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6. AUTHOR(S)
R.R. Fujczak, J.A. Kapp, and C.J. Nolan

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13. ABSTRACT *(Maximum 200 words)*

Two different steels, AISI 4150H and maraging 250, were tested in torsional fatigue to failure. Both materials were prepared with three surface conditions: (1) as-machined (machining grooves left on the outside surface); (2) as-polished; and (3) polished and shot peened. All specimens converge at low cycle life (about 1,000 cycles), but at lower torsional stresses, the greatest improvement in fatigue life is shown by the shot peened specimens, followed by the as-polished specimens. This is true for both materials. The 4150H steel shows the greatest fatigue lives on the torsional S-N curves, but the maraging 250 displays the greatest degree of improvement throughout the range of surface conditions.

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INTRODUCTION

Large recoil springs are used in applications that require huge stored energy. These springs are usually made from very high strength materials in very large section sizes for spring applications; wire diameters are on the order of one inch (25 mm). Since the loading of springs produces a state of stress that is primarily torsion, and furthermore, since the springs must perform for many recoil cycles, the material property that governs the performance of these springs is the torsional fatigue property (refs 1-3) of the spring material. There is little or no available torsion fatigue data for the class of materials used in these springs, which suggests that the springs were designed considering static strength or using empirical approaches. Since there have been some historical fatigue failure problems with recoil springs, a program to measure the torsional fatigue properties of the class of materials used for the recoil springs should be supported. The results of such a program will lead to future product improvements and optimal designs for future springs.

MATERIALS

Presently, two classes of materials are used to manufacture recoil springs. The first is high strength, low alloy steels (8660, 8650, 4150, 5150), and the second is maraging steels. The alloy steels chosen for this program are 4150H steel and maraging 250 grade.

The average mechanical property values for the 4150H steel and the maraging 250 steel are given in Table 1. The maraging 250 steel tensile data indicates higher strength and toughness than the 4150 steel.

TEST PLAN

There are many factors that affect the fatigue performance of a material. Those that may contribute to the fatigue response of large recoil springs are mean stress from preloads, surface finish from forming processes, and residual stresses from shot peening. To address all of these parameters in detail requires a very involved testing program. A more limited approach is warranted here. The base line data is established for each of the materials mentioned above. The torsional fatigue properties are measured with polished samples under a stress varying from zero to several positive values ($R = 0$). The effect of surface finish is accounted for by testing nonpolished samples under similar stress conditions. Finally, the effects of residual stress are accounted for by testing polished samples that have been shot peened after final polishing.

SPECIMEN CONFIGURATION

Figure 1 shows the torsional test specimen designed for use in an Instron Model No. 1323 Triaxial Test Machine capable of static and fatigue testing in combinations of 100,000 lbs (445 kN) tension-compression, 50,000 in.-lbs. (5650 N-m) torsion, and 50,000 psi (345 MNm^{-2}) pressure. In our case, only the torsion capability was used. Figure 1a shows the general specimen designed to be gripped circumferentially on the outside diameter edges by the test machine. Figures 1b, 1c, and 1d show the surface conditions of the test specimens--1b: rough as-machined (unpolished); 1c: polished; 1d: shot peened.

The as-machined specimens are considered to be in a condition to minimize fatigue crack initiation because of the presence of the machining marks acting as fatigue crack starters. The polished specimens should deter the crack from initiating immediately and contribute to the overall fatigue life by introducing some initiation fatigue life before the crack propagates. The shot peening will enhance the fatigue crack initiation life even further by introducing compressive residual stresses on the outside surface of the specimens.

STATIC TORSION TESTS AND RESULTS

The elastic and plastic equations for torsional stress on the outside surface of the specimens are given in Reference 1. It has been demonstrated in Reference 4 that torsional stresses may be calculated throughout the elastic-plastic range with the plastic equation by using values from a torque-twist curve.

Static torsion tests were performed on both 4150H and marage 250 steels. Since the torsional stress is zero at the center of the test specimen's cross section and increases to a maximum on the outside surface, the specimens were tested until the twist moment reached a maximum and started to drop in value with increasing twist. This allowed calculation of torsional stress values up to the ultimate stress.

Figure 2 compares torsion stresses calculated from unit twist angle and machine twist angle. Both methods give very close correlation up to the limit of the unit twist, which was about five degrees/inch (two degrees/centimeter). Since the correlation was close up to about 85 percent of the ultimate torsion stress, stresses beyond this point were calculated by using values of machine twist (ref 4). The data for the unit and machine twist angles for 4150H specimen AA-51 are given in Table 2. The method for calculating torsion stresses using derivatives of twist moment with respect to twist angle was done by utilizing a spline approximation technique (ref 5).

Figure 3 compares 4150H steel and maraging 250 steel in static torsion. The maraging 250 remained elastic on the outside surface at a much higher torsional stress than the 4150H, which started becoming plastic at very low torsional stress. The values of ultimate torsion stress for both materials are as follows:

maraging 250:	153.7 Ksi (1059 MPa)
4150H:	139.6 Ksi (963 MPa)

From the comparisons of mechanical properties, the ultimate tensile strength values for maraging 250 were about 15 percent higher than those for 4150H, and the static ultimate torsional values were about 10 percent higher.

TORSIONAL FATIGUE TESTS AND DATA

Torsional fatigue tests were performed on both materials for each surface condition: as-machined, polished, and shot-peened. Each group was tested in torsional fatigue to failure at various levels of twist moment, from 33 to 100 percent of the maximum static value. Three specimens were run at each value except for low values of twist moment that failed at more than one million cycles or lasted beyond one million cycles without fatigue failure. Any specimens that did not fail beyond this point were considered runouts approaching the endurance limit for purposes of saving time in the testing program.

The torsional fatigue data for both materials in each condition are given in Table 3.

FATIGUE TEST RESULTS

4150H Steel

A comparison of the effects of surface finish on the torsional fatigue life of 4150H is shown in Figure 4. The plots have been normalized to indicate applied fatigue twist moment as a percentage of the ultimate static twist moment calculated from the static torsion tests.

It is apparent that the effects of surface finish are minimized at very high torsion stresses, as shown by the convergence of all three lines at close to 100 percent twist moment ratio. At lower torsion stresses, however, the effects of surface finish improvements appear by fanning the lines out. The lowest torsional fatigue life is displayed by the as-machined condition, as expected. The next increase in fatigue life is contributed by the polished specimens. The greatest increase appears from the shot peened specimens. Qualitatively, the increase in torsional fatigue life is related to the degree of compressive residual stresses contributed by the surface treatment. Shot peening contributes the most. This improvement appears to be related to the enhancement of the life required for fatigue crack initiation and is demonstrated by the changes in the slope of the lines.

At first, the failure mode for the 4150H specimens was very confusing to interpret, because it appeared that they were failing in the brittle mode in the 45-degree twist plane. However, it was discovered that the grain texture in the longitudinal direction was so elongated in some cases from the extrusion process, that the weakest direction of some specimens was the longitudinal direction. In an attempt to fail in the weakest direction, some of the specimens crossed over the 45-degree tensile twist plane and exhibited failure in all three directions as a compromise. The longitudinal failures appeared like a failed laminate bundle with poor longitudinal adhesion, causing shear to occur in the longitudinal direction before the transverse direction.

Maraging 250 Steel

Figure 5 demonstrates the effects of surface improvement on the torsional fatigue life of maraging 250 steel. The effects are similar to those shown by 4150H. The fatigue life improvement appears in the same order, from polished to shot peened. The lines also converge at high torsional stresses, similar to 4150H. The differences between both materials can be seen when compared at the same surface condition.

Most of the maraging 250 specimens failed in the ductile torsional fatigue mode in the transverse direction radially through the axis normal to the longitudinal direction. However, a handful of maraging 250 specimens exhibited fatigue crack initiation and on the 45-degree tensile plane, as opposed to the expected transverse shear plane shown by the specimens previously mentioned. These 45-degree cracks were caused by the presence of a brittle inclusion at or near the outside surface of the specimens. A more detailed discussion of this phenomenon has already been presented in Reference 6.

COMPARISON BETWEEN 4150H AND MARAGING 250 STEELS

Table 3 contains the complete listing of the torsional fatigue data for both 4150H and maraging 250 specimens tested under three surface conditions.

Figure 6 shows the comparison between 4150H and maraging 250 in the as-machined condition. It can be clearly seen that the 4150H offers greater torsional fatigue life at all stress levels. A comparison of slopes shows that 4150H is more sensitive to changes in twist moment.

Figure 7 shows the comparison in the polished condition. The 4150H still offers greater torsional fatigue life, but there is convergence at the higher stresses. Again, 4150H shows more sensitivity to changes in twist moment by comparison of the slopes.

Figure 8 shows the comparison in the shot peened condition. In this case, both materials offer similar life improvement because the convergence occurs in mid-range. The slope of the 4150H still shows greater sensitivity to changes in twist moment, so at lower stress levels, the 4150H will prevail over the maraging 250.

CONCLUSIONS

1. Surface improvement enhances torsional fatigue life in two ways: minimization of fatigue crack starters by polishing and introduction of surface compressive residual stresses to retard fatigue crack initiation.

2. The usefulness of surface improvement in torsional fatigue life enhancement diminishes as the applied stress increases, so surface improvement is more beneficial at lower operating stresses.

3. Surface improvement integrity must be maintained in order to benefit from the fatigue life enhancement. Otherwise, surface damage will sacrifice the gains caused by surface improvement.

4. The 4150H steel yields similar (shot peened) or higher fatigue lives (as-machined and polished) compared to maraging 250 at equivalent applied torsional stresses. However, the maraging 250 allows the greatest degree of improvement over the range of surface conditions.

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3. "Torsion Testing," *Metals Handbook*, 9th Edition, American Society for Metals, Metals Park, OH, Vol. 8, 1985, pp. 137-184.

4. R. Fujczak, "Correlation Between Machine Twist Angle and Unit Twist Angle in Calculating Shear Stresses For Elastic and Plastic Strains in Torsion," ARCCB-TR-91013, Benet Laboratories, Watervliet, NY, April 1991.

5. A. Ralston and P. Rabinowitz, *A First Course in Numerical Analysis*, McGraw-Hill, Inc., New York, 1978.

6. R. Fujczak and A. Kapusta, "Brittle Torsional Fatigue Crack Initiation in an Otherwise Ductile Environment," ARCCB-TR-90008, Benet Laboratories, Watervliet, NY, March 1990.

Table 1. Mechanical Properties For 4150H and Marage 250

	Property	1	2	3	4	Average Value
4150 Steel Tensile Data	0.2% Yield Strength, Ksi	219	233	220	-	224.0
	Ultimate Tensile Strength, Ksi	236	240	239	-	238.3
	% Elongation	9	16	9	-	11.3
	% Reduction-in-Area	33	45	43	-	40.3
	Charpy V:					
	Test Temperature, °F	-40	-40	-40	-	-40.0
	Ft-Lbs	10	10	10	-	10.0
	Slow Bend:					
	Test Temperature, °F	-40	-40	-40	-	-40.0
	K_{Ic} - Ksi√in.	56.4	54.5	49.8	-	53.6
Heat Treatment: 1500°F 1 hour oil quench + 700°F 4 hours air-cooled, Hardness: Rc 49 All specimens: longitudinal direction from 1 1/2-inch round bar stock						
Marage 250 Steel Tensile Data	0.2% Yield Strength, Ksi	255	264	259	258	259.0
	Ultimate Tensile Strength, Ksi	274	278	274	275	275.3
	% Elongation	10	9	10	9	9.5
	% Reduction-in-Area	55	53	54	54	54.0
	Charpy V:					
	Test Temperature, °F	-40	-40	-40	-	-40.0
	Ft-Lbs	16	15	15	-	15.3
	Slow Bend:					
	Test Temperature, °F	-40	-40	-40	-	-40.0
	K_{Ic} - Ksi√in.	89.7	82.0	93.4	-	-
		91.0	82.3	95.8	-	89.0
Heat Treatment: 1700°F 1 hour air-cooled + 1400°F 4 hours air-cooled + 900°F 3 hours air-cooled, Hardness: Rc 52-55 All specimens: longitudinal direction from 1 1/2-inch round bar stock						

Table 2. Torque Data for 4150H Specimen AA-51

	MACH <	UNIT <	M(T)	(dy/dx)M	Tau-a	dy/dx	Tau-M
pt 0	0.00	0.00	0	4,626.86	0.00	16,868.75	0.00
pt 1	1.75	0.48	8,097	3,963.30	41,237.68	16,868.75	39,759.16
pt 2	3.00	0.85	12,218	2,894.50	57,381.58	9,898.10	57,725.50
pt 3	4.25	1.20	15,369	2,377.00	71,198.65	8,176.91	71,567.84
pt 4	5.55	1.59	18,278	1,869.50	83,192.97	6,607.30	83,027.60
pt 5	7.10	2.01	20,702	1,664.40	92,283.91	5,161.00	94,121.99
pt 6	8.45	2.53	23,126	1,616.70	101,669.05	4,139.40	105,728.68
pt 7	10.00	3.06	25,066	1,082.80	108,406.27	3,249.70	109,531.71
pt 8	11.85	3.73	27,005	945.80	115,405.34	2,580.20	117,421.63
pt 9	14.25	4.55	28,944	752.40	122,810.64	2,115.00	124,209.23
pt 10	16.25	N/A	30,399	655.40	N/A	N/A	129,675.95
pt 11	20.20	N/A	32,338	397.80	N/A	N/A	133,753.25
pt 12	25.00	N/A	34,035	291.40	N/A	N/A	139,279.67
pt 13	29.75	N/A	35,102	140.00	N/A	N/A	139,382.81
pt 14	34.70	N/A	35,732	68.00	N/A	N/A	139,490.52
pt 15	40.00	N/A	36,023	37.50	N/A	N/A	139,507.58
pt 16	60.00	N/A	36,556	0.00	N/A	N/A	139,633.63

MACH < = machine twist angle in degrees
UNIT < = unit twist angle in degrees/inch
M(T) = twist moment in inch-pounds
dy/dx = derivative of M(T) with respect to UNIT <
(dy/dx)M = derivative of M(T) with respect to MACH <
Tau-a = torsion stress calculated from dy/dx, psi
Tau-M = torsion stress calculated from (dy/dx)M, psi

Table 3. 4150H and Marage 250 Torsional Fatigue Data

	M, in-#	% of M-4150	% of M-Marage	Cycles
AA-3	29,245	80	72.66	21,940
AA-4	29,245	80	72.66	24,820
AA-5	29,245	80	72.66	18,810
AA-6	25,589	70	63.58	79,590
AA-48	25,589	70	63.58	122,490
AA-46	25,589	70	63.58	100,470
AA-47	21,934	60	54.49	242,280
AA-50	21,934	60	54.49	718,500
AA-45	21,934	60	54.49	287,400
AA-9	32,890	90	81.71	3,900
AA-11	32,890	90	81.71	7,540
AA-12	32,890	90	81.71	6,860
AA-32	36,556	100	90.82	1,180
AA-41	36,556	100	90.82	1,590
AA-49	36,556	100	90.82	1,110
AM-1	21,934	60	54.49	44,640
AM-2	21,934	60	54.49	64,120
AM-3	21,934	60	54.49	48,040
AM-4	25,589	70	63.58	40,750
AM-5	25,589	70	63.58	34,000
AM-6	25,589	70	63.58	37,820
AM-7	18,280	50	45.42	106,300
AM-8	18,280	50	45.42	114,000
AM-9	18,280	50	45.42	119,600
AM-10	14,620	40	36.32	1,017,200
AM-13	29,245	80	72.66	8,900
AM-14	29,245	80	72.66	9,300
AM-15	29,245	80	72.66	14,080

	M, in-#	% of M-4150	% of M-Marage	Cycles
AM-16	32,890	90	81.71	790
AM-17	32,890	90	81.71	690
AM-18	32,890	90	81.71	1,620
SP-1	29,245	80	72.66	124,470
SP-2	29,245	80	72.66	258,000
SP-3	29,245	80	72.66	165,030
SP-4	32,890	90	81.71	14,150
SP-5	32,890	90	81.71	20,440
SP-6	32,890	90	81.71	18,480
SP-7	36,556	100	90.82	2,030
SP-8	36,556	100	90.82	1,600
SP-9	36,556	100	90.82	1,170
MSP-1	25,589	70	63.58	1,000,000
MSP-3	29,245	80	72.66	300,500
MSP-4	29,245	80	72.66	297,250
MSP-7	29,245	80	72.66	226,500
MSP-8	32,890	90	81.71	12,420
MSP-9	32,890	90	81.71	106,070
MSP-10	32,890	90	81.71	136,750
MSP-11	36,556	100	90.82	29,000
MSP-12	36,556	100	90.82	26,850
MSP-13	36,556	100	90.82	27,700
MSP-14	40,212	110	99.91	1,850
MSP-15	40,212	110	99.91	1,680
MSP-16	40,212	110	99.91	2,300
MM-1	29,245	80	72.66	2,250
MM-2	29,245	80	72.66	2,590
MM-4	29,245	80	72.66	2,610
MM-5	25,589	70	63.58	9,630

	M, in-#	% of M-4150	% of M-Marage	Cycles
MM-6	25,589	70	63.58	5,650
MM-7	25,589	70	63.58	4,000
MM-8	21,934	60	54.49	15,780
MM-9	21,934	60	54.49	20,430
MM-10	21,934	60	54.49	23,210
MM-11	18,280	50	45.42	66,780
MM-12	18,280	50	45.42	46,070
MM-13	18,280	50	45.42	66,030
MM-14	14,620	40	36.32	183,160
MM-15	14,620	40	36.32	255,540
MM-16	14,620	40	36.32	113,970
MM-17	12,185	33	30.27	254,900
MM-18	12,185	33	30.27	1,000,000
MM-19	12,185	33	30.27	452,050
MM-20	32,890	90	81.71	1,710
MM-21	32,890	90	81.71	1,330
MM-22	32,890	90	81.71	1,300
MP-1	29,245	80	72.66	70,200
MP-2	29,245	80	72.66	16,140
MP-3	29,245	80	72.66	34,840
MP-4	32,890	90	81.71	11,240
MP-5	32,890	90	81.71	9,450
MP-6	32,890	90	81.71	12,350
MP-7	25,589	70	63.58	93,350
MP-8	25,589	70	63.58	60,620
MP-9	25,589	70	63.58	142,520
MP-10	36,556	100	90.82	3,600
MP-11	36,556	100	90.82	4,950
MP-12	36,556	100	90.82	4,840

	M, in-#	% of M-4150	% of M-Marage	Cycles
MP-13	21,934	60	54.49	429,340
MP-14	21,934	60	54.49	146,370
MP-15	21,934	60	54.49	108,820
MP-16	40,212	110	99.91	740
MP-17	40,212	110	99.91	900
MP-18	40,212	110	99.91	580

Specimen Identification Code:

M, in-# = twist moment in inch-pounds
% of M-4150 = (applied twist moment)/(ultimate twist moment) • 100 for 4150H steel
% of M-marage = (applied twist moment)/(ultimate twist moment) • 100 for maraging 250 steel
cycles = cycles to failure

AA = As-Polished 4150H
AM = As-Machined 4150H
SP = Shot Peened 4150H
MSP = Shot Peened Marage 250
MM = As-Machined Marage 250
MP = As-Polished Marage 250

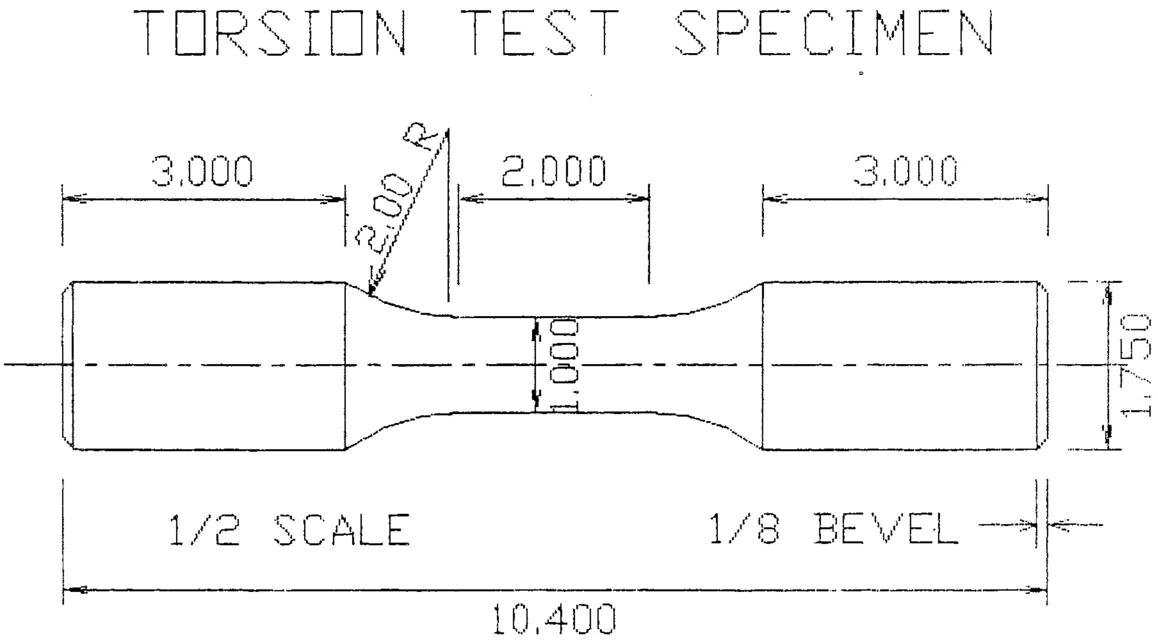


Figure 1. Torsional test specimen: (a) schematic.

Figure 1. Torsional test specimen: (b) as-machined (unpolished).

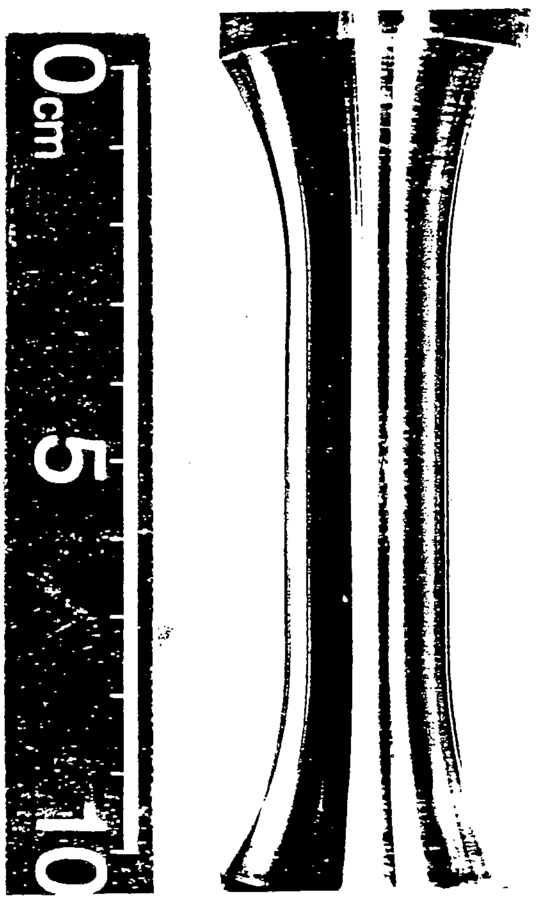


Figure 1. Torsional test specimen: (c) polished.

Figure 1. Torsional test specimen: (d) shot peened after final polish.

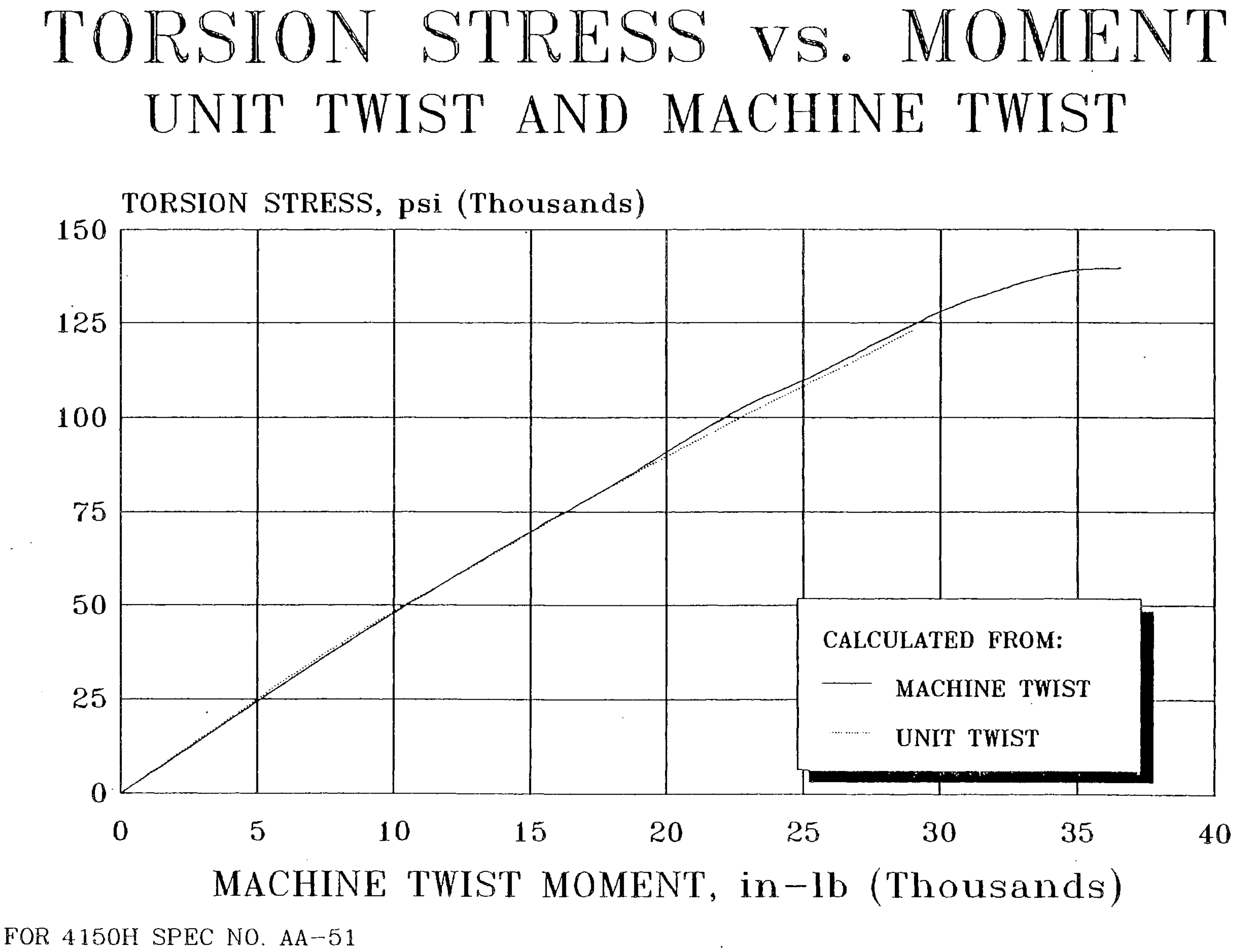


Figure 2. Comparison of torsional stresses from unit twist angle and machine twist angle.

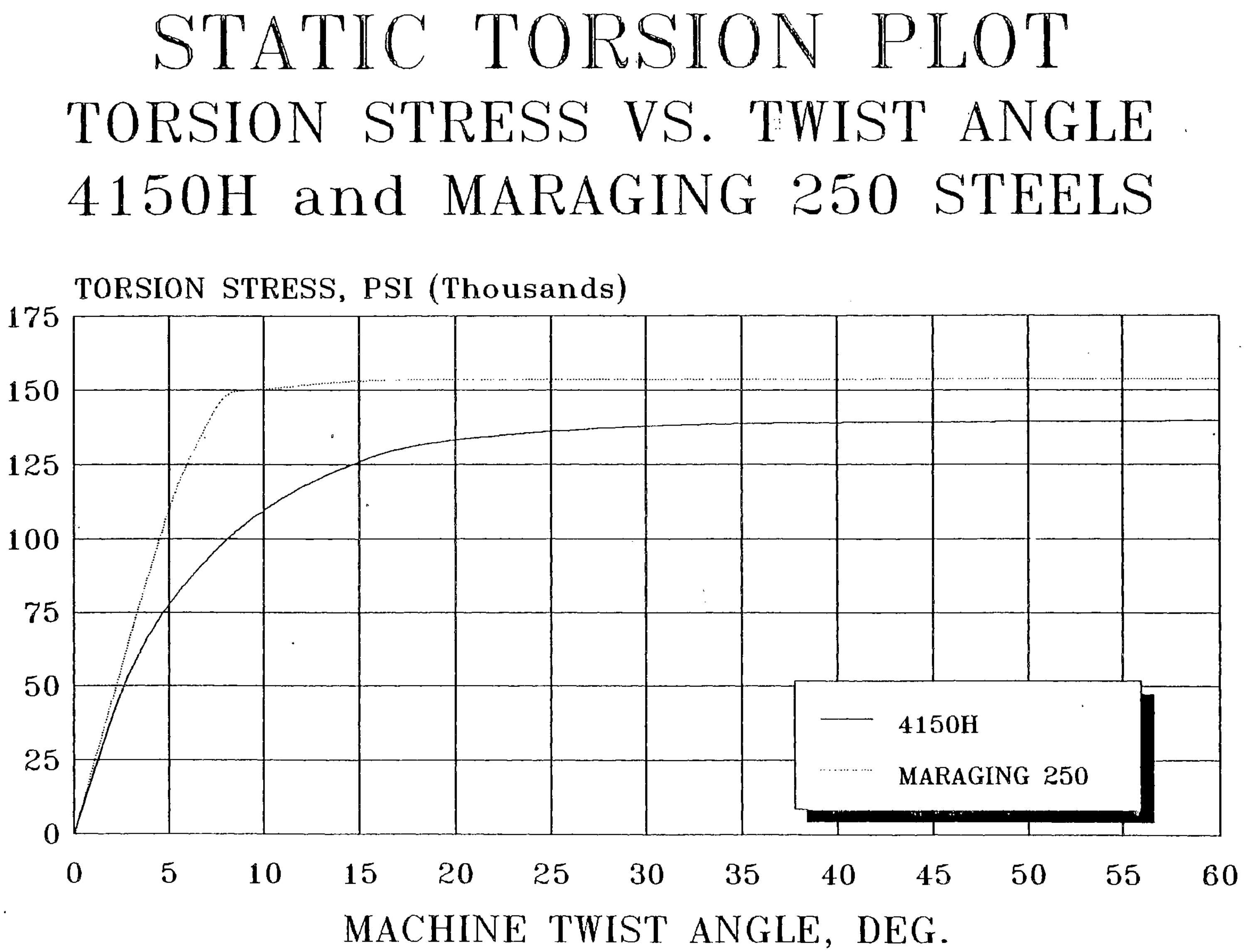


Figure 3. Comparison between 4150H and maraging 250 in static torsion.

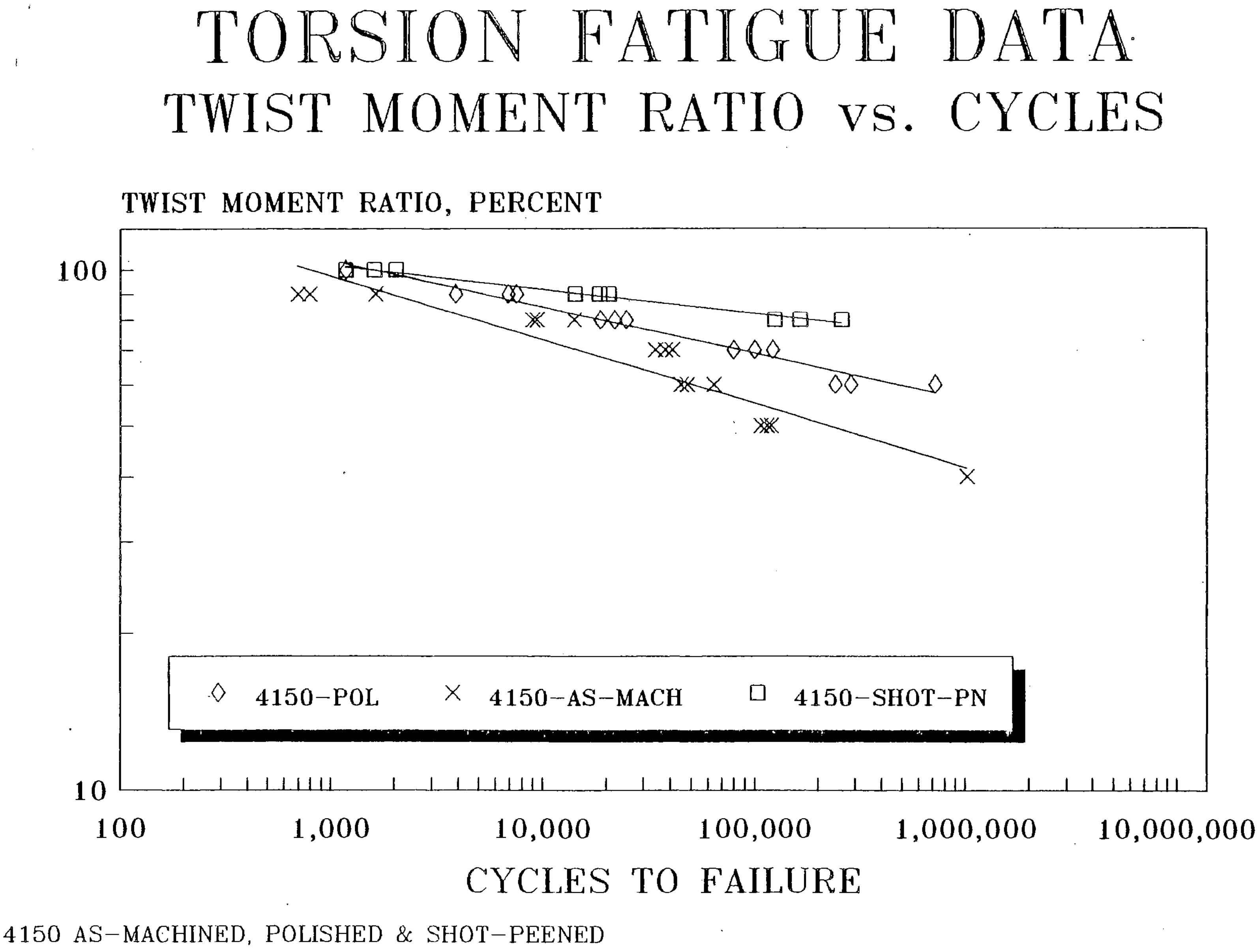


Figure 4. Effects of surface finish on torsional fatigue life of 4150H steel.

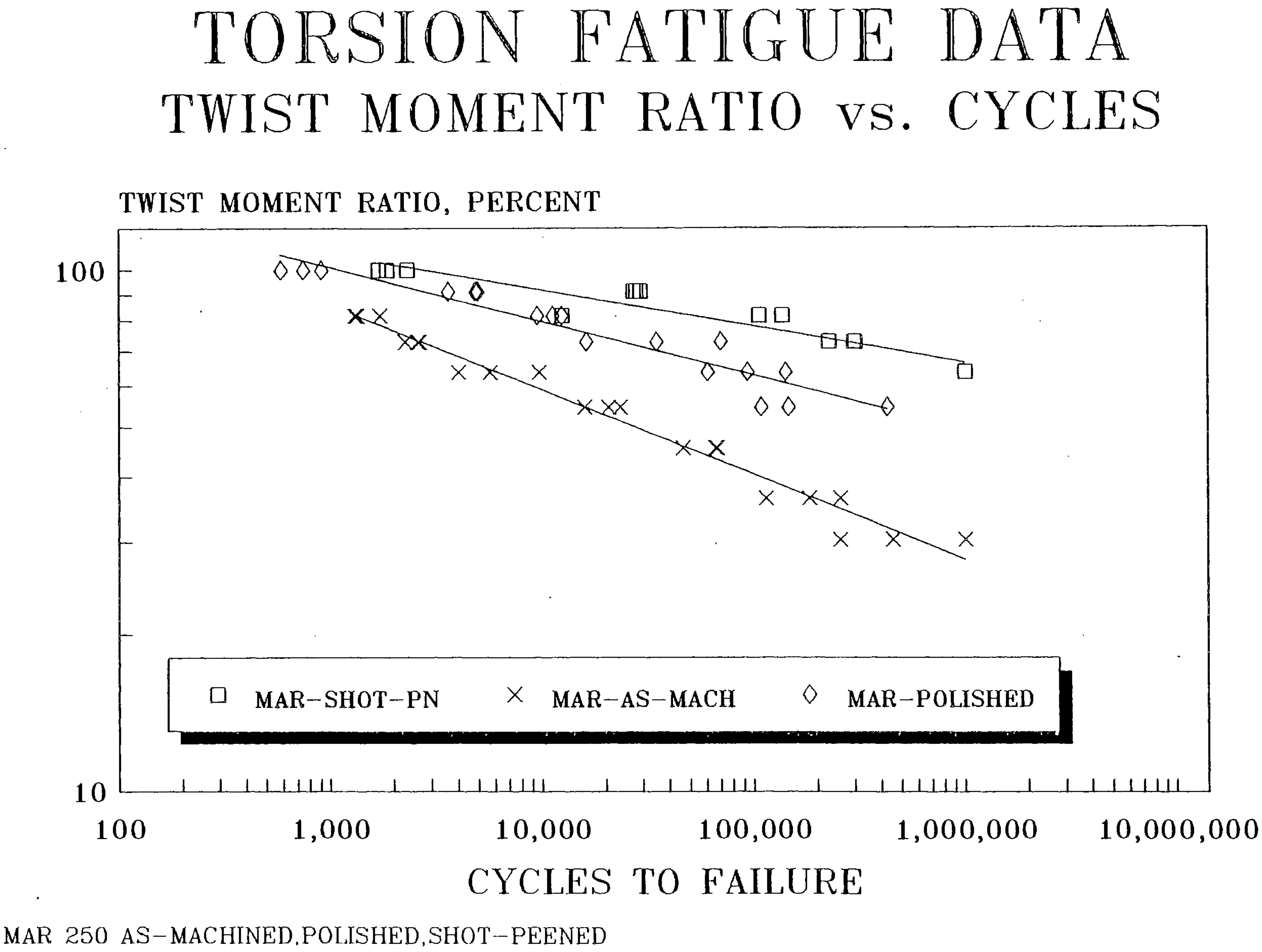


Figure 5. Effects of surface finish on torsional fatigue life of maraging 250 steel.

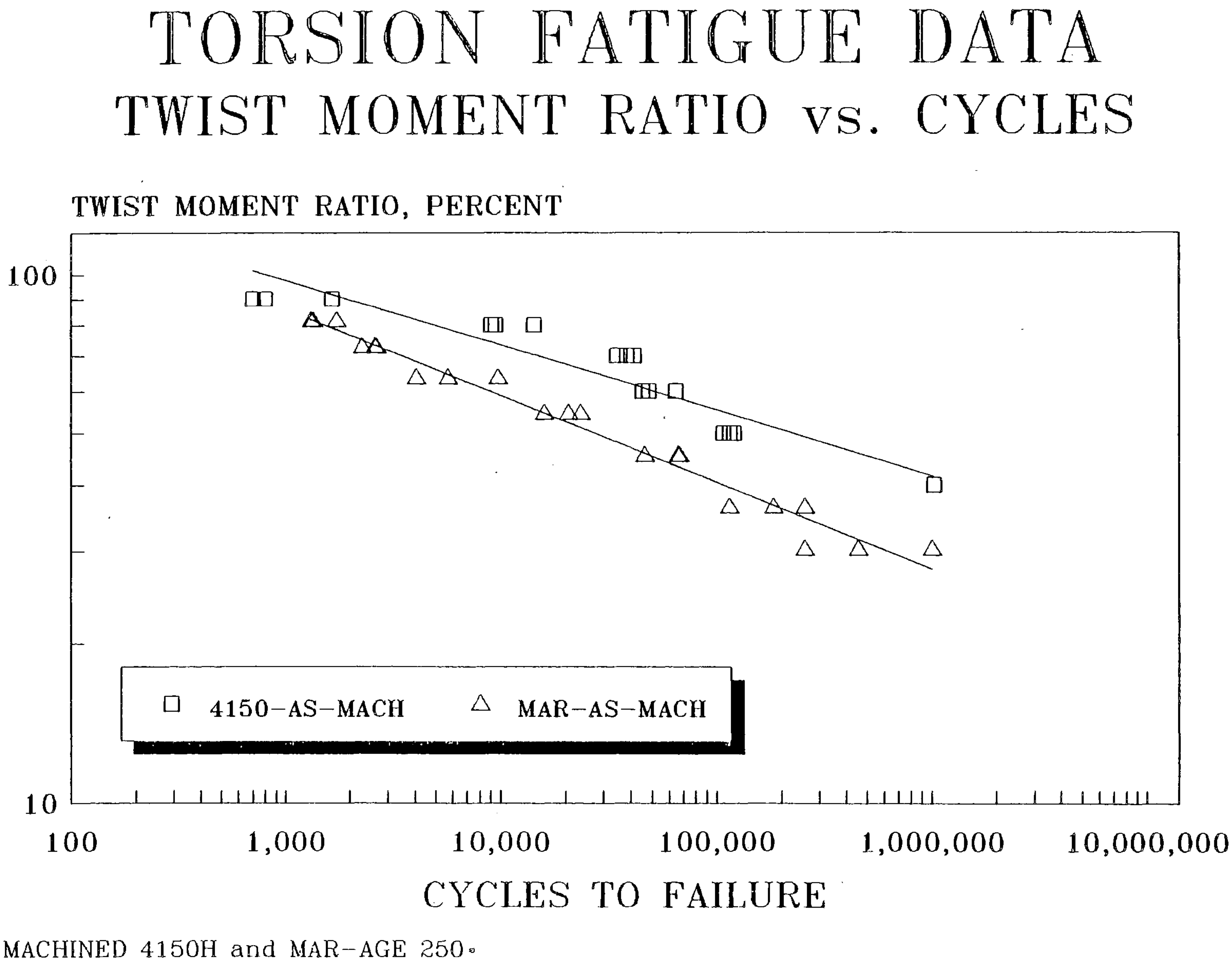
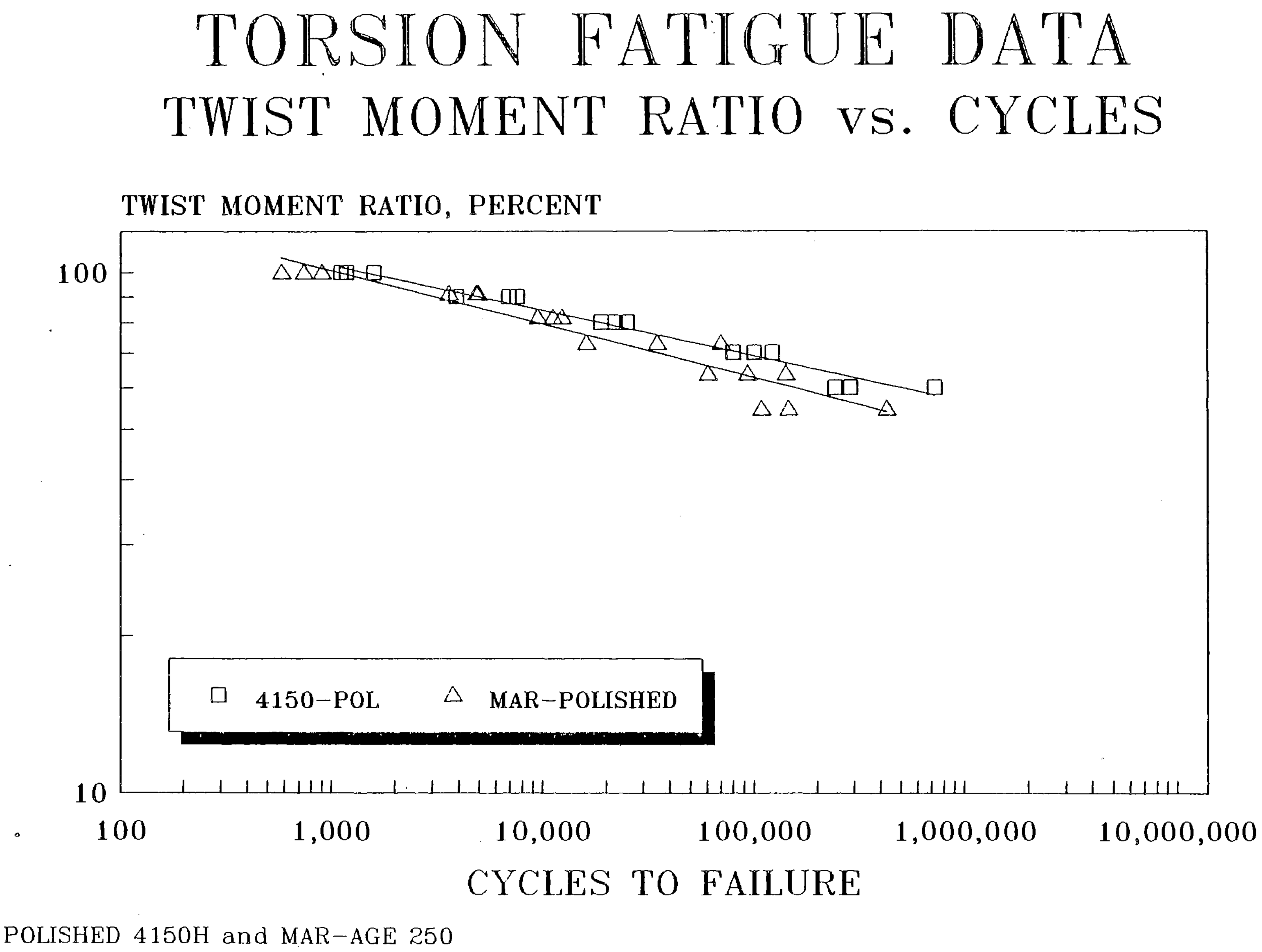


Figure 6. Comparison between 4150H and maraging 250 as-machined torsional fatigue life.



TORSION FATIGUE DATA

TWIST MOMENT RATIO vs. CYCLES

POLISHED 4150H and MAR-AGE 250

Figure 7. Comparison between 4150H and maraging 250 polished torsional fatigue life.

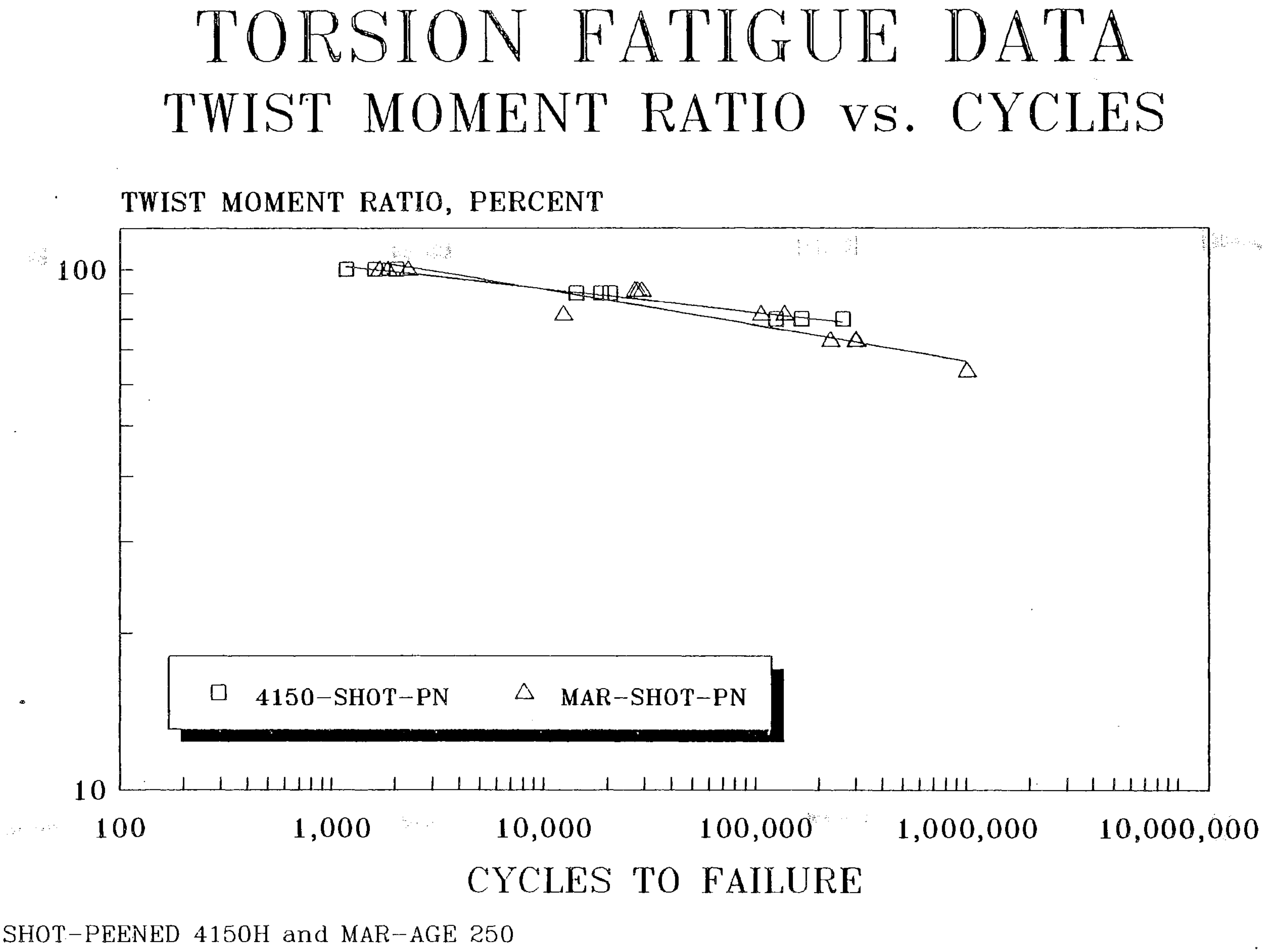


Figure 8. Comparison between 4150H and maraging 250 shot peened torsional fatigue life.

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