tables 1a and 1b along with that of the material utilized in References 5, 6 and 7. Considerable difference in structure existed between the A and B heats of the 250 and 300 grade materials utilized. The B heats of both the 250 and 300 grades of maraging steel contained a severely "banded" structure as shown in Figure 1a. This is caused by a concentration gradient within the melt as the steel solidifies into the ingot. Subsequent hot forming operations extend the defects along the longitudinal axis of the billet. The structure consists of large elongated grains with stringer-like inclusions within the bands as shown in Figure 1b. For comparison the microstructure of heat A is shown in Figure 2a. The banding is much less severe and has nearly equi-axed grains as can be observed in Figure 2b.

The specimens of 4330 modified steel were obtained from transverse sections of an air-melt forging in the form of a 120mm gun tube having an O.D. = 12.5 inches and I.D. = 4.5 inches. The chemical analysis is given in Table 1c along with that from References 2 and 3.

Heat Treatment

The maraging steel specimens were cut into blanks 1" x 1" x 5" and re-solution treated at 1500°F for 1 hour and air cooled. Specimens were machined to within 20 thousands of an inch of final tolerance followed by aging at various temperatures for 4 hours. Final machining was then completed. The aging temperatures and corresponding tensile properties are shown in Tables 2a and 2b.

The 4330 modified steel was cut into blanks 1" x 1" x 5" and re-austenitized at 1550°F for one hour and water quenched followed by tempering at various temperatures and then final machined. A slightly different treatment was given to obtain the highest strength level for this material. This was annealed at 1650°F for 3 hours, furnace cooled and the specimens machined to within 30 thousands of an inch of final tolerance. They were then austenitized at 1550°F for 1 hour, water quenched, tempered at 350°F for 3 hours and then machined to final dimensions. The tempering temperatures and corresponding mechanical properties are shown in Table 2c.

Specimen Configuration

Modified Krouse rotating beam type specimens were used in this study. The dimensions are shown in Figures 3 and 4. The notched tensile specimen dimensions are shown in Figure 5. The geometrical configurations to provide theoretical stress concentration factors of 3 and 5 in tension and pure bending were taken from Neuber's work[10]. Dimensional tolerances for all of the notched specimens were checked using an optical comparator having a 50X magnification.

Test Procedure

The fatigue tests were conducted on two Krouse rotating beam machines which were modified with gear reducers to reduce the cyclic rate from 10,000 cpm to 200 cpm. In this type of test, the specimen is loaded in 4 point bending which produced a constant bending moment across the gage section. The nominal bending stresses at the outer fibers of the specimen were computed from the standard engineering flexural formula. Since the assumption of a linear stress variation from the neutral axis to the surface is violated, some of the stresses to give lives in the low cycles region are only approximately correct. In using this equation effects of the notches on the stresses were not taken into consideration and the stresses were calculated as though the stress raiser was not present.

The present experiments were run at 200 cpm in order to minimize temperature effects and to facilitate a reasonable length of time for the life of the specimen. Since the weights are placed on the pans after the machine is rotating, too great a testing speed would result in the time of loading to total time of life ratio to be disproportionate for the high stress-low cyclic life region.

Another point that should be considered in choosing a cyclic rate in the low cycle region is the possibility of strain aging due to hysteretic heating. Self heating due to hysteresis can produce temperatures of 300-400°F which can significantly alter the behavior of the specimen. Some of the aspects of strain aging due to cycling at moderate temperatures above room temperature are discussed by Oates and Wilson[11] and Wang and Marco[12] relative to low carbon steels and tantalum.

The strain rate effect due to a wide range in cyclic frequency is another variable which may significantly influence fatigue results. This is pointed out in papers by Benham[13], Shabalin[14], Yamane and Sudo[15], and Dolan[16] . The influence of cyclic rate is much more apparent for notched specimens where the strains and consequently strain rates may become very large in the root of the notch.

RESULTS AND DISCUSSION

The mechanical properties of the maraging and 4330 steels in various heat-treated conditions are listed in Tables 2a, 2b and 2c.

It is to be noted that only a single heat treatment is recommended for obtaining optimum properties for both the 250 and 300 type maraging material. This consisted of solution treatment at 1500°F for 1 hour and aging at 900°F. However, underaging treatments were carried out on both the 250 and 300 maraging material as well as an overaging on one series of specimens of the 300 type material in order to determine what effect this would have on standard mechanical properties and fatigue characteristics.

Tables 2a and 2b show that overaging and underaging lowers the strength and slightly enhances ductility and toughness for both grades of steel. It can also be noted that the ductility and toughness of the under- and overaged

300 grade steel are lower than those values for the 250 grade steel at the same strength level.

Two different heats of the 250 and 300 maraging steel were investigated. Heat A had approximately twice the ductility and toughness of heat B. The cause of this drastic difference in lieu of the nearly identical chemical composition is not known but may be due to the banding as previously described.

The graphs of nominal bending stress, normalized by ultimate tensile strength, versus number of cycles to failure for the three categories of steel having smooth and two different notched configurations are shown in Figures 6a - 10b. The statistical least squares line, shown in Figures 6a through 10b, is extrapolated (by dashed lines) from approximately 2500 cycles back to 1000 cycles. Data from these extrapolated regions should be used with care. The letter linking the line on the graph to the particular metal and strength level is given in Tables 2a - 2c. The correlation coefficients for the curves, which give an indication of the relative data spread, and other statistical information is listed, by material, in Tables 3a - 3c. The data was analyzed according to the regression analysis approach given in Reference 17.

It is apparent from Figures 6a, 6b and 9a that the smooth fatigue data is effectively proportional to the tensile strength with the exception of the 4330 material heat treated to the 261 ksi tensile strength level. Although the reason for this exceptional behavior of the 261 ksi tensile strength 4330 steel is not fully understood, a possible cause may be due to its low ratio of yield to tensile strength as compared to the other materials studied. Bairstow[18] observed that the endurance stress in steel corresponded closely to the stress at which microscopic plastic flow first occurred which is at some fraction of the measured macroscopic yield stress. Thus, a material with a low yield to tensile strength ratio might exhibit lower fatigue propties at equivalent strength levels than a material with a high ratio. It can also be observed from these figures that wide variations in ductility, and toughness, due to structure and heat treatment do not manifest themselves in significant differences in smooth fatigue properties for materials at approximately the same strength level. The exception to this is the highest strength 4330 material.

For the purpose of comparison Figures 6a - 6b show rotating beam fatigue data for smooth specimens from several sources[5, 6 and 7]. The cyclic bending stresses from these references were normalized by appropriate UTS values so that the data could be compared on an equivalent basis.

The smooth fatigue results for two types of Cr-Ni-Mo-V steels from other investigators[2, 3] are shown in Figure 9b. As can be seen, there is good correlation between these and the results of the current investigation. The results of Oberg and Ward[2] show that poorer fatigue behavior is exhibited by the highest strength level 4340 steel. This is consistent with the present work.

The nominal bending stress, normalized by ultimate tensile stress, vs cycles to failure curves for notched specimens of $K_t = 3$ and $K_t = 5$ for the various steels are shown in Figures 7a - 8b and 10a - 10b. The results from other investigators are also included for comparison. Figures 8a and 8b show a comparison between the results of the present study and limited data from other sources of notched 250 maraging steel fatigue data. Again the nominal bending stresses have been normalized with appropriate ultimate strength levels.

Although it has been previously shown that good correlation exists between the smooth fatigue results of the current work and other investigators, considerable deviation can be noted for the notched data. This deviation is attributed to a cyclic rate effect which is much more significant for notched than smooth fatigue behavior as borne out by Shabalin[14]. The fatigue tests of References 7 and 6 were carried out at 5,000 and 10,000 cycles per minute as compared to 200 in the present work.

Figures 7a and 7b show the results of this study compared with limited data from others for the 300 grade maraging steel for smooth and notched specimens. This again shows the strong influence of cyclic rate on notched fatigue for these steels.

Figure 10a shows the notched fatigue data for the 4330 steel of the present work as compared to that of Finch[3]. Finch's stress concentration factors are the average of the stated estimated values given in the reference. Here again an excellent correlation is seen to exist particularly for the lower ultimate strength level materials.

It can be observed in Figures 7a - 8b and 10a - 10b that considerable differences exist between the notched fatigue properties of the various steels. The notched fatigue strengths are not proportional to the ultimate tensile strength as is the case for the smooth fatigue results. The significance of these differences can best be seen by examining the fatigue notch strength reduction factor (K_f) which is the ratio of smooth to notched fatigue strength at a given number of cycles to failure. Thus, the larger the value of K_f, the poorer the fatigue properties of a material in the presence of a notch.

Plots of K_f, fatigue notch strength reduction factor versus number of cycles to failure for the three different steels are shown in Figures 11, 12 and 13 for $K_t = 5$. Poor notch sensitivity is indicated by the lines having steeper slopes and relatively higher K_f values.

Examination of Figure 11 for the 250 grade steel reveals two significant points. First, underaging has a large effect upon notch sensitivity. Slight underaging(H), i.e. 860°F as compared to the optimum 900°F, does not significantly change K_f even though the strength is slightly lower and ductility higher. A further degree of underaging(I), i.e. 800°F, substantially reduces K_f. However, severe underaging(J) at 735°F drastically increases the notch sensitivity to values far above those for the highest strength levels attainable. It becomes apparent then that underaging to decrease strength and enhance ductility and toughness can have a detrimental effect upon notched fatigue characteristics.

The second interesting point shown in Figure 11 is that the material of heat A(F) and B(G), although having approximately a 50% difference in ductility and toughness at the same strength level and aging conditions, has effectively the same notch sensitivity. This is in contrast to what one would generally expect considering the severe segregation (banding) in the B heat material and the fact that the specimens were oriented in the billet so as to maximize any effects of the banded structure.

The results for the 300 grade maraging steel, as shown in Figure 12, are effectively the same as for the 250 grade. Slight underaging(C) at 800°F slightly decreases notch sensitivity whereas severe underaging(E) at 760°F drastically increases notch sensitivity. It should be noted that the 300 material underaged at 800°F(C) has effectively the same notch sensitivity as the optimum aged 250 grade which has a comparable strength level even though the ductility and toughness of the former is considerably less. However, the notch sensitivity of the severely underaged 300 grade(E) is much greater than the slightly underaged 250 grade(H) material at an equivalent strength level. Overaging of the 300 grade(D) yields notch sensitivity characteristics comparable to the slightly underaged[C] which has nearly the same strength and ductility.

Due to differences in strength level, it is not possible to directly compare the lower ductility banded B heat material with that of the A heat. However, the trend is the same as in the case of the 250 grade, i.e. the notch sensitivity is not affected by the severe banding characteristic of the B heat material.

In summary then, the notch sensitivity in fatigue as defined by K_f of the maraging steels is highly dependent upon aging conditions, i.e. the degree of aging with no measurable dependence upon severe microstructural differences associated with processing. Underaging to reduce strength and enhance ductility can severely increase notch sensitivity. Very slight under- or overaging resulting in small decreases in strength have only a slight effect upon notch sensitivity as compared to the material given an optimum aging treatment.

Fatigue notched reduction factors for the 4330 modified steel are shown in Figure 13. In contrast to the maraging steel, notch sensitivity increases more or less systematically with increase in strength. The notch sensitivity of the 261,300 tensile strength material[K] is approximately the same as that for the maraging steels at the same strength level. How, ever, as was shown in Figure 9a, the smooth fatigue properties of this alloy were far below those of the other materials in the same strength range. In reality then, it has a higher notch sensitivity than maraging steels of equivalent strength.

One may question whether fatigue properties may be related to ductility and toughness in view of the insensitivity to structure and sensitivity to aging treatment as related to notched fatigue behavior. In a very early work by Moore and Kommers[19], it was shown that no correlation existed between ductility as measured by percent elongation and percent reduction in area and fatigue strength in the high cycle region. Very recent work reported by Manson[20] indicated no correlation could be found between uniaxial fatigue data and charpy impact toughness for a 410 stainless steel which had been heat treated to give nearly identical tensile properties.

Figures 14, 15, 16 and 17 show plots of notch strength reduction factor (K_f) versus the smooth-to-notch tensile ratio, percent reduction in area, percent elongation and room temperature charpy impact values respectively for the materials of this current work. The K_f values were taken from Figures 6a, 6b, 7b, 8b, 9a and 10b at $N = 20 \times 10^3$ cycles. Although the various points appear to somewhat cluster for each of the three different steels, it can be observed no direct correlation exists between notch fatigue behavior in rotating bending and the engineering properties associated with ductility and toughness.

CONCLUSIONS

The following conclusions appear evident from the results of this study.

1. Fatigue behavior is effectively proportional to the ultimate strength for smooth specimens of three different steels having large variations in structure and strength level. An exception to this occurs for the highest strength 4330 material.

2. Notched fatigue behavior, expressed by notch strength reduction factor, is independent of ductility, notched tensile strength, and toughness.

3. Underaging can drastically impair the notched fatigue behavior of the maraging steels.

4. Microstructural segregation in the form of banding in the maraging steels showed no detrimental effect on the smooth or notched fatigue properties even though the ductility and toughness are greatly reduced as compared to the "unbanded" material.

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TABLE Ia - CHEMICAL COMPOSITION 300 GRADE MARAGING STEEL

	Watervliet Arsenal HT07329 (A)	Watervliet Arsenal HT07010 (B)	Vanadium Alloys[7] 6461	North American[5] 06461	International Nickel Co.[6]
C	.03	.02	.01	--	Information not Available
Si	.08	.09	.10	--	
Mn	.05	.09	.11	--	
S	.005	.007	.010	--	
P	.003	.005	.007	--	
Ti	.57	.55	.65	.77	
Al	.15	.07	.03	--	
Mo	4.96	4.82	4.81	4.88	
Co	9.30	8.94	9.04	8.98	
Ni	18.80	18.56	18.18	18.77	
B	.004	.003	.002	--	
Zr	.019	.018	.010	--	
Ca	.05	--	.05	--	

TABLE Ib - CHEMICAL COMPOSITION 250 GRADE MARAGING STEEL

	Watervliet Arsenal HT07329 (A)	Watervliet Arsenal HT07010 (B)	Vanadium Alloys[7] 6461	North American[5] 06461	International Nickel Co.[6]
C	.02	.02	.01	--	Information not Available
Si	.02	.09	.10	--	
Mn	.05	.08	.10	--	
S	.005	.006	.009	--	
P	.004	.004	.008	--	
Ti	.35	.31	.42	.50	
Al	.11	.10	.10	--	
Mo	4.92	4.57	4.70	4.78	
Co	8.02	7.78	7.48	7.22	
Ni	18.59	18.60	17.60	18.20	
B	.003	.002	.004	--	
Zr	.005	.011	.01	--	
Ca		.05	.05	--	

TABLE Ic - CHEMICAL COMPOSITION
Cr-Ni-Mo-V ALLOY STEELS

	*Watervliet Arsenal	ϕOberg-Ward	+Finch #2[3]	+Finch #3[3]
C	.30	.35-.45	.32	.36
Mn	.61	.60-.80	.66	.72
P	.007	.040	.015	.016
S	.010	.050	.025	.042
Si	.22	--	.25	.30
Ni	2.40	1.65-2.00	2.33	2.02
Cr	1.05	.60-.90	.98	.45
Mo	.48	.20-.30	.39	.36
V	.11	--	.10	.08

* Specimens taken from transverse sections of a 120mm gun tube.

ϕ Specimens taken from transverse sections of a 76mm gun tube.

\+ Specimens taken from 1-1/2" and 1-1/8" diameter bars; 15½ O.D. tube with 1-7/8" wall, and B36 Aircraft Landing Gear.

Table 2a - MECHANICAL PROPERTIES 300 MARAGING STEEL

Material Code	Heat Treat Data			Tensile Strength	Yield Strength		Notched Tensile Ratio		Elongation	Reduction in Area	Charpy Impact (ft-lb)		
	Aging Temp. (°F)	Aging Time (hrs)	Heat	ksi	0.1% ksi	0.2% ksi	$K_t = 3$	$K_t = 5$	(%)	(%)	-40°F	R.T.	212°F
A	900	4	A	301.4	283.1	292.2	1.16	.95	4.6	18.9	7.0	8.7	8.3
B	900	4	B	275.9	257.9	267.8	1.13	.99	3.5	13.6	5.3	6.7	8.0
C	800	4	A	266.9	240.3	251.3	1.27	1.14	7.8	28.4	7.3	8.3	9.8
D	1055	4	A	261.0	240.1	252.8	1.29	1.03	6.5	22.7	6.1	6.7	7.5
E	760	4	A	251.2	224.0	234.6	1.38	1.27	8.6	27.9	6.5	8.2	8.5
Ref (7)	900	3		295	--	285			10.0	55.0			
Ref (5)	900	3		293	--	286							

Table 2b - MECHANICAL PROPERTIES 250 MARAGING STEEL

Material Code	Heat Treat Data			Tensile Strength	Yield Strength		Notched Tensile Ratio		Elongation	Reduction in Area	Charpy Impact (ft-lb)		
	Aging Temp. (°F)	Aging Time (hrs)	Heat	ksi	0.1% ksi	0.2% ksi	$K_t = 3$	$K_t = 5$	(%)	(%)	-40°F	R.T.	212°F
F	900	4	A	262.2	244.4	254.2	1.47	1.41	9.7	46.9	15.2	16.8	19.0
G	900	4	B	259.3	238.9	249.5	1.29	1.13	5.0	21.1	7.9	8.7	10.5
H	860	4	A	248.8	229.3	239.2	1.46	1.46	10.9	48.7	17.2	20.0	17.5
I	800	4	A	229.6	205.9	216.4	1.50	1.48	12.5	50.7	16.5	21.7	23.7
J	735	4	A	198.6	170.1	181.1	1.56	1.55	14.7	52.8	21.7	25.5	28.3
Ref (7)	900	3		265	--	255			11-12	60.0			
Ref (5)	900	3		269	--	286			--	--			

Table 2c - MECHANICAL PROPERTIES
Cr-Ni-Mo-V Alloy Steels

Material Code	Heat Treat Data Tempering Temp. (°F)	Heat Treat Data Tempering Time (hrs)	Tensile Strength ksi	Yield Strength 0.1% ksi	Yield Strength 0.2% ksi	Notched Tensile Ratio $K_t = 3$	Notched Tensile Ratio $K_t = 5$	Elongation (%)	Reduction in Area (%)	Charpy Impact (ft-lb) -40°F	Charpy Impact (ft-lb) R.T.	Charpy Impact (ft-lb) 212°F
K	350	3	261.3	191.6	206.4	--	1.18	7.5	16.3	14.6	17.5	16.9
L	950	3	192.7	175.2	178.4	1.46	1.43	8.9	18.2	16.4	18.3	21.4
M	1100	3	173.7	155.9	160.2	1.49	1.46	11.6	26.9	22.3	24.8	25.4
N	1185	3	151.8	136.7	139.0	1.52	1.49	12.1	25.1	29.8	34.7	36.8
O	1225	3	137.4	123.3	124.5	1.48	1.46	16.2	36.0	40.8	41.4	44.5
Ref (3)	*	*	165	--	140			14	31.5			
Ref (3)	*	*	181	--	146			13	35.5			
Ref (2)	+	+	220.8	--	217.5			5.7	--			
			208.0	--	189.0			8.7	--			
			195.0	--	--			11.9	--			
			188.0	--	179.0			11.0	--			
			158.5	--	146.9			15.0	--			

*See Ref (3) for complete heat treatment

+Not given in Ref (2)

Table 3a - STATISTICAL DATA
300 Maraging Steel

Material Code	U.T.S. (ksi)	Stress U.T.S.	K_t	Predicted Life	Confidence Limits 99% Upper	99% Lower	95% Upper	95% Lower	*Corr. Coeff.	** N
A	301.4	.80	1	6628	24056	1826	16716	2628	.9380	13
		.40	1	69582	252559	19171	175494	27589		
		.40	3	2663	7186	987	5450	1301	.9884	14
		.10	3	158350	427332	58677	324101	77367		
		.30	5	5762	20578	1613	14548	2282	.9506	17
		.10	5	94979	339202	26595	239806	37618		
B	275.9	.60	1	9163	47148	1781	29435	2852	.8949	12
		.40	1	74182	381712	14416	238308	23092		
		.30	5	7139	15228	3348	12091	4216	.9936	9
		.10	5	137191	292605	64324	232215	81017		
C	266.9	.70	1	8054	21791	2977	16452	3943	.9670	13
		.40	1	68490	185310	25314	139904	33530		
		.30	3	5970	11527	3092	9540	3736	.9853	12
		.20	3	20256	39111	10491	32369	12676		
		.30	5	6902	18696	2548	14165	3363	.9759	14
		.15	5	57458	155649	21210	117924	27996		
D	261.0	.60	1	19675	80043	4836	53465	7241	.9436	12
		.50	1	61010	248201	14997	165788	22452		
		.30	3	10062	23582	4294	18380	5508	.9868	11
		.15	3	88100	206464	37593	160923	48232		
		.30	5	8611	12434	5964	11187	6629	.9970	12
		.15	5	63061	91053	43675	81925	48541		
E	251.0	.70	1	18353	117830	2859	66876	5037	.8876	10
		.50	1	71438	458639	11127	260304	19606		
		.30	3	3949	15042	1037	10364	1505	.9588	14
		.10	3	54045	205852	14189	141837	20593		
		.30	5	3764	6504	2179	5530	2562	.9940	10
		.10	5	49994	86377	28937	73448	34031		

*The correlation coefficients for all of the data sets are statistically significant at both the 95% and 99% confidence levels.

**Number of specimens.

Table 3b - STATISTICAL DATA
250 Maraging Steel

Material Code	U.T.S. (ksi)	Stress U.T.S.	K_t	Predicted Life	Confidence Limits 99% Upper	99% Lower	95% Upper	95% Lower	*Corr. Coeff.	** N
F	262.2	.70	1	5954	10491	3379	8963	3955	.9920	15
		.40	1	80530	141899	45702	121225	53496		
		.30	3	10298	41013	2586	28086	3776	.9567	16
		.20	3	30858	122893	7748	84159	11314		
		.30	5	8869	33192	2370	22865	3440	.9517	13
		.20	5	23694	88672	6331	61085	9190		
G	259.3	.60	1	12464	66428	2339	40712	3816	.8654	11
		.50	1	28440	151572	5336	92894	8707		
		.30	5	8308	24109	2863	17652	3910	.9807	11
		.10	5	135251	392513	46604	287384	63653		
H	248.8	.70	1	7741	12487	4798	10794	5551	.9950	9
		.50	1	46774	75454	28996	65226	33542		
		.30	3	12069	18458	7892	16400	8883	.9922	14
		.20	3	38514	58902	25183	52328	28346		
		.30	5	9618	17357	5329	14730	6280	.9749	15
		.20	5	27752	50084	15377	42504	18120		
I	229.6	.70	1	9013	19066	4261	15370	5285	.9861	12
		.45	1	75900	160558	35800	129436	44506		
		.30	3	12118	28966	5070	22724	6462	.9785	14
		.20	3	39627	94720	16578	74308	21132		
		.30	5	15096	49632	4592	35246	6466	.9814	12
		.15	5	123793	406992	37654	289026	53022		
J	198.6	.80	1	7186	16300	3168	13023	3965	.9784	16
		.50	1	99396	225468	43818	180147	54841		
		.30	3	11126	24426	5067	19482	6353	.9782	12
		.15	3	63348	139081	28853	110930	36176		
		.30	5	8163	21848	3050	16545	4027	.9635	13
		.15	5	40026	107129	4955	81127	19748		

*The correlation coefficients for all of the data sets are statistically significant at both the 95% and 99% confidence levels.

**Number of specimens.

Table 3c - STATISTICAL DATA
4330 Modified Steel

Material Code	U.T.S. (ksi)	Stress / U.T.S.	K_t	Predicted Life	Confidence Limits 99% Upper	99% Lower	95% Upper	95% Lower	*Corr. Coeff.	** N
K	261.3	.50	1	8434	17009	4182	13901	5116	.9865	12
		.30	1	53702	108305	26628	88518	32580		
		.20	5	10227	21307	4909	17368	6023	.9691	14
		.10	5	42016	87532	20168	71349	24743		
L	192.6	.60	1	14230	40496	5000	30263	6691	.9732	14
		.45	1	62922	179062	22111	133813	29587		
		.50	3	5159	7615	3496	6834	3895	.9972	15
		.20	3	92708	136836	62810	122800	69989		
		.50	5	5185	9042	2973	7747	3469	.9929	15
		.20	5	74997	130800	43002	112063	50192		
M	173.6	.80	1	5917	22776	1537	15744	2224	.9635	16
		.50	1	69445	267198	18042	184767	26101		
		.45	3	13365	27504	6494	22570	7914	.9887	16
		.30	3	61740	127060	30000	104264	36559		
		.60	5	5492	8805	3426	7742	3896	.9964	17
		.30	5	76825	123156	47992	108300	54497		
N	151.8	.80	1	4849	21256	1106	14212	1654	.9557	17
		.52	1	72611	318287	16565	212804	24776		
		.60	3	5173	12424	2154	9772	2738	.9794	16
		.30	3	66102	158766	27521	124882	34989		
		.60	5	6838	17248	2711	13386	3493	.9723	16
		.30	5	91791	231526	36392	179688	46890		
O	137.4	.80	1	5235	17631	1554	12641	2168	.9688	16
		.50	1	81446	274296	24184	196670	33729		
		.80	3	2726	5829	1274	4733	1570	.9834	16
		.30	3	103436	221196	48368	179613	59567		
		.60	5	7540	20131	2824	15322	3710	.9774	15
		.40	5	37688	100615	14117	76581	18547		

*The correlation coefficients for all of the data sets are statistically significant at both the 95% and 99% confidence levels.

**Number of specimens.

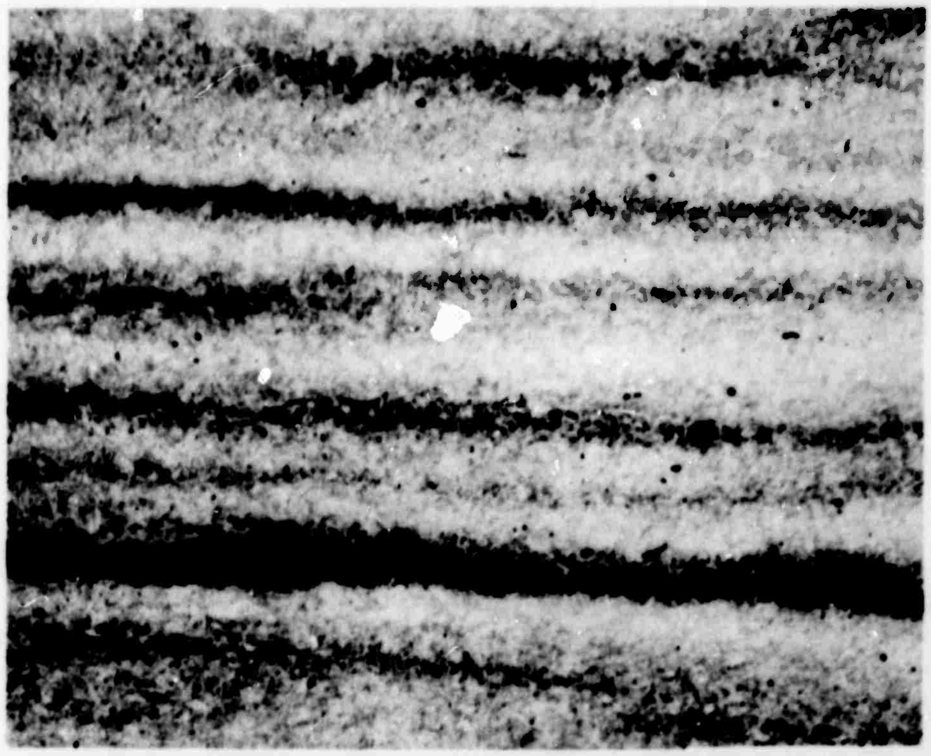


Figure 1a. Banded Microstructure of 250 Grade Maraging Steel 100X

Figure 1b. Banded Microstructure of 250 Grade Maraging Steel 500X

Figure 2a. Microstructure of 250 Grade Maraging Steel 100X

Figure 2b. Microstructure of 250 Grade Maraging Steel 500X

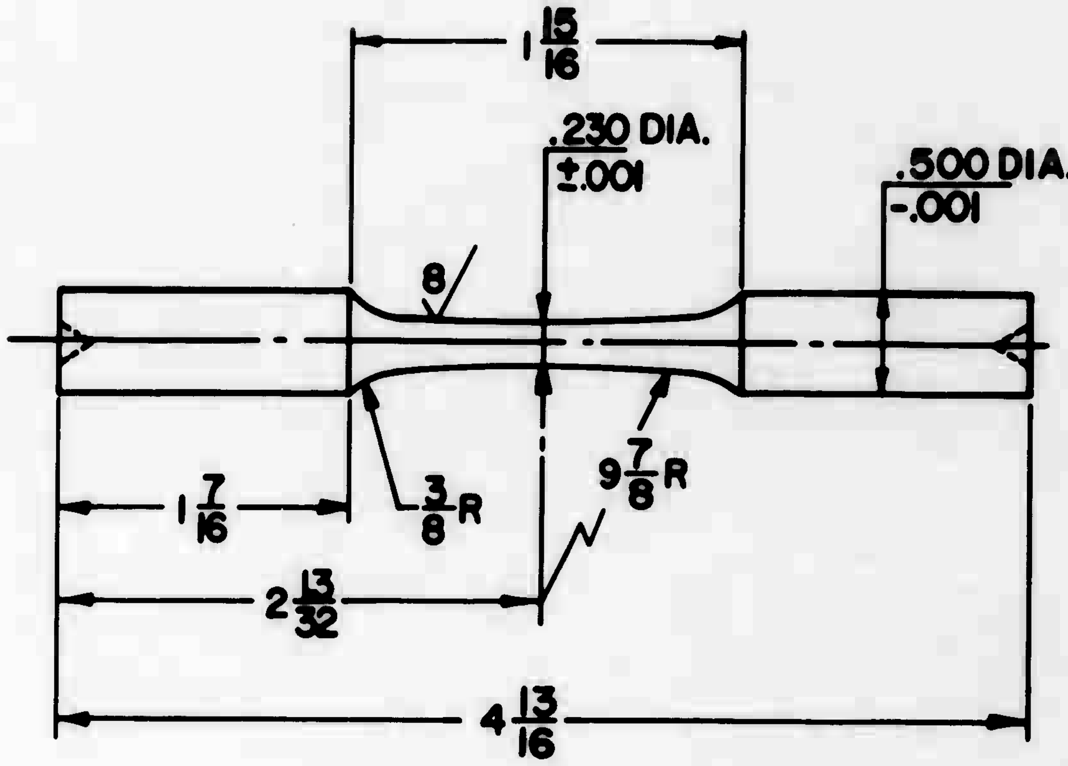
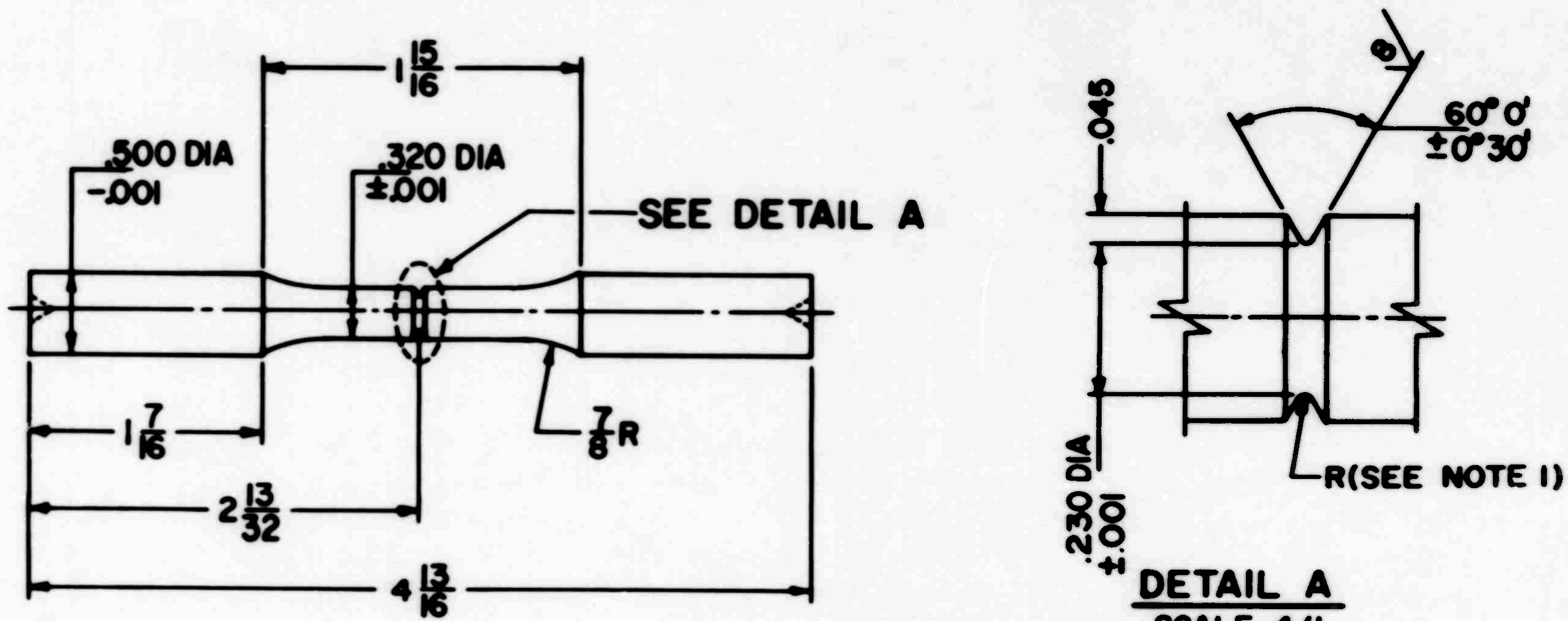


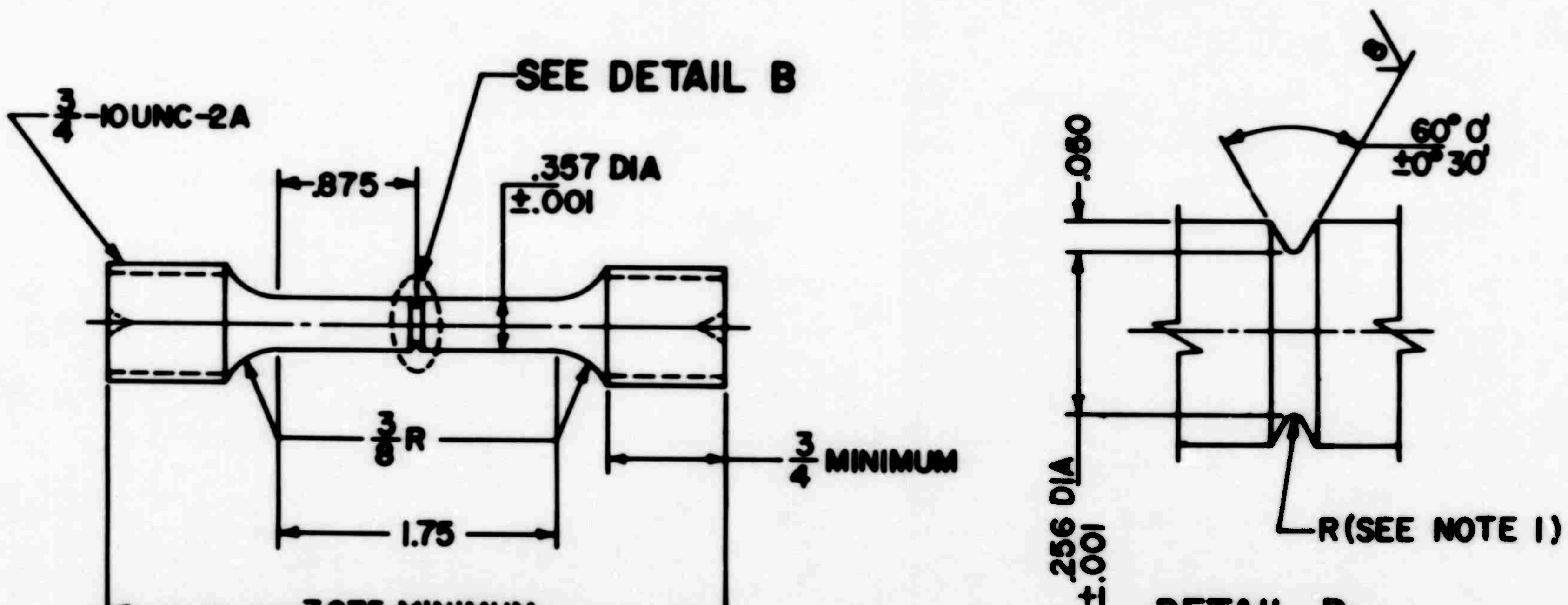
FIG. 3 KROUSE ROTATING BENDING FATIGUE SPECIMEN, UNNOTCHED



DETAIL A
SCALE 4/1

NOTES:
1 NOTCH DETAIL
@K_t =5, R=.0022±.0003
@K_t =3, R=.0065±.0003

FIG. 4 KROUSE ROTATING BENDING, NOTCHED, FATIGUE SPECIMEN



DETAIL B
SCALE 4/1

NOTES:
1 NOTCH DETAIL
@ K_t=5, R=.0046 ±.0003
@ K_t=3, R=.0134 ±.0003

FIG. 5 MODIFIED STANDARD, NOTCHED, TENSILE SPECIMEN

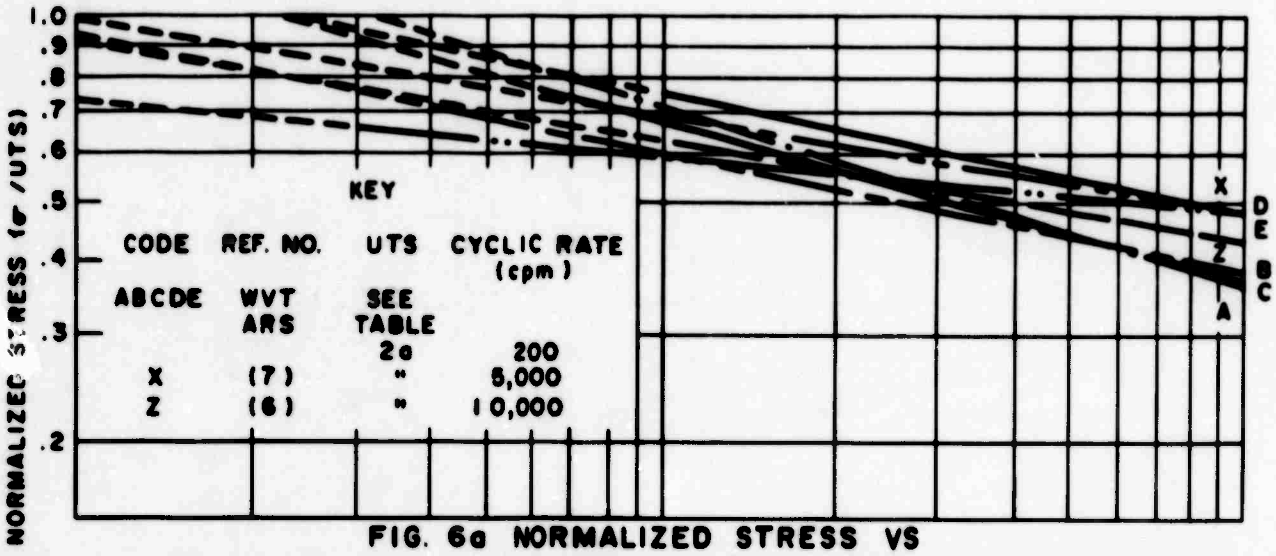


FIG. 6a NORMALIZED STRESS VS
CYCLES TO FAILURE FOR 300 GRADE MARAGING STEEL-SMOOTH SPECIMENS

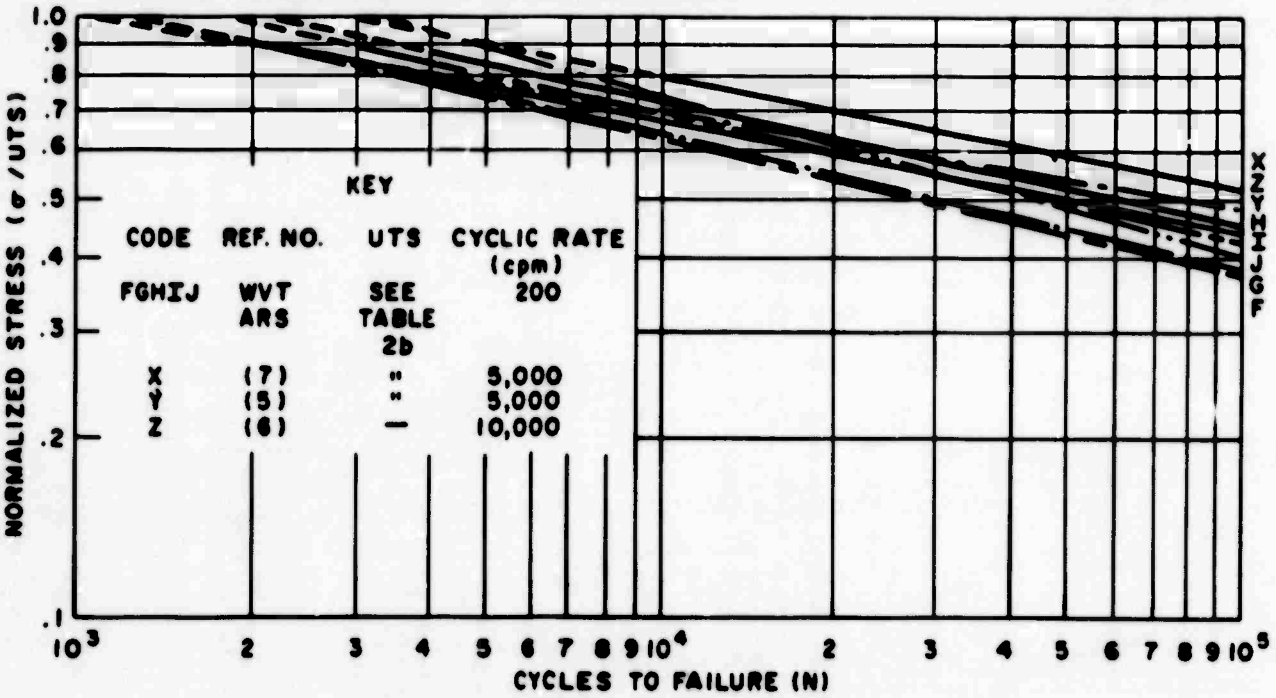


FIG. 6b NORMALIZED STRESS VS
CYCLES TO FAILURE FOR 250 GRADE MARAGING STEEL-SMOOTH SPECIMENS

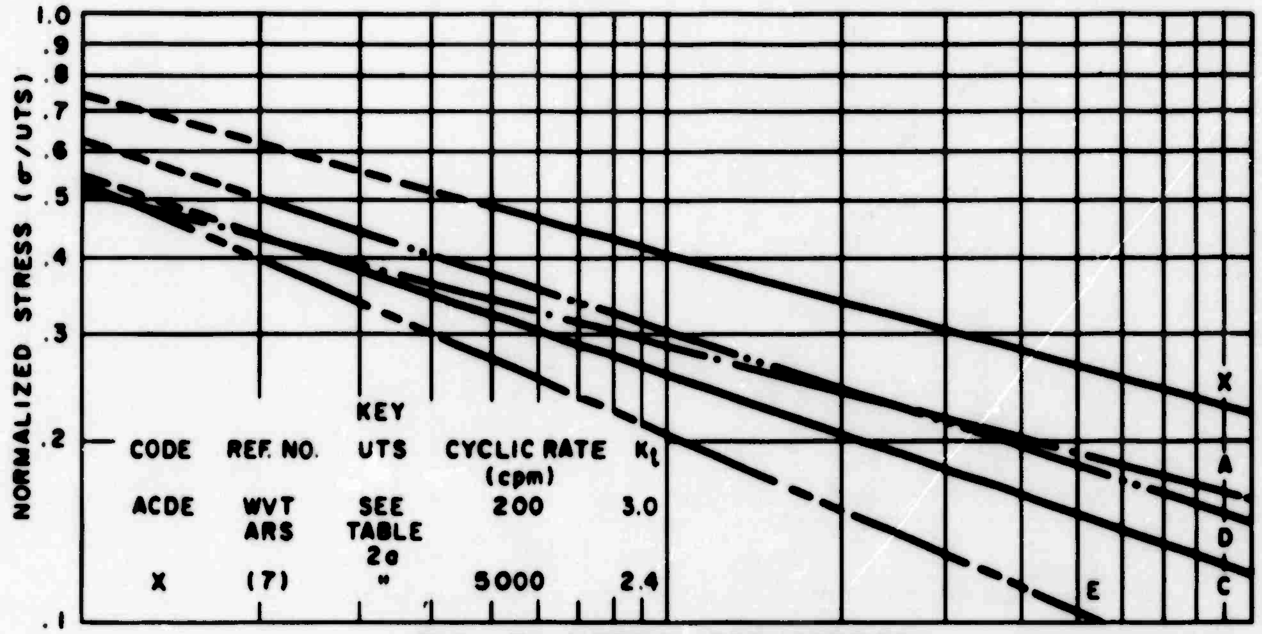


FIG. 7a NORMALIZED STRESS
VS CYCLES TO FAILURE FOR 300 GRADE MARAGING STEEL

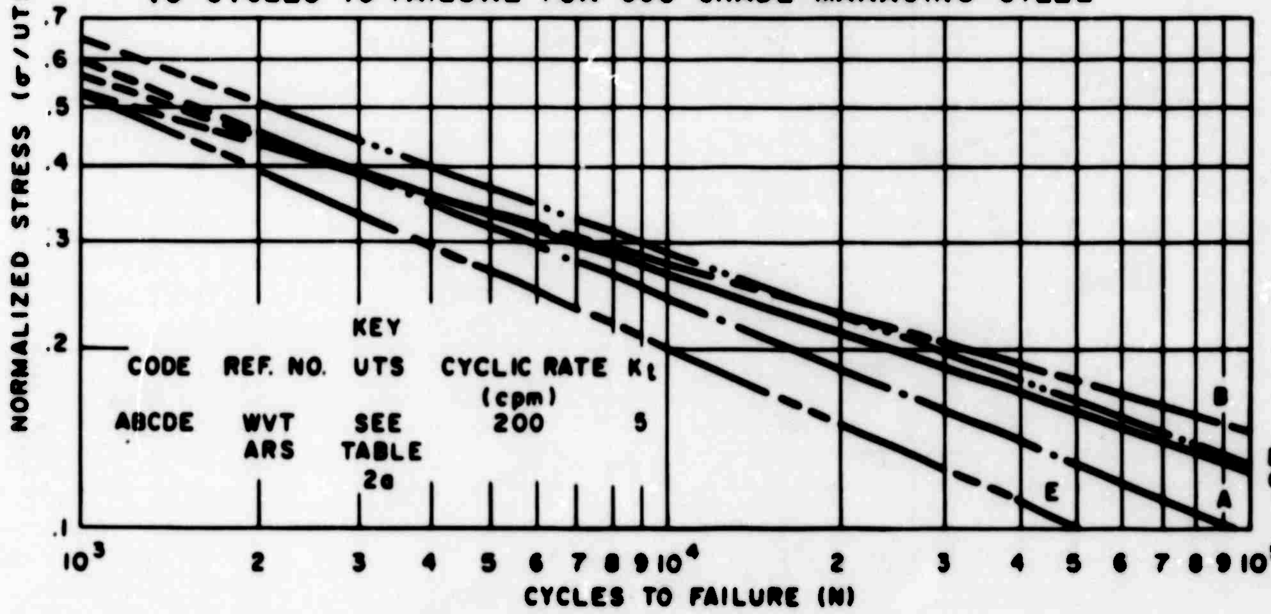


FIG. 7b NORMALIZED STRESS
VS CYCLES TO FAILURE FOR 300 GRADE MARAGING STEEL

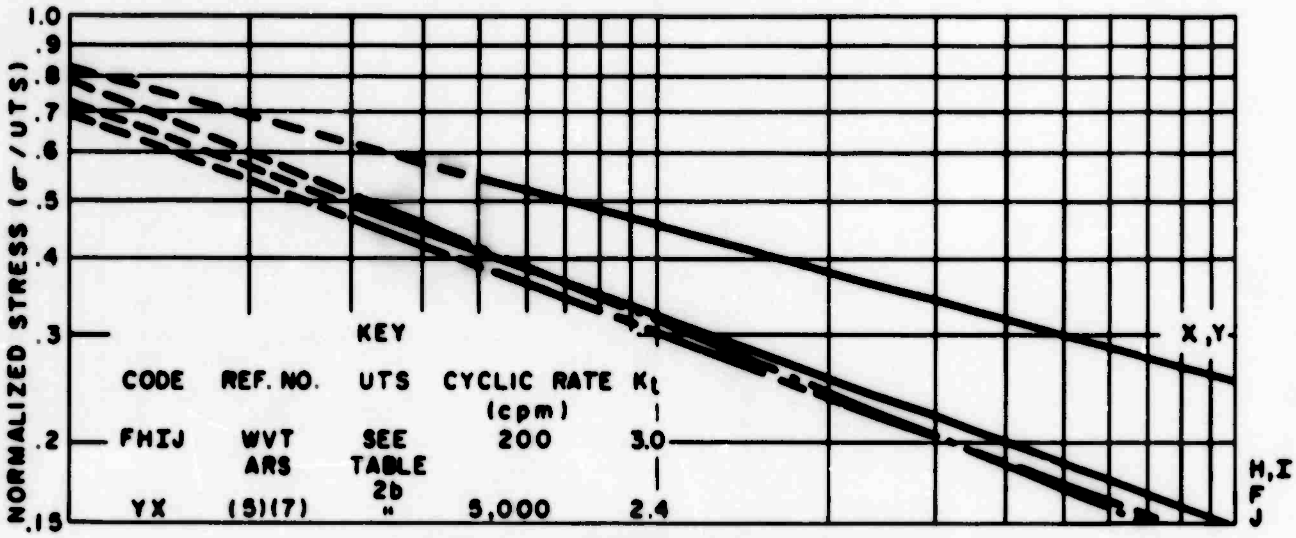


FIG. 8a NORMALIZED STRESS
VS CYCLES TO FAILURE FOR 250 GRADE MARAGING STEEL

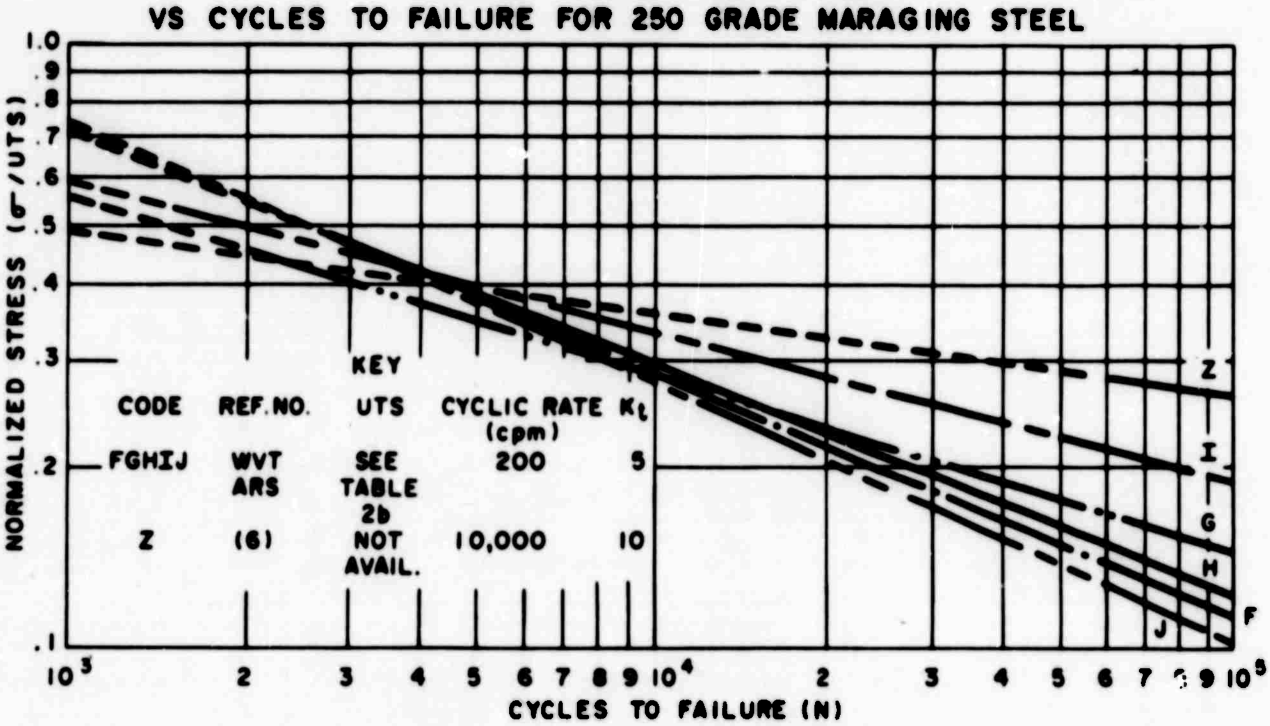


FIG. 8b NORMALIZED STRESS
VS CYCLES TO FAILURE FOR 250 GRADE MARAGING STEEL

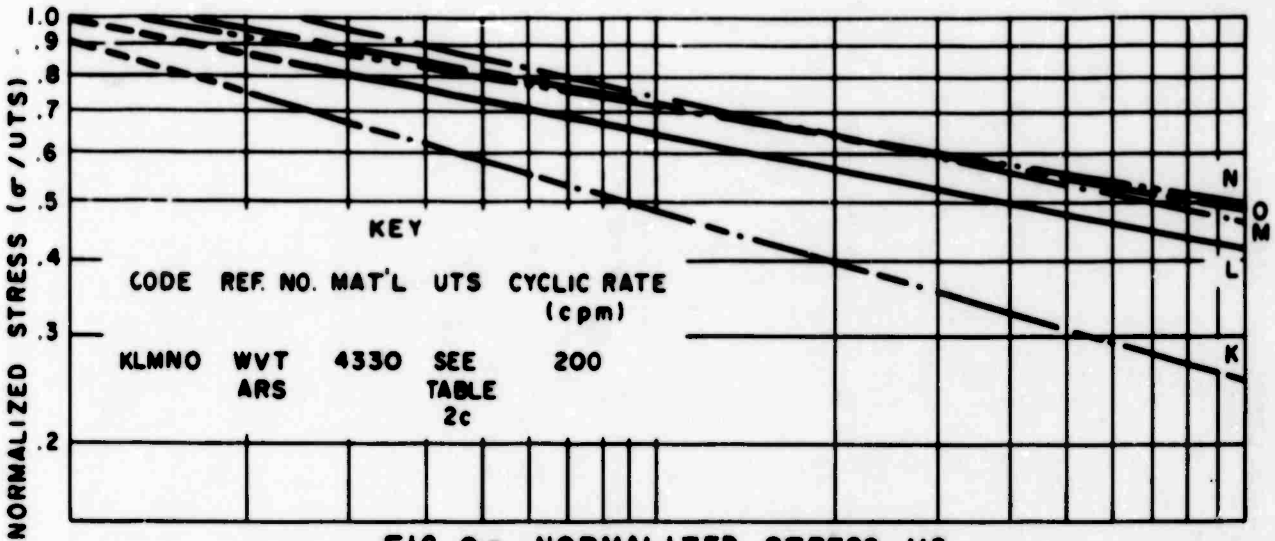


FIG. 9a NORMALIZED STRESS VS
CYCLES TO FAILURE FOR MODIFIED 4330 STEEL-SMOOTH SPECIMENS

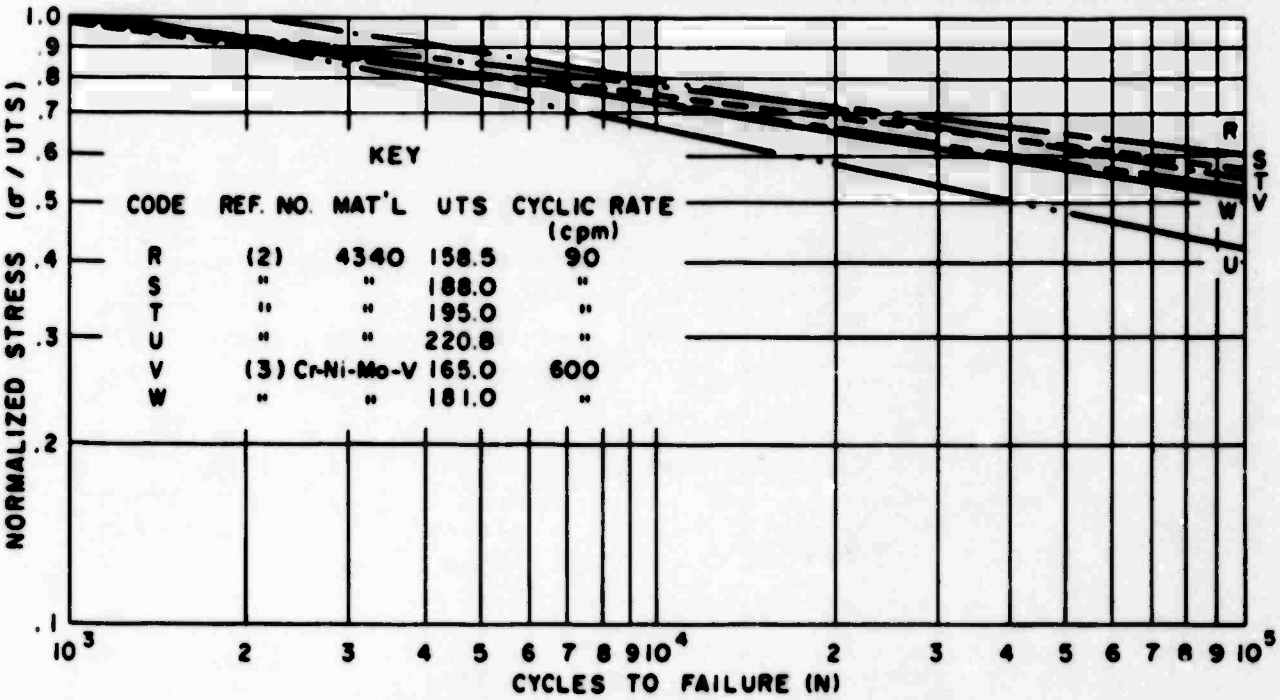


FIG. 9b NORMALIZED STRESS VS
CYCLES TO FAILURE FOR Cr-Ni-Mo-V STEEL-SMOOTH SPECIMENS

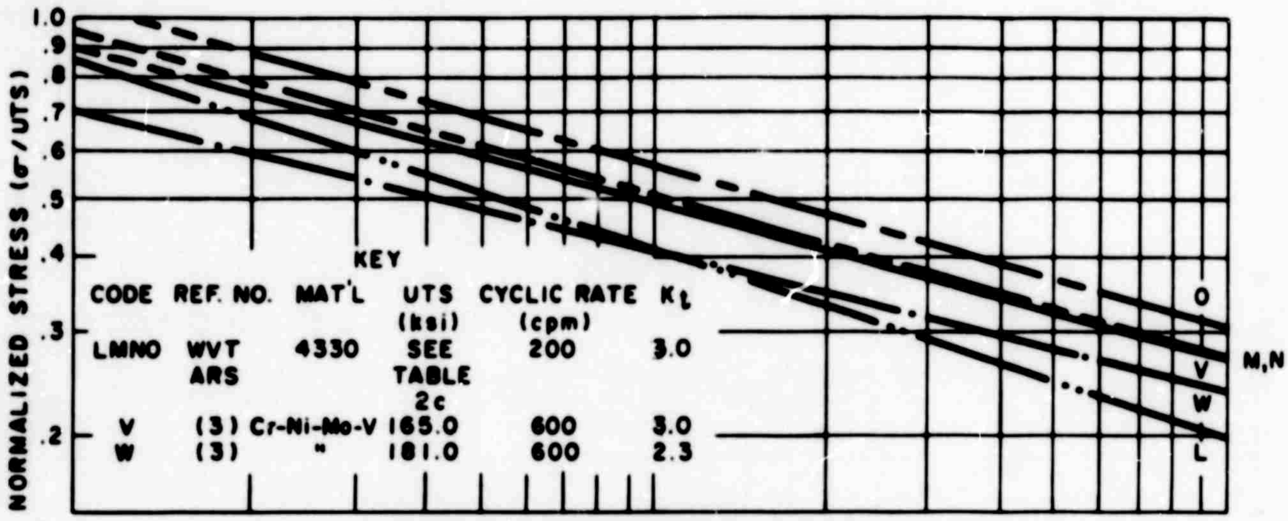


FIG. 10a NORMALIZED STRESS
VS CYCLES TO FAILURE FOR MODIFIED 4330 STEEL

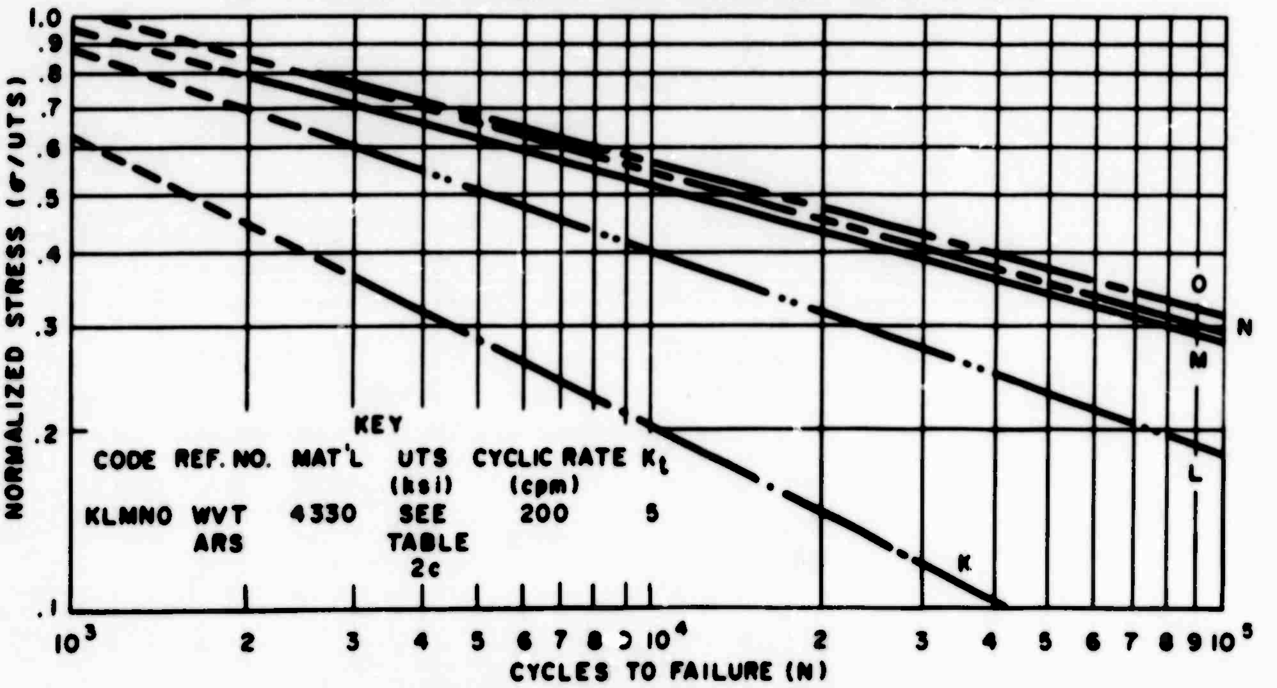


FIG. 10b NORMALIZED STRESS
VS CYCLES TO FAILURE FOR MODIFIED 4330 STEEL

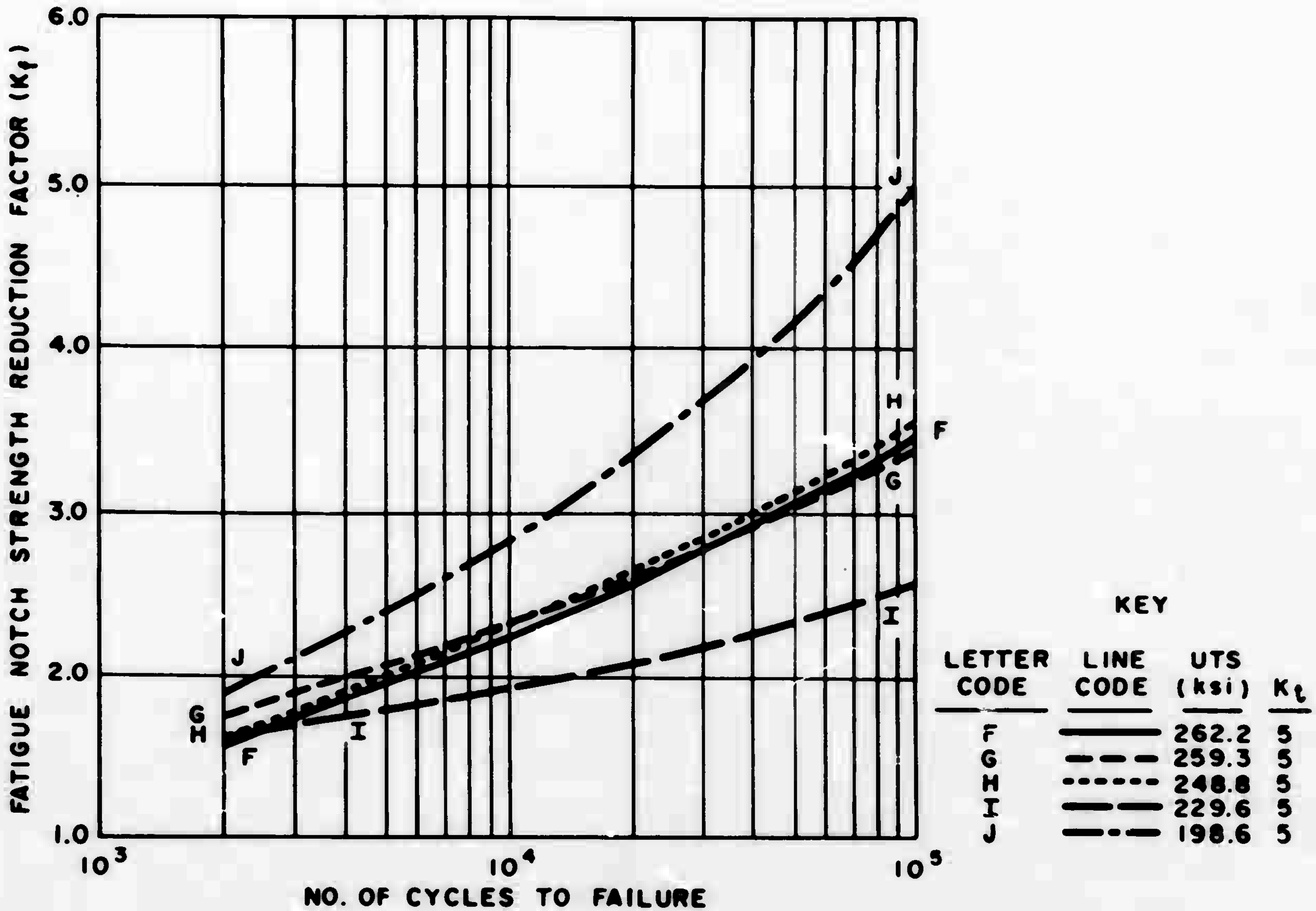


FIG. 11 FATIGUE NOTCH STRENGTH REDUCTION FACTOR VS NO. OF CYCLES TO FAILURE FOR 250 MARAGING STEEL

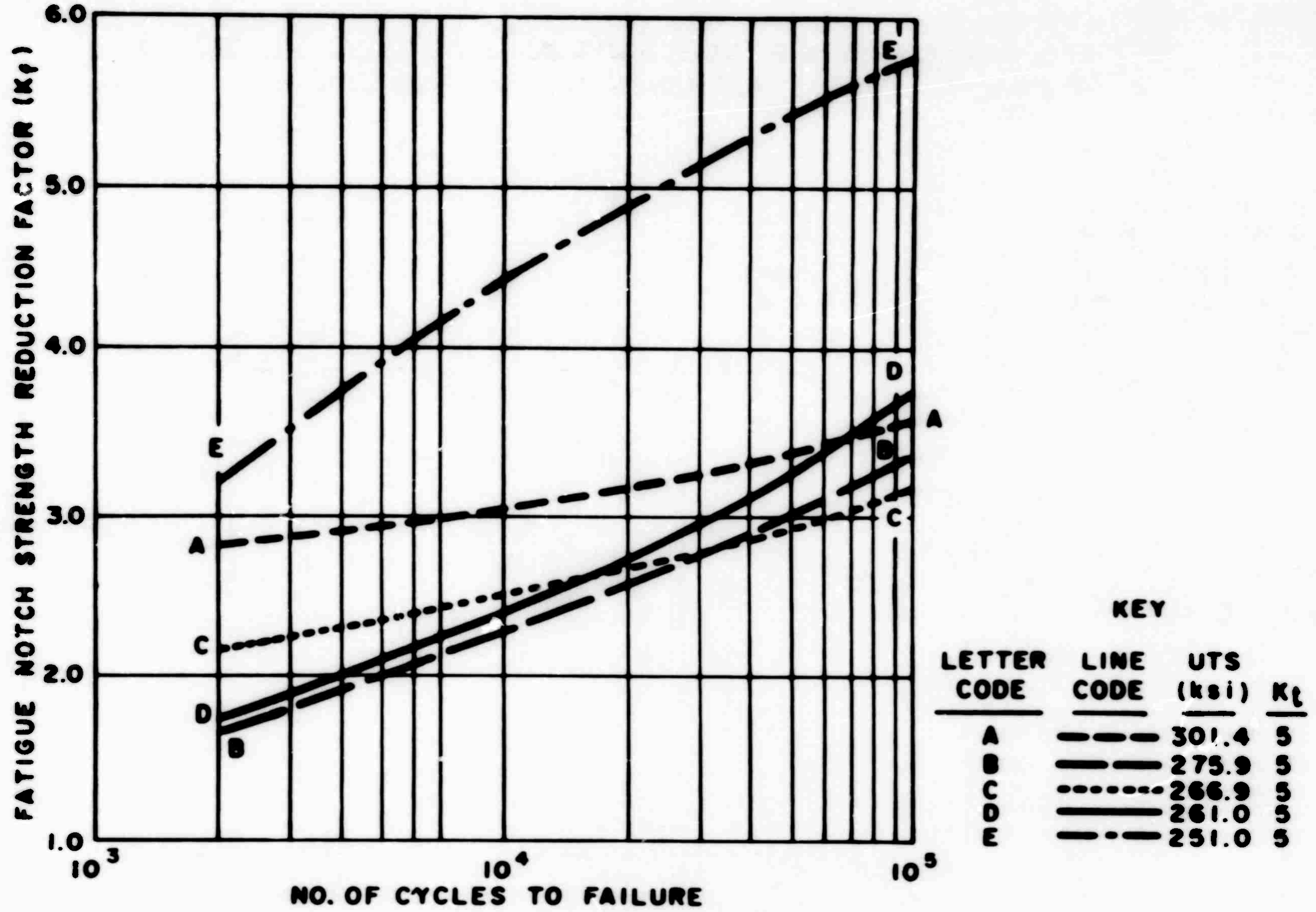


FIG. 12 FATIGUE NOTCH STRENGTH REDUCTION FACTOR VS NO. OF CYCLES TO FAILURE FOR 300 MARAGING STEEL

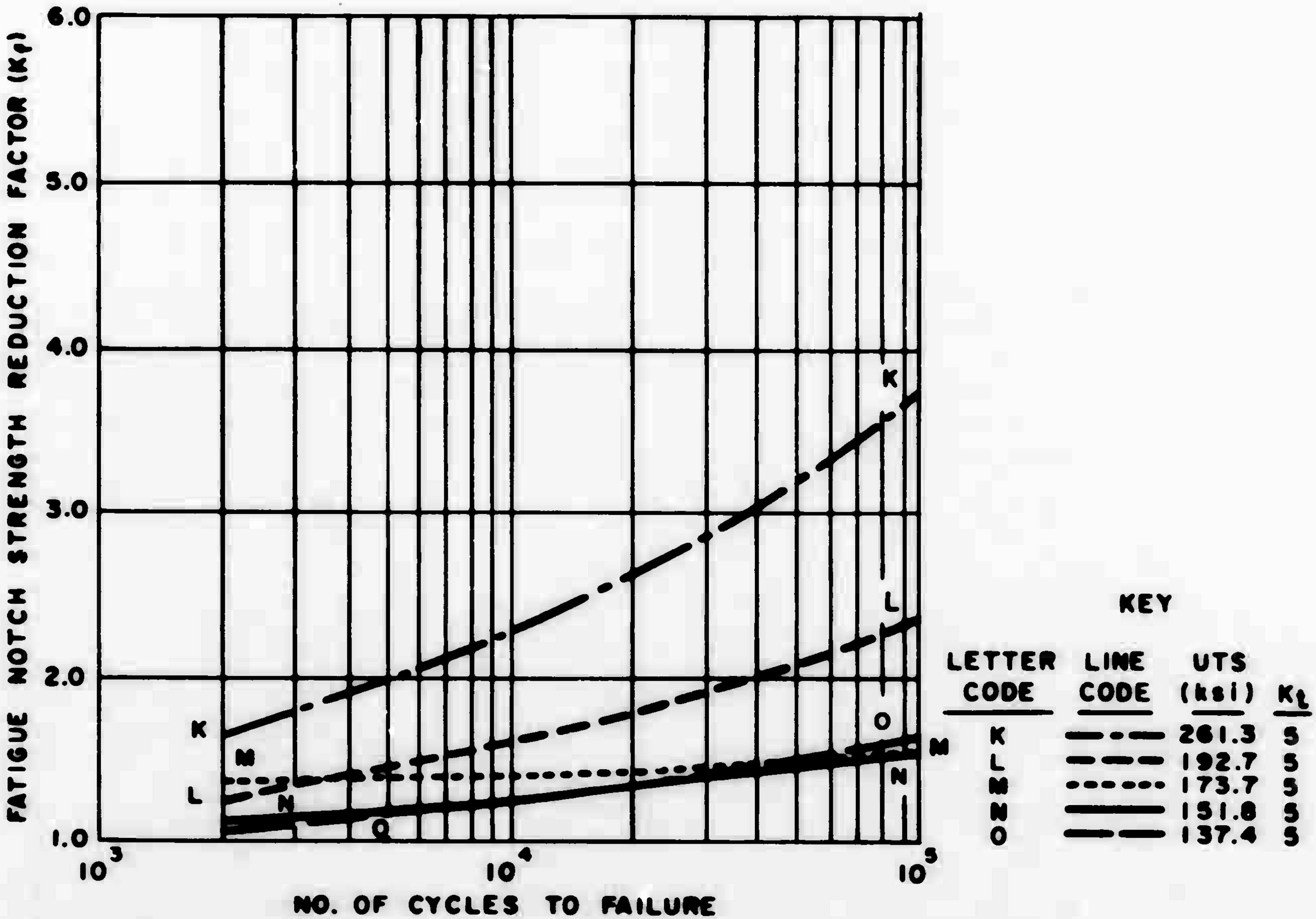


FIG. 13 FATIGUE NOTCH STRENGTH REDUCTION FACTOR VS NO. OF CYCLES TO FAILURE FOR 4330 MODIFIED STEEL

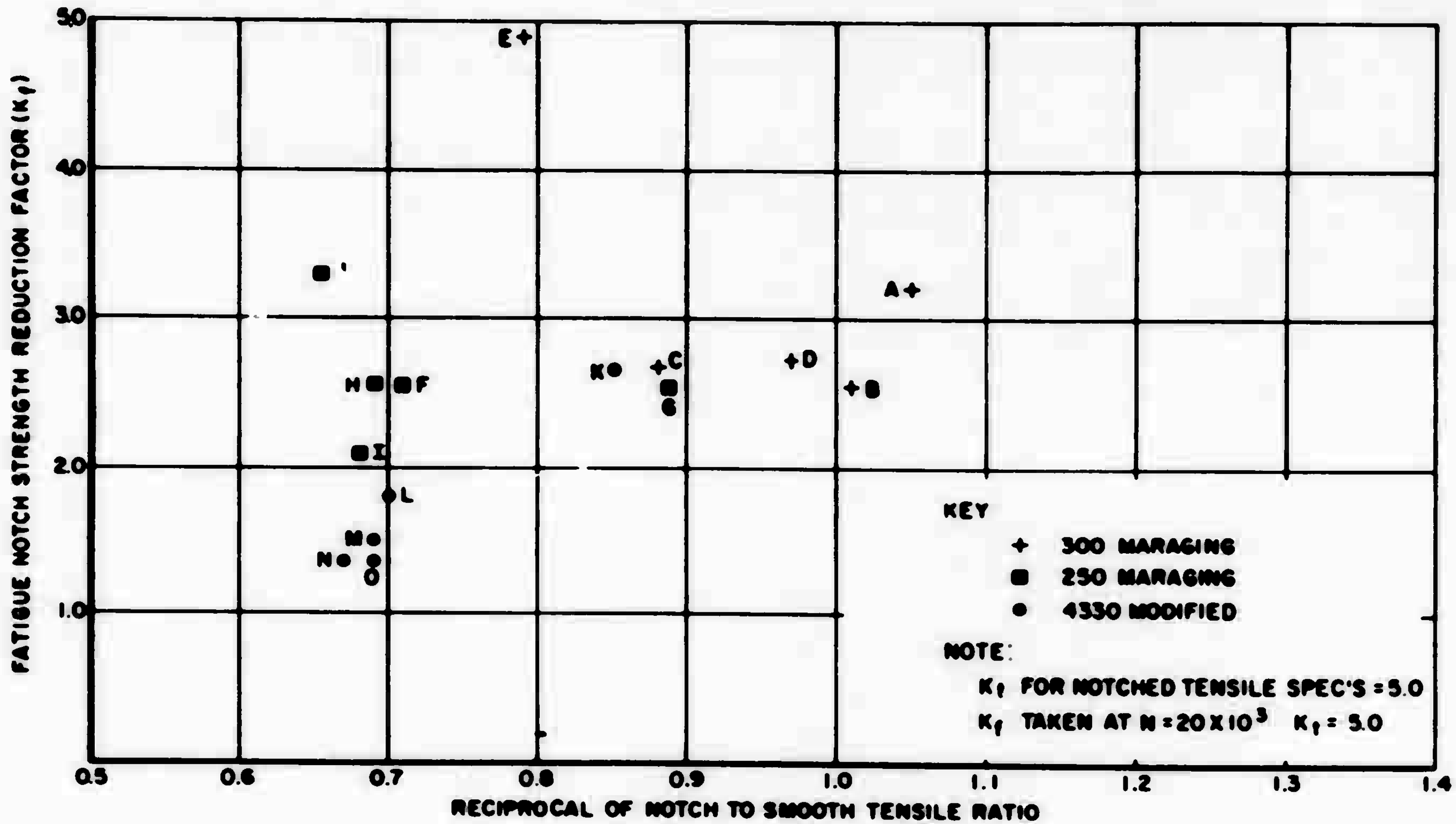


FIG. 14 FATIGUE NOTCH STRENGTH REDUCTION FACTOR
VS
RECIPROCAL OF NOTCH TO SMOOTH TENSILE RATIO

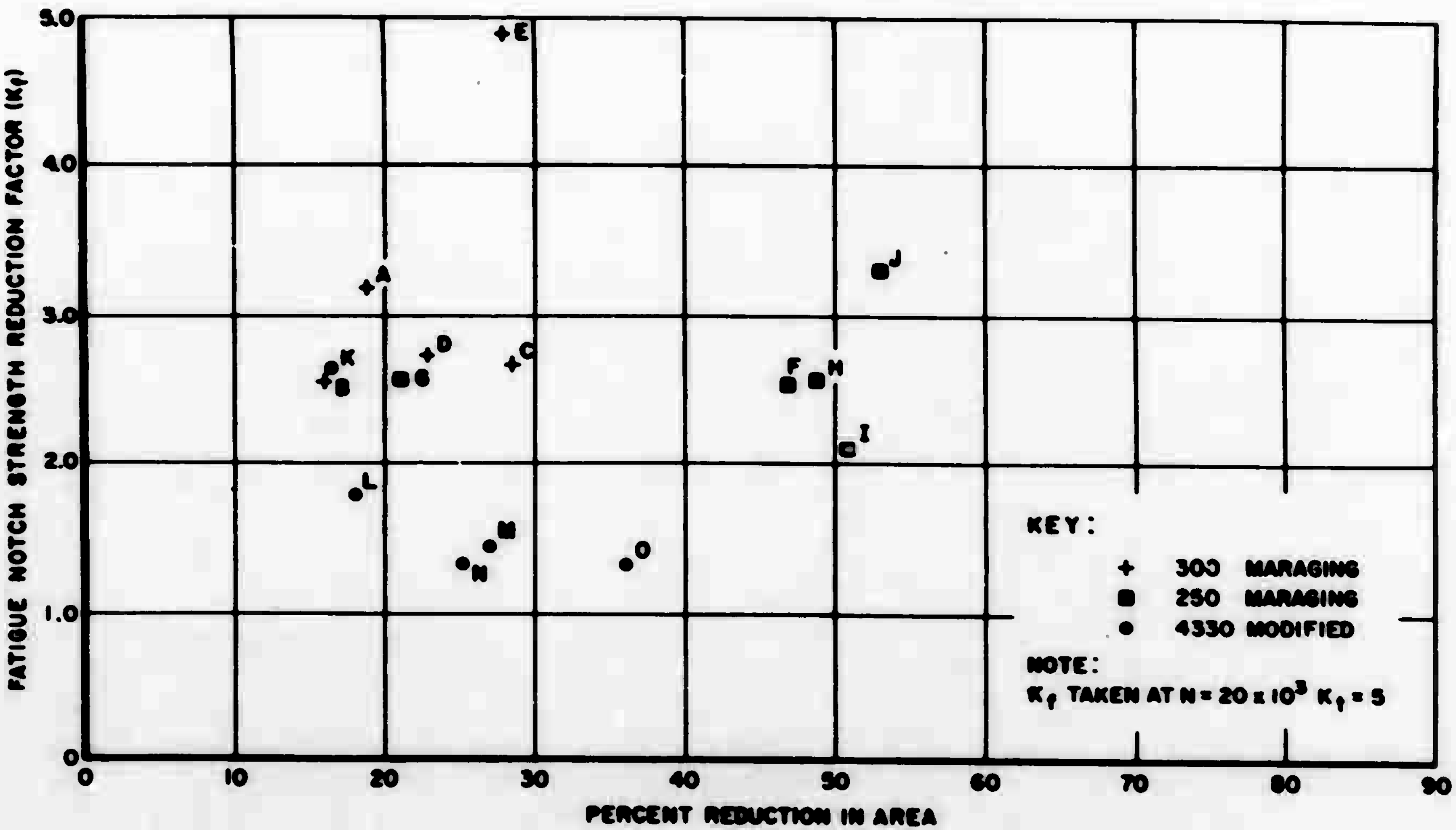


FIG. 15 FATIGUE NOTCH STRENGTH REDUCTION FACTOR VS PERCENT REDUCTION IN AREA

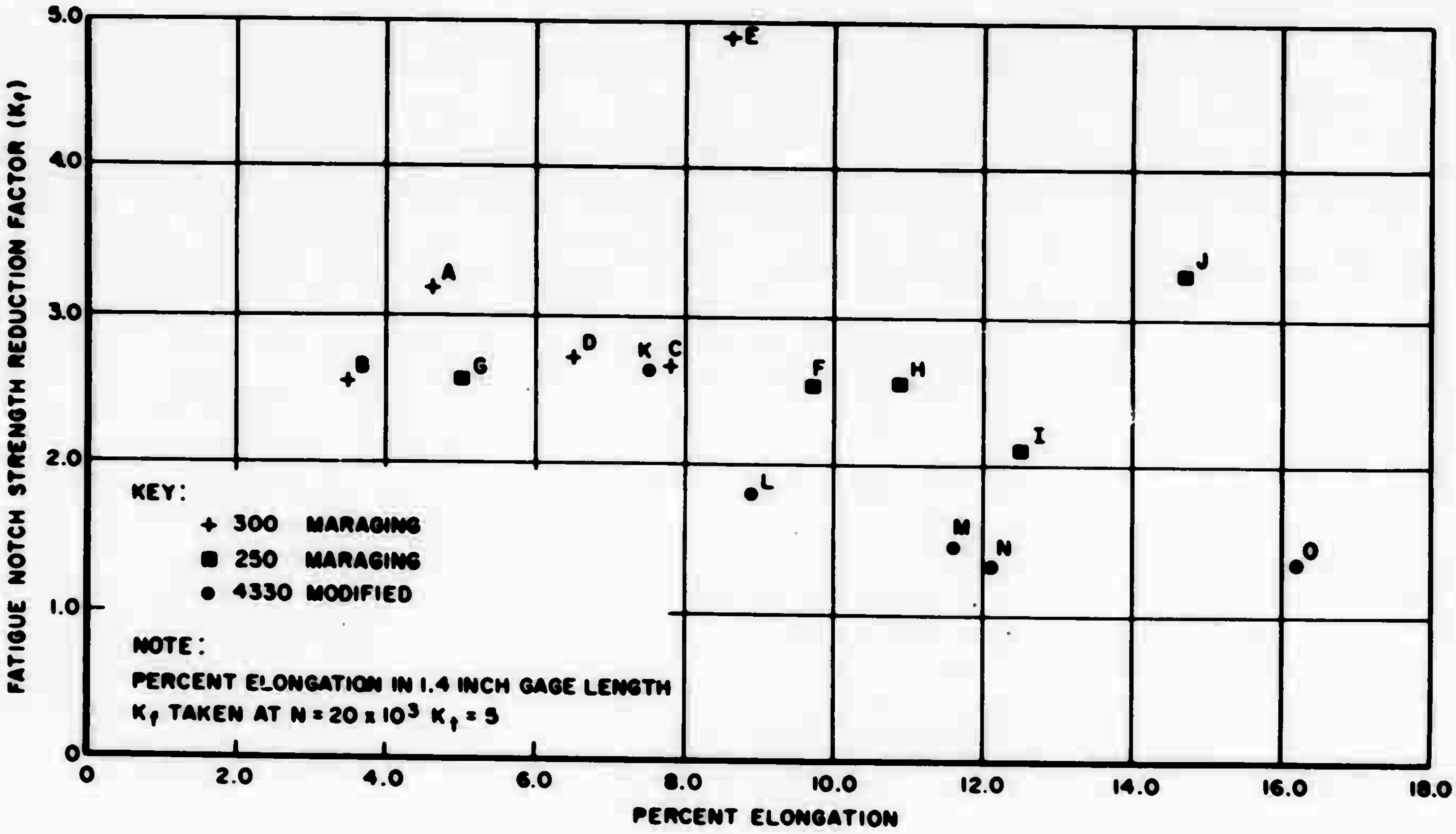


FIG. 16 FATIGUE NOTCH STRENGTH REDUCTION FACTOR VS PERCENT ELONGATION

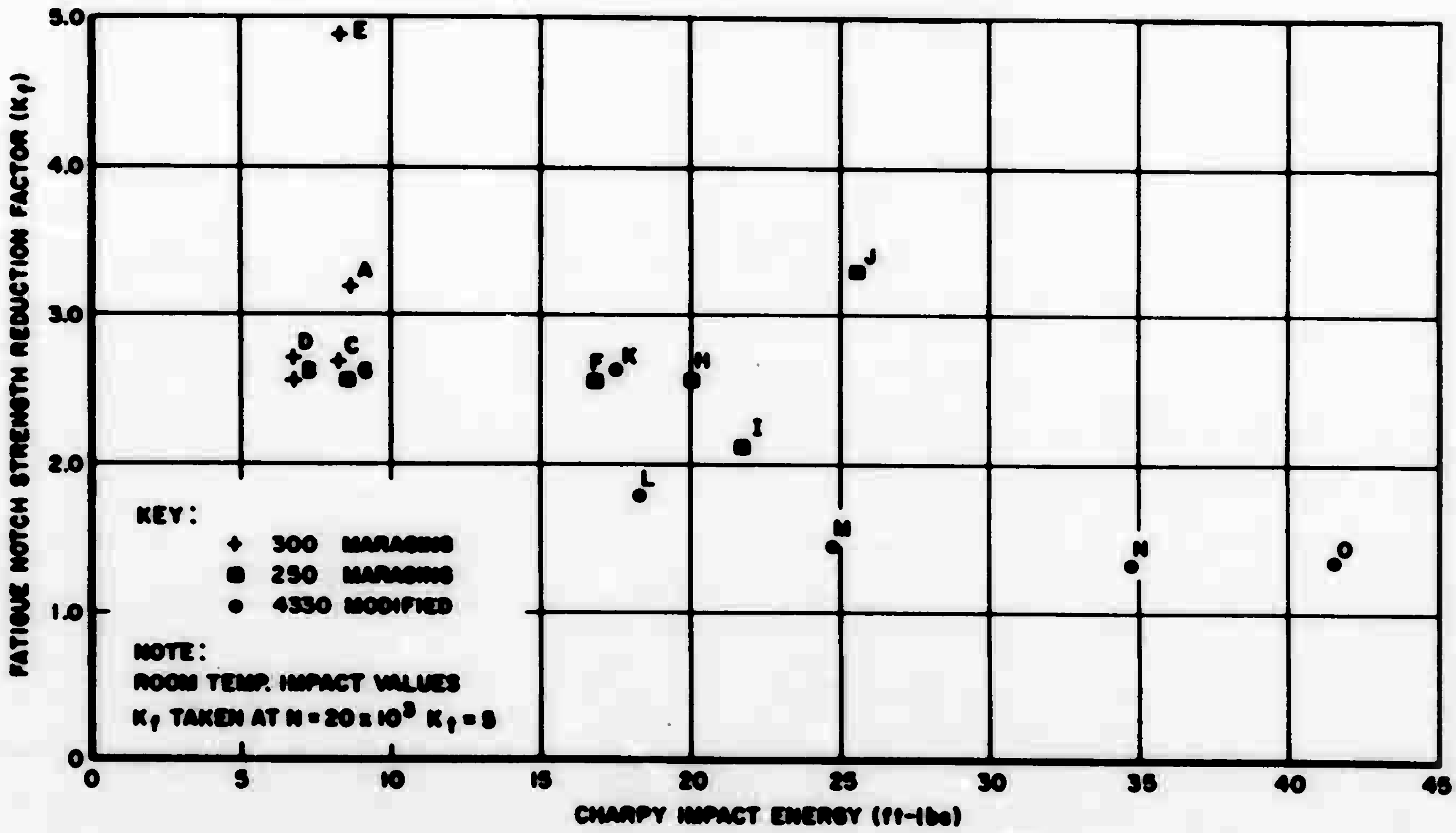


FIG. 17 FATIGUE NOTCH STRENGTH REDUCTION FACTOR VS CHARPY IMPACT ENERGY