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AGENDA

6 February 1964

ATTENDANCE FOR
CONFERENCE ON APPLICATION OF MARAGING STEELS

6 February 1964

INDUSTRIAL MEMBERS

Name	Affiliation
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Mr. R. F. Decker	International Nickel Company
Mr. T. W. Landig	International Nickel Company
Mr. B. W. Schaaf	International Nickel Company
Mr. H. V. Beasley	International Nickel Company
Mr. D. P. Cassidy	International Nickel Company
Mr. E. L. Fowler	International Nickel Company
Mr. D. J. Paquett	International Nickel Company
Mr. H. J. Weil	International Nickel Company
Mr. N. A. Matthews	International Nickel Company

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Lt Col C. A. Conlin	Watervliet Arsenal, Watervliet, N. Y.
Lt K. J. Kundig	Watervliet Arsenal, Watervliet, N. Y.
Dr. R. Weigle	Watervliet Arsenal, Watervliet, N. Y.
Mr. P. K. Rummel	Watervliet Arsenal, Watervliet, N. Y.
Mr. H. Musch	Watervliet Arsenal, Watervliet, N. Y.
Mr. J. G. Schatz	Watervliet Arsenal, Watervliet, N. Y.
Mr. J. Penrose	Watervliet Arsenal, Watervliet, N. Y.

Name	Affiliation
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Mr. M. L. Slawsky	Watervliet Arsenal, Watervliet, N. Y.
Mr. W. G. McEwan	Watervliet Arsenal, Watervliet, N. Y.
Mr. L. Liuzzi	Watervliet Arsenal, Watervliet, N. Y.
Mr. V. J. Colangelo	Watervliet Arsenal, Watervliet, N. Y.
Mr. C. Nolan	Watervliet Arsenal, Watervliet, N. Y.
Mr. J. Uy	Watervliet Arsenal, Watervliet, N. Y.
Mr. J. Barranco	Watervliet Arsenal, Watervliet, N. Y.
Mr. R. V. Milligan	Watervliet Arsenal, Watervliet, N. Y.
Mr. D. Kendall	Watervliet Arsenal, Watervliet, N. Y.
Mr. T. E. Davidson	Watervliet Arsenal, Watervliet, N. Y.
Mr. R. F. Tario	Watervliet Arsenal, Watervliet, N. Y.
Mr. F. Bachmann	Watervliet Arsenal, Watervliet, N. Y.
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Mr. L. W. Craven	Watervliet Arsenal, Watervliet, N. Y.
Mr. W. Sheslar	Watervliet Arsenal, Watervliet, N. Y.
Mr. A. Costa	Watervliet Arsenal, Watervliet, N. Y.
Mr. F. Schneider	Watervliet Arsenal, Watervliet, N. Y.
Mr. P. Mathe	Watervliet Arsenal, Watervliet, N. Y.
Mr. D. Bisceglia	Watervliet Arsenal, Watervliet, N. Y.
Mr. R. Betner	Watervliet Arsenal, Watervliet, N. Y.
Mr. J. Purtell	Watervliet Arsenal, Watervliet, N. Y.

Name	Affiliation
Mr. F. A. Heiser	Watervliet Arsenal, Watervliet, N. Y.
Mr. J. M. Miller	U. S. Army Weapons Command, Rock Island, Ill.
Mr. J. L. Sliney	U. S. Army Materials Research Agency
Mr. C. Hickey	U. S. Army Materials Research Agency
Mr. N. F. Armiento	Frankford Arsenal, Philadelphia, Pa.

MINUTES OF

CONFERENCE ON APPLICATION OF MARAGING STEELS

Monday, 6 February 1964

V. Colangelo: I would like to introduce Harry Weil of International Nickel Company, who will make a brief introduction of personnel from INCO.

Harry Weil: "INTRODUCTION OF INTERNATIONAL NICKEL COMPANY REPRESENTATIVES"

It is a pleasure for us to be here this morning. On behalf of INCO, I wish to express our appreciation to Watervliet Arsenal for arranging this meeting to review the 18% nickel maraging steel, and for extending an invitation to INCO to participate in the program. Since the 18% nickel steel is an INCO development, we are extremely interested in any of its intended applications. It is our opinion that this material does provide both the engineer and designer with a material having the unusual combination of ultra high strength and ductility combined with ease of fabrication. We feel that this combination of properties makes the 18% nickel steel a most suitable choice for consideration as heavy weapon components including recoilless rifles and mortar tubes, and possibly for your heavier and larger gun tubes in the howitzer class.

As we all realize, the development, evaluation and subsequent adoption of any new alloy is not without problems. However, the problems or deficiencies of any material can be worked out and overcome by cooperative effort of the developer, the producer, and the consumer. Meetings such as the one being held here today can be of benefit to all concerned. Our realization, and the subsequent discussion of the problems encountered in your evaluation of this material, we hope, will aid you in successfully adopting it for suitable applications which will take full advantage of its inherent properties.

At this point I would like to compliment the Arsenal on the work they have performed during their evaluation of maraging steel and for the information and data resulting from this evaluation which they have submitted to INCO. It is information of this type and this type cooperation which is invaluable to INCO in their continual development program.

Our participation in the program is not scheduled to take place until this afternoon but I would like to take the opportunity to introduce the INCO personnel in attendance. First of all, in our contingent from New York, we have Mr. Herschel Beasley, manager of INCO's district offices; Norm Matthews, who is head of our steel group and our product development department; Bernie Schaaf, of our iron nickel alloys section and product development; Tom Landig (same department); Ed Fowler, technical services group, product development; and Don Cassidy, who handles the ordnance industry for application engineering. From Hartford we have

Don Paquette, manager of our Hartford district office, and from Wilmington, Dick Green, manager of the Wilmington district office. We are also pleased to have with us, from our Bayonne Research Lab, Ray Decker who is our inventor of the 18% nickel maraging steel. We hope we will have a very interesting meeting. We look forward to the discussion following our talks.

L. Penrose: "HISTORY AND PERFORMANCE OF MARAGING STEELS AT WATERVLIET ARSENAL"

Gentlemen, I would like to review very briefly the work we have been conducting in our Development Lab during the last two years using the maraging steels.

We first became familiar with maraging steels about two years ago. They were brought to our attention by a visit from some people from Curtiss-Wright who had brought with them some mechanical property data. They proposed a development contract with us to make some tubing.

The results which they brought amazed most of us. Frankly, we did not believe them. It was 280,000 yield strength material with 40% reduction in area and 45 and 30 ft-lbs impact energy at room temperature. Before we consider any type of development contract for hardware, we thought it advisable to investigate some of this material ourselves. Fortunately, our neighbors, Allegheny-Ludlum Steel, were one of the first steel producers to melt the maraging heats. Consequently, we were able to obtain both the 300 type and the 250 type in the form of 1" bar stock from the metallurgical group at Allegheny.

We then actually conducted some of our own tests. Our standard acceptance test here for most of our materials consists of a yield strength requirement, a reduction of area requirement, and a V-notch Charpy impact test at -40°F. Because this was 1" bar stock we could test this material only in the longitudinal direction. However, we did run these tests on about 4 heats of steel, and verified, in fact, the data that we had seen from Curtiss-Wright. Now we did believe that this was possible. We now had a type of material which we had not seen before and which looked very promising.

While we were investigating the maraging material, we had a program for the development of the 81mm Mortar. One of the basic requirements for a mortar is that it be capable of being carried around in the field by the troops. Therefore, the item is built as light as possible.

For this reason we were again interested in maraging material. We considered extruded tubing but because of the high tooling costs and small quantities involved, we decided on bar stock.

The first billet was about 5 inches in diameter and approximately 5 feet long. This was procured from Vanadium Alloy Steel Company in

Latrobe, Pennsylvania. Because we were looking for the maximum strength possible, we selected the 300 grade. These tubes were successfully manufactured. You will hear later about any problems we might have had machining it.

The material after heat treatment exhibited about 265,000 psi yield strength with about 18 ft-lbs impact strength at -40°F, about 35% R. A. All tests were longitudinal because, although we bought this as a solid, we trepanned it to get out the bore. Consequently our wall was such that we could not get transverse properties from it. These properties looked very good to us.

We were also interested in what would happen to this material when we heat treated it, since fully heat treated it had a hardness of Rc 52. We anticipated machining and distortion difficulties. So we made a test block, i.e., a test block in which we cut some holes and grooves and notches with specified relationships to each other. It was about 8" square and about an inch thick. This was very carefully measured in our Gage Lab, then solution treated and aged at 900°F to determine the distortion we could expect. Distortion was very slight in agreement with some data from Vanadium Alloys. They had reported that the dimensions would change approximately .0004 inches per inch of dimension. This was just about what we had found. So we finished our 81mm Mortar tube to our drawing, heat treating at 900°F for three hours. Our dimensional change fell in line with the prediction.

The mortar presently is at Aberdeen Proving Ground where it now has better than 3000 rounds. As far as we know, everything is fine. Unfortunately, our 81mm Mortar program has since been suspended. We don't know when we will pick this up again, but at least we did gain some information on actual firing tests on maraging material.

At the same time, we encountered a serious problem on one of our howitzers. We were having failures with the breech ring. The breech ring as you may know goes on the back end of the tube. The breech ring feels the maximum pressure when a gun fires. It is a very critical component and very highly stressed. I won't go into details of the problem. However, it boiled down to a combination design and strength problem. We thought that perhaps maraging steel might help to solve the problem.

Again we were only going to procure one or two, so rather than go to the expense of paying for expensive dies and since casting had not reached the state-of-the-art where we could depend on it, we bought a solid forging of 300 grade material. This breech ring finishes at about 16" in diameter. The solid forging we bought was processed from a 32 inch ingot to 22" in diameter. There wasn't a considerable amount of reduction on it. However, we manufactured this breech ring. We trepanned from the middle of it a 9" core and took our tests in the middle of this core after aging at 900°F for three hours.

The results were disappointing. Strength was no problem. In the middle of the 22 inch section we got about 260,000 yield strength. Incidentally, when I quote yield strength we, at the arsenal, always report our yield strengths at 0.1% offset whereas most of the industry report it at 0.2%. These figures are about 10,000 psi lower than the 0.2% Y.S. The reduction in area (and these are transverse tests by the way) was about 4%, and the -40°F impact test about 4 ft-lbs. These were about the worse results we had seen. However, since we had gone this far, we completed the breech ring. We then tested it locally under a test which very closely simulates firing. It failed in a ridiculously low number of cycles. So, obviously maraged steel was not the material to solve our problem on the breech ring.

In addition, we learned that in heavy sections we really had a problem because, while we could develop the strength, we could not develop the ductility and toughness that we require.

Because of the success in the 81mm Mortar, however, we have considered the maraging material for a larger mortar, the 107mm Mortar, which is currently in development and about ready to be transferred to industrial.

Again, because of small quantities, we bought this material in solid shapes. The first pieces we bought were 300 grade material bars furnished by Vanadium Alloys. These were all procured on competitive bids and Vanadium was the low bidder.

The mechanical tests on this material showed that we achieved the proper strength level of about 265,000 psi. The reduction in area was about 12% and the impact strengths were around 6-7 ft-lbs in the transverse direction.

We have fired two mortars with this material with these properties: One a total of about 300 rounds, the other a total of about 700 rounds. To date they are performing in good shape, though we were not too happy with the mechanical properties.

In discussing the property problem with some of the steel producers and some of your own people, we came up with a purchase description. We have no formal specification for this material so we wrote a set of specifications very briefly and used this as a basis for procurement.

We thought that the requirements we came up with were realistic for procurement. Because of the work we had continued to do at the arsenal, we believed that we would realize much better properties with the 250 material than with the 300 material in the ductility and toughness area. For this reason we changed from the 300 material to the 250 material, and as a requirement established a qualification test. Since we were going to buy the material in the annealed condition, we required that the supplier heat treat a sample from his forging and meet a yield strength requirement of 230 to 260,000, a transverse reduction in area requirement of 18% and an impact requirement of 12 ft-lbs at -40°F. This appeared satisfactory to the industry and we purchased 13 seven inch rounds with a 3 1/2 inch hole trepanned from the center. We received competitive bids with no exception to our requirements. Again Vanadium was the low bidder.

About a week before their required delivery date, we received a call from them. They said they could not meet the impact requirements. They were getting about 8 and 9 ft-lbs. We discussed possible heat treatment and/or re-aging cycles. They tried some of these. The best they could come up with over 3 heats of material, with 6 pieces in one heat, 6 in another, and one in the third, was a range of 9 - 14 ft-lbs. We bought the material on a deviation to our requirement of 12 ft-lbs. The actual average was about 10 1/2 ft-lbs.

Presently I'm afraid our position is that if we were to go out today with the same purchase description, we probably would not get a firm bid from any steel producers. They feel they have this problem in heavy sections. At the moment they do not know exactly how to solve it.

We do not want material that has any possibility of giving us a catastrophic failure. Our experience has shown that we need toughness. This is a realistic thing and we must have it. Therefore, I would say that we are at this stage right now: we used it in the 81mm and 107mm Mortars, we fired it: it is performing at least in these two areas; and the one area it has not performed well was in our breech ring. We attribute this to the very poor ductility and toughness but we would like to see more data on the performance of this material on repeated applications of heavy loads to be sure that it will actually perform. We hope we will get into this type of discussion this afternoon. When we get a chance to fire some of these questions at you fellows. This is where we stand right now in the development of this material at the arsenal.

DISCUSSION:

R. Decker: Did you relate the firing experience on the tubes of the 18 nickel steel with the firing life of your conventional gun material?

J. Penrose: If you are talking life I guess it is no secret the figure on the conventional 81mm Mortar tube is probably 10,000 rounds. This particular maraged tube will probably never see 10,000 rounds because we just can't afford to buy this kind of ammunition. It would be very nice if we had a simulated test for our gun tubes. I mentioned earlier we do have such a test for breech rings. We hope we will have one for tubes. We could approach this sort of thing.

J. Barranco: "LOW CYCLE FATIGUE DATA"

The notch sensitivity in low-cycle fatigue of a series of high-strength materials is being investigated at Watervliet Arsenal. In the current phase of this work, the notch sensitivity as a function of strength-level for 4330 (modified), 250 and 300-type maraged steels, is being determined using a rotating-beam type of specimen and theoretical stress-concentration factors of 3 and 5. The testing covers a range from 1000 to 150,000 cycles-to-failure. Subsequent work will include the study of additional high-strength materials, and notch sensitivity in low-cycle tensile fatigue below 1000 cycles-to-failure. In addition, the effect of inherent ductility and toughness on notch sensitivity for the two categories of maraged steel will be investigated.

The 4330 (modified) specimens were obtained from transverse sections of a 120mm gun tube having the following chemical analysis:

C	-	.30
Mn	-	.61
P	-	.007
S	-	.010
Si	-	.22
Ni	-	2.40
Cr	-	1.05
Mo	-	.48
V	-	.11

The 250 and 300-type maraged steels were obtained from transverse sections of 6-inch-square forgings. All material was consumable-vacuum melted. Two different heats of each material with different ductility and toughness were used. The chemical analyses of the heats were as follows:

	HT07303 250(A)	HT07032 250(B)	HT07329 300(A)	HT07010 300(B)
C	.02	.02	.03	.02
Si	.02	.09	.08	.09
Mg	.05	.08	.05	.09
S	.005	.006	.005	.007
P	.004	.004	.003	.003
Ti	.35	.31	.57	.55
Al	.11	.10	.15	.07
Mo	4.92	4.57	4.96	4.82
Co	8.02	7.78	9.30	8.94
Ni	18.59	18.60	18.80	18.56
B	.003	.002	.004	.003
Zr	.005	.011	.019	.018
Ca		.05	.05	

The mechanical properties of the materials used are summarized in Table I. Although it is planned to investigate four strength levels for each material, including both the over-aged and under-aged conditions for the maraged steels, only those properties currently available are listed.

As shown in Table I, the notched-to-smooth tensile strength ratios for all four strength levels of the 4330 (modified) steel, range between 1.43 and 1.52 with the higher strength level having only a slightly lower value than the others. The 300-type maraged steel shows a notched-to-smooth ratio of 1.16 to 0.95 for Kt = 3 and 5, respectively. As will be shown later, these low, notched tensile properties are reflected in the fatigue characteristics.

Table I indicates that one of the 300 maraged steels had been over-aged and two had been under-aged. These treatments were used to obtain differences in ductility and strength. It should be noted also, that for the 250 maraged steel only a single kind of heat-treatment is needed to obtain optimum strength. For the 300 maraged steel, similarly, only a single kind of heat-treatment is needed. Additional information on tensile strength and other properties of maraged steel can be found in the attached Interim Data Sheet "18% -Nickel Maraging Steel".*

The relation of cyclic stress (normalized by the tensile strength) to cycles-to-failure for several of the material categories tested to date, is summarized in Figure I. As would be expected, the fatigue strength is effectively proportional to tensile strength, regardless of material.

Typical curves showing the relations between normalized cyclic stress and cycles-to-failure, for the 192,700 psi tensile strength 4330 (modified) and the 301,400 tensile strength 300 maraged steel are shown in Figures 2 and 3 respectively. Figure 4 is a plot of notch sensitivity (q), as a function of tensile strength. Notch sensitivity (q) is defined as

$$q = \frac{K_f - 1}{K_t - 1}$$

where K_f is the ratio of unnotched-to-notched fatigue strength at a given number of cycles-to-failure, and K_t is the theoretical stress-concentration factor. It is apparent then, that q approaches 0 for a notch-insensitive material and becomes 1.0 or greater for a highly notch-sensitive material. As can be noted from Figure 4, for any given number of cycles, q is effectively constant for the 4330 material, over a tensile strength range of 137,000 to 173,000 psi yield strength. At the 192,000 psi tensile strength level, q increases to approximately double the value for

*By Development and Research Dept., The International Nickel Co., Inc., 67 Wall Street, New York 5, New York. 11/26/62.

the three lower strength levels. The 300 type maraged steel with a tensile strength level of 301,000 psi is much more notch-sensitive than the lower strength 4330. It exhibits values of q approaching 0.9 for $K_t = 3$ and100,000 cycles-to-failure, as compared to 0.56 and 0.32 respectively, for the 192,000 and 173,000 tensile strength 4330 material. The 251,000 tensile strength, 300 type maraged steel in the under-aged condition, exhibited q values closely approaching that for the 301,000 psi tensile strength.

Recent fatigue testing of the 300 maraged steel at the 240 ksi yield-strength level for both the over-aged and under-aged conditions, revealed almost identical values of notch-sensitivity determined at 20,000 and 100,000 cycles per minute, for both the $K_t = 3$ and $K_t = 5$ cor 'itions, as shown in Table II.

Two groups of 250 maraged steel were heat treated to give nearly the same values of yield and tensile strengths as shown in Table I. Material of Group A showed a ductility of more than twice that of Group B as measured by reduction in area. However, the notch-sensitivity values for a given number of cycles are nearly identical in both materials. Whether notch-sensitivity in low-cycle fatigue is actually not dependent upon inherent ductility, or whether the insensitivity is simply a manifestation of a rotating-beam type of test, has not yet been completely ascertained. However, in the near future low-cycle strain-amplitude tensile fatigue investigations of high strength materials will be initiated using a tensile fatigue machine now being developed. These tensile fatigue experiments should reveal the true role of ductility in low-cycle fatigue fracture.

Summarizing the available data:

(1) The notch-sensitivity of 4330 (modified) steel in the low-cycle fatigue region is low and essentially constant to tensile-strength levels of 173,000 psi. Between 173,000 psi and 192,000 psi tensile strength, there is a marked increase in q to about twice that for lower strength levels.

(2) Under-aging of the 300 type maraged steel at lower strength levels enhances ductility but does not substantially improve the notch-sensitivity.

(3) Two groups of 250 maraged steel having vastly different reduction-in-area properties show nearly identical values of notch-sensitivity.

Table 1. Properties of Materials Used

Yield Strength (ksi)	Tensile Strength (ksi)	Reduction in Area (%)	Elongation (%)	Charpy Impact (ft lbs) -40°F	Charpy Impact (ft lbs) Room Temp	Charpy Impact (ft lbs) 212°F	Ratio of Notched Tensile-Strength to Unnotched Tensile-Strength $K_t=3$	Ratio of Notched Tensile-Strength to Unnotched Tensile-Strength $K_t=5$
				4330 MODIFIED STEEL				
123.3	137.4	36.0	16.2	40	41	44	1.48	1.46
136.7	151.8	25.1	12.1	30	35	37	1.52	1.49
155.9	173.7	26.9	11.6	22	25	25	1.49	1.46
175.2	192.7	18.2	9.0	16	18	21	1.46	1.43
				300 MARAGED (A) STEEL				
240.2*	261.0	22.7	6.5	6.1	6.7	7.5	1.29	1.03
224.0**	251.2	27.9	8.6	6.5	8.2	8.5	1.38	1.27
240.4**	266.9	28.4	7.8	7.3	8.3	9.8	1.27	1.14
283.1	301.4	14.1	4.6	7.0	8.7	8.3	1.16	.95
				300 MARAGED (B) STEEL				
257.9	276.0	13.6	3.5	-	-	-	-	-
				250 MARAGED (A) STEEL				
244.4	262.2	46.9	9.7	15.2	16.8	19.0	1.47	1.41
				250 MARAGED (B) STEEL				
240.0	259.0	20.0	5.0	7.9	8.7	10.5	1.29	1.13

ksi = thousands of lb. per sq. in.
K_t = theoretical stress-concentration factor

*Overaged
**Underaged

Table 2. Notch Sensitivity

4330 STEEL (MODIFIED)

K_t	STRENGTH LEVEL (ksi)	HEAT TREATMENT	NOTCH SENSITIVITY, q 2 kpm	20 kpm	100 kpm
3	123.3 YS	(1225°F)	.04	.12	.31
5	137.4 TS	(Temper*)	.01	.09	.15
3	136.7 YS	(1185°F)	.07	.17	.35
5	151.8 TS	(Temper*)	.03	.08	.13
3	156.0 YS	(1100°F)	.02	.27	.32
5	173.7 TS	(Temper*)	.09	.12	.14
3	175.2 YS	(950°F)	.12	.37	.58
5	192.7 TS	(Temper*)	.06	.22	.37
		300-TYPE MARAGED STEEL			
3	283.1 YS	(900°F)**	.87	.95	1.01
5	301.4 TS		.45	.55	.64
3	240.4 YS	(800°F)**	.66	.87	1.09
5	267.0 TS		.29	.42	.54
3	224.1 YS	(760°F)**	1.05	1.68	2.32
5	251.2 TS		.55	.97	1.32
3	240.2 YS	(1055°F)**	.29	.73	1.16
5	261.0 TS	(Overaged)	.17	.43	.69
5	257.9 YS 276.0 TS	(900°F)** (Embrittled)	.17	.39	.85
		250-TYPE MARAGED STEEL			
3	244.4 YS	(900°F)**	.305	.625	1.08
5	262.2 TS		.225	.363	.61
5	239.0 YS 259.3 TS	(900°F)** (Embrittled)	.18	.39	.60

K_t = theoretical stress-concentration factor
ksi = thousands of lb. per sq. in.
kpm = kilocycles per min.
YS = yield strength
TS = tensile strength

*Temper for 3 hours
**Hold at temperature for 4 hours

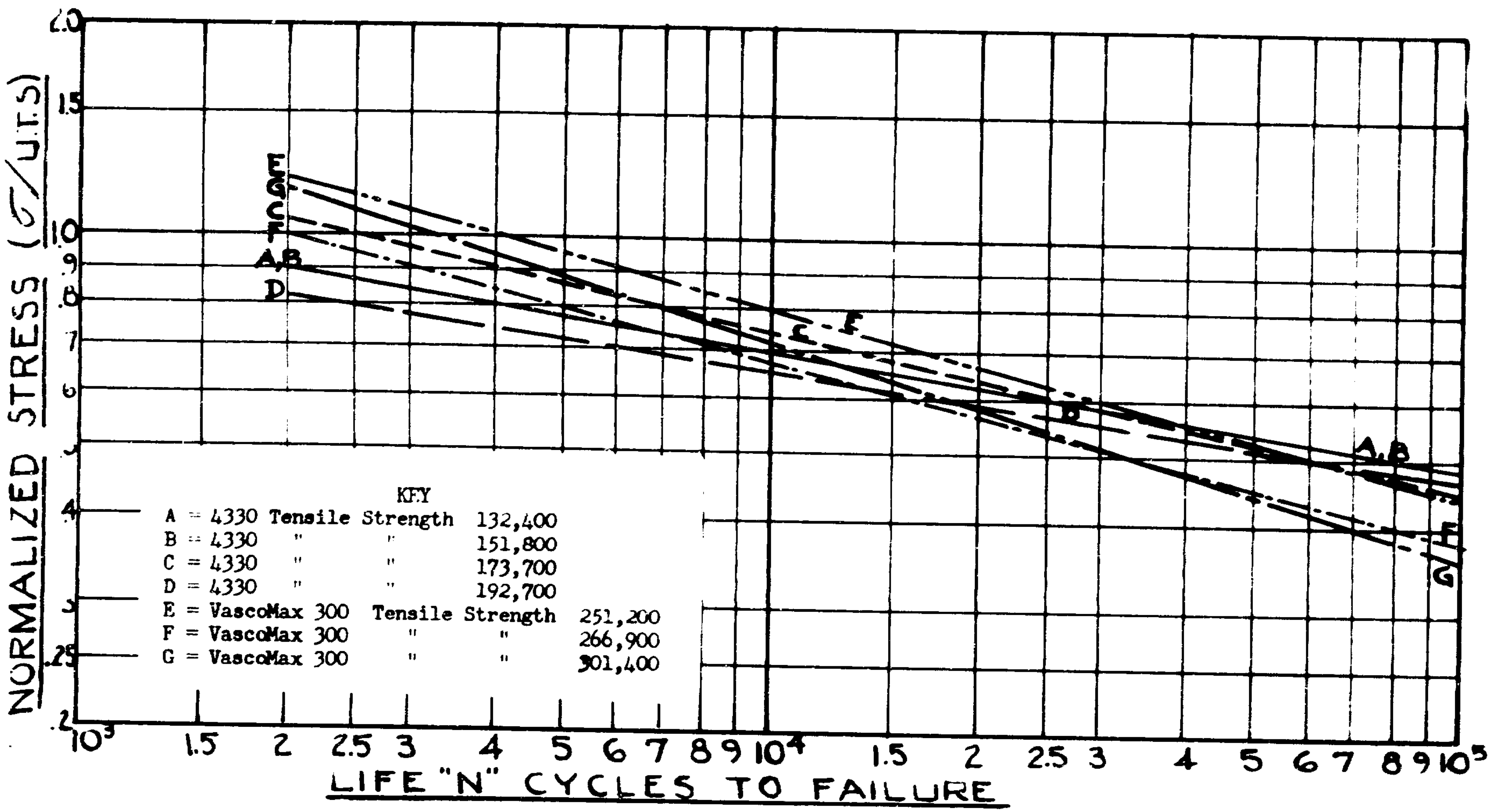


Figure 1. Normalized stress vs. cycles-to-failure, 4330 and Vascomax

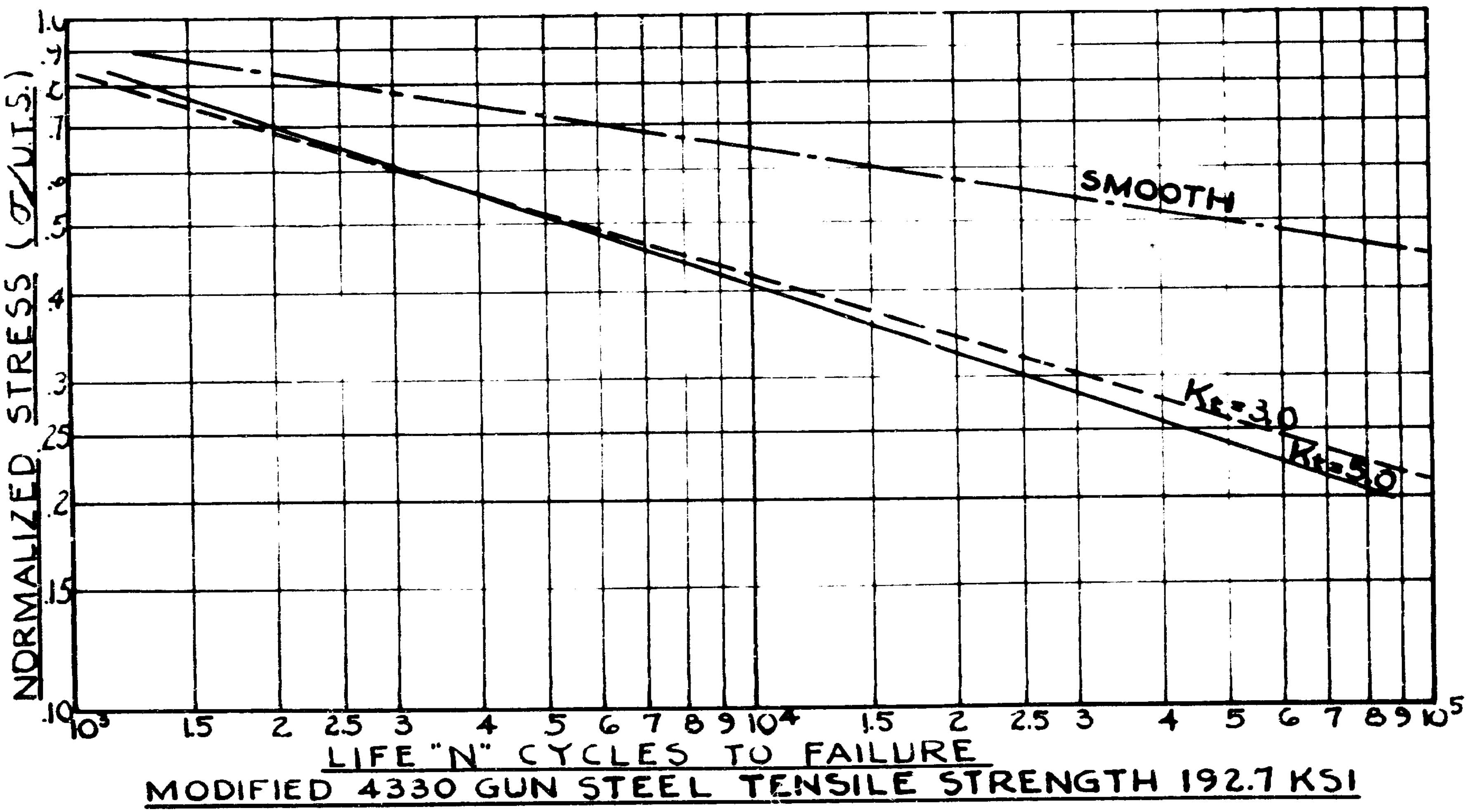


Figure 2. Normalized stress vs. cycles-to-failure, modified 4330 gun steel

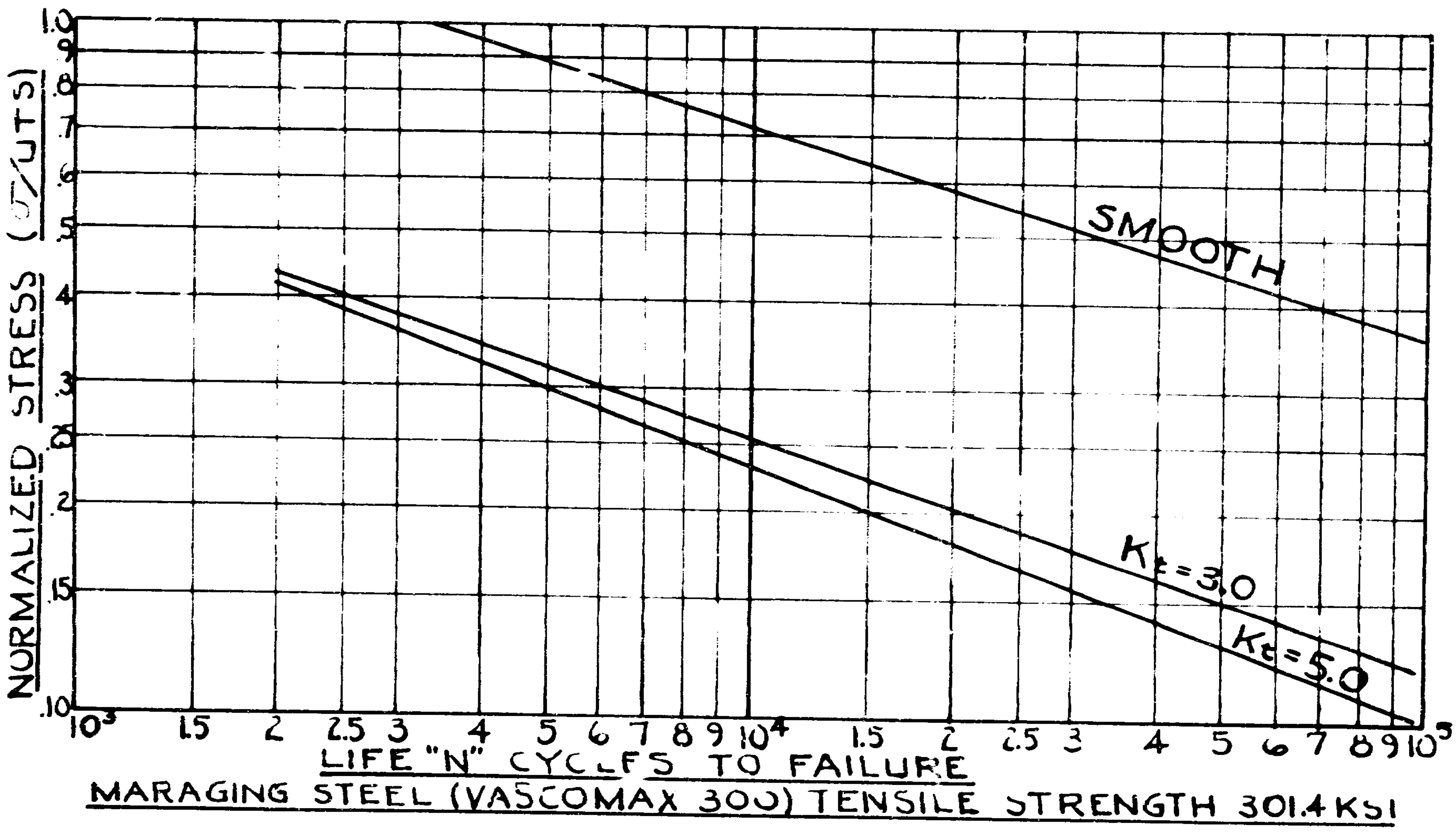


Figure 3. Normalized stress vs. cycles-to-failure, maraging steel, Vascomax 300

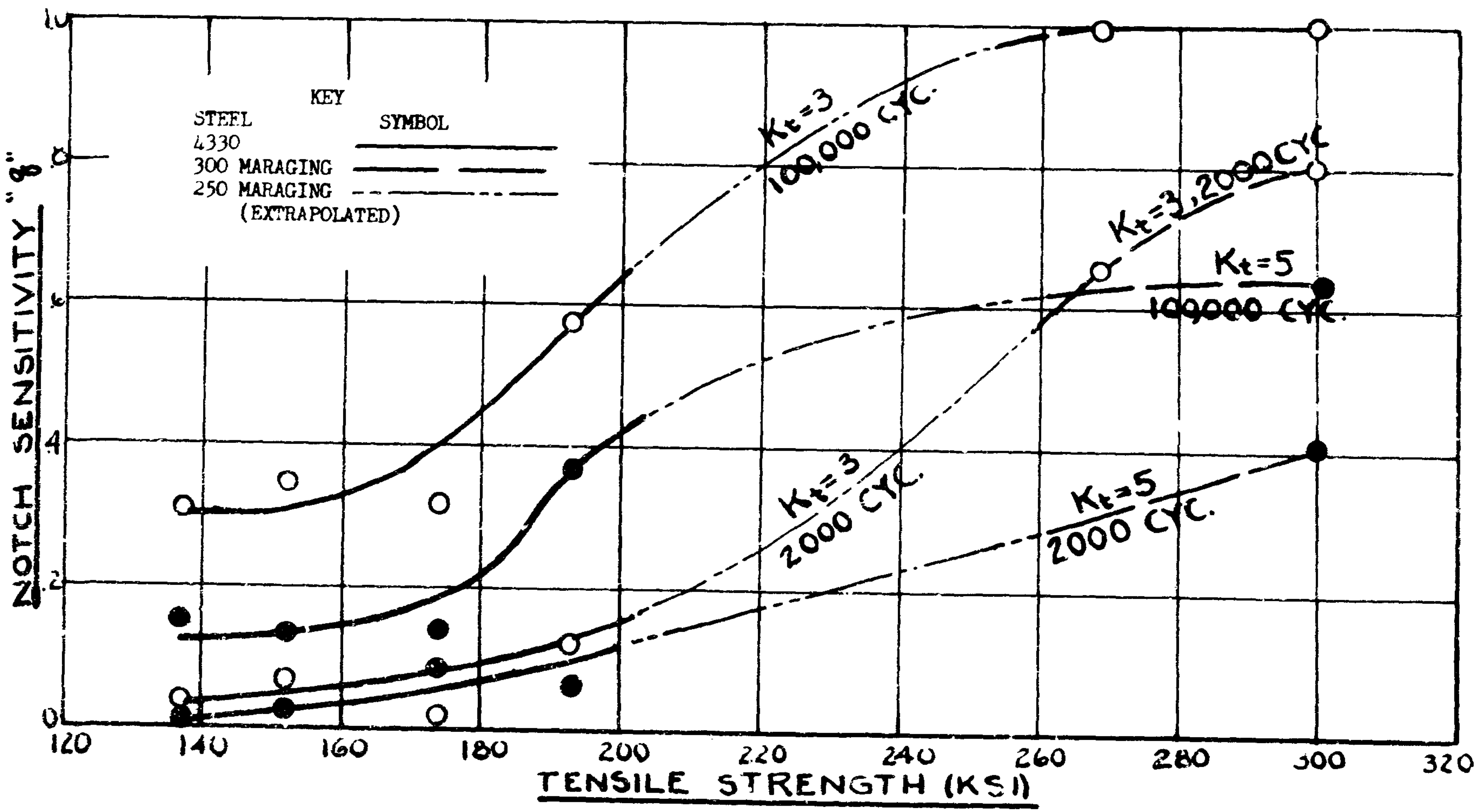


Figure 4. Notch sensitivity factor "q" vs. tensile strength

F. Heiser: "INVESTIGATION OF XM103 GUN TUBES"

Three 105mm Howitzer XM103 maraged gun tubes were procured for evaluation. They were purchased to a chemistry specification (Table 1), solution annealed. The three tubes were then aged at 900°F for 3 hours at Watervliet. It was later learned that the tubes had been forged from 23" ingots for a reduction in cross sectional area of approximately 11 to 1. Transverse test bars were taken from tube No. P2. The average results of four transverse tensile and six transverse Charpy tests were:

241.5 ksi YS
24% RA

10.7 ft-lb impact strength at -40°F

Based on these results, the remaining two tubes were machined for test firing. The main intent of this presentation is to discuss a metallurgical examination of the first of these tubes.

Tube No. P1 was fired for 400 rounds and No. P3 for 500 rounds before each was declared dangerous and removed from firing.

Failure was determined by borescope inspection which revealed several longitudinal "cracks" in the region of the origin of rifling (Figures 1 & 2).

The mechanical property results taken from the muzzle and breech ends of the tube (P1) prolongations are shown in Table 2. Additional data from the sectioned tube are shown in Table 3. The longitudinal results are fairly consistent. However, the transverse RA results are considerably lower at approximately the same yield strength. The impact energy results, in general, are not adequate.

Visual examination showed that the bore of the gun tube at the origin of rifling exhibited heavy erosion with numerous deep longitudinal impressions (Figures 3-4). A similar erosion, without the deep impressions, was noted also at the muzzle end of the gun tube. This double erosion, i.e., at both breech and muzzle, is typical of gun tubes.

Sections were taken through the eroded area. Figures 5-6 are general views of the roughened surface. Figure 6 shows several cracks extending from the surface.

Figures 7-8 are views of two cracks extending from the deep impressions on the surface. Note that in both cases, secondary cracks extend approximately normal to the major crack. The depth of one crack was measured at 5/16", approximately 1/4 the wall thickness. This crack was broken open showing a discolored fracture surface.

Figures 9-12 show that the cracks are definitely intergranular. It can be seen that the cracks take sharp turns to move around the grains.

This is particularly evident in Figure 12, where grain separation is clearly noticeable.

A metallographic survey was made of the breech end to determine the uniformity of structure and the possible existence of a secondary phase in the grain boundary. The grain structure was fairly uniform (Figure 13) However, the grain size is comparable to that exhibited by International Nickel Company of a steel, solution treated at 1800°F, whereas this tube was purportedly solution treated at 1500°F. The effect of this disparity on final results is unknown. Some evidence of a grain boundary precipitat was found, but could not be related to the cracking.

Figures 14-15 show the structure of the steel to be filled with small inclusions. They appear generally as small holes. (The large black mark is a defect in the print.) The triangular shaped inclusion in Figure 15 is interesting. This is probably a Titanium carbide. Regularly shaped inclusions were apparent in numerous sections.

All the specimens from tube P1 contain a large amount of rounded precipitate, as in Figure 15. The precipitate appears throughout the entire structure. In several instances, the precipitate forms along grain boundaries. These precipitates are evident in only one test section of tube P3. Even then, it is very slight, not approaching that in tube P1.

A "white" precipitate can be seen in all the microstructures. They occur throughout the entire microstructure, but can be seen as a grain boundary film in several (Figure 16). There does not appear to be any relation between these precipitates and the differences in mechanical properties, since they appear in all the test bars.

For comparison, the results of tensile and impact tests from the breech end of tube P-3 are shown in Table 4. This is the tube that had fired 500 rounds. The major difference between tubes P-1 and P-3 is in the transverse RA values. Tube P-3 is being returned to Watervliet Arsenal for evaluation.

To summarize, tube P1 was subjected to approximately 400 rounds, after which firing was discontinued. Information from Aberdeen Proving Ground asserts that the gun tube was borescope inspected after every 50 rounds. The defect which caused stoppage appeared only at the 400 round inspection. The bore of the tube was washed with a sulfuric acid solution to remove copper deposited from the rotating band, after 300 rounds and again after 350 rounds. However, this was not done with the second tube.

The heat checking pattern appears to be not peculiar to this alloy. A similar pattern is observed in gun steel for tubes. However, the deep cracks are not common.

It is hard to imagine that a crack of this depth could occur as abruptly as is intimated, i.e., not observed until 400 rounds. However, based on the lack of knowledge of this metal and previous tests in which a 155mm breech ring and breechblock shattered in two-three rounds of impact testing, after showing no magnetic particle defects previously, this is possible. It is interesting that one crack was greater than 1/4 the wall thickness. There was nothing on the borescope investigation to indicate the depth actually observed.

The cause of the cracking cannot be ascertained with any certainty. Due to the intergranular nature of the fracture, the cracks may be due to stress corrosion cracking or the presence of grain boundary precipitate, complicated by the heat generated during firing. As noted, a grain boundary precipitate was found but could not be related to the cracking.

Table 1. Chemical Analysis of the XM103 Gun Tube Steel

Specified Percentage		Actual Percentage
C	.03 maximum	.02
Mn	.10 maximum	Nil
Si	.10 maximum	.04
P	.010 maximum	< .010
S	.010 maximum	< .010
Mo	4.5 / 5.0	4.65
Ni	18 / 19	18.9
Co	7.1 / 7.9	7.2
Ti	.4 / .6	.55
Al	.05 / .15	.12
B	.002/.003 added	-
Zr	.02	-

Table 2. Muzzle and Breech Prolongations

Breech	Impact @ -40°F, ft-lbs	TS, ksi	YS, ksi	% El	% RA
Longitudinal	14.0	271.0	250.8	8.9	37.7
Longitudinal	7.5	273.0	252.6	8.6	37.7
Transverse	6.5	270.0	248.4	3.5	11.4
Transverse	11.5	269.5	241.8	3.3	9.4
Muzzle					
Longitudinal	13.0	272.0	252.0	10.0	42.9
Longitudinal	12.0	271.8	252.0	9.0	41.1
Longitudinal	13.5	270.2	250.8	5.5	38.7
Longitudinal	12.0	272.2	252.6	10.0	38.7

Table 3. Mechanical Properties of Sectioned Tube P1

Location	Orientation	TS, ksi	YS, ksi	% El	% RA	Impact Energy @ -40°F, ft-lbs
Muzzle	Longitudinal	254.9	234.6	8.0	42.5	15.0
		255.2	235.8	9.0	41.9	12.5
Center	Longitudinal	255.5	257.0	10.0	44.2	12.5
		255.0	257.0	10.0	41.1	12.5
Origin of Rifling	Transverse	268.5	253.2	8.8	29.9	8.5
Breech	Longitudinal	268.0	248.4	9.5	36.9	12.0
		259.2	240.6	10.0	40.1	12.0
	Transverse	258.0	239.4	7.0	27.7	8.0

Table 4. Test Results of Breech End of Tube P3

Orientation	Impact @ -40°F, ft-lbs	TS, ksi	YS, ksi	% El	% RA
Longitudinal	14.5	276.0	256.5	7.9	33.6
Longitudinal	14.0	275.7	256.8	8.6	36.8
Transverse	9.0	274.5	255.3	3.8	17.7
Transverse	6.0	274.5	254.4	5.5	20.2

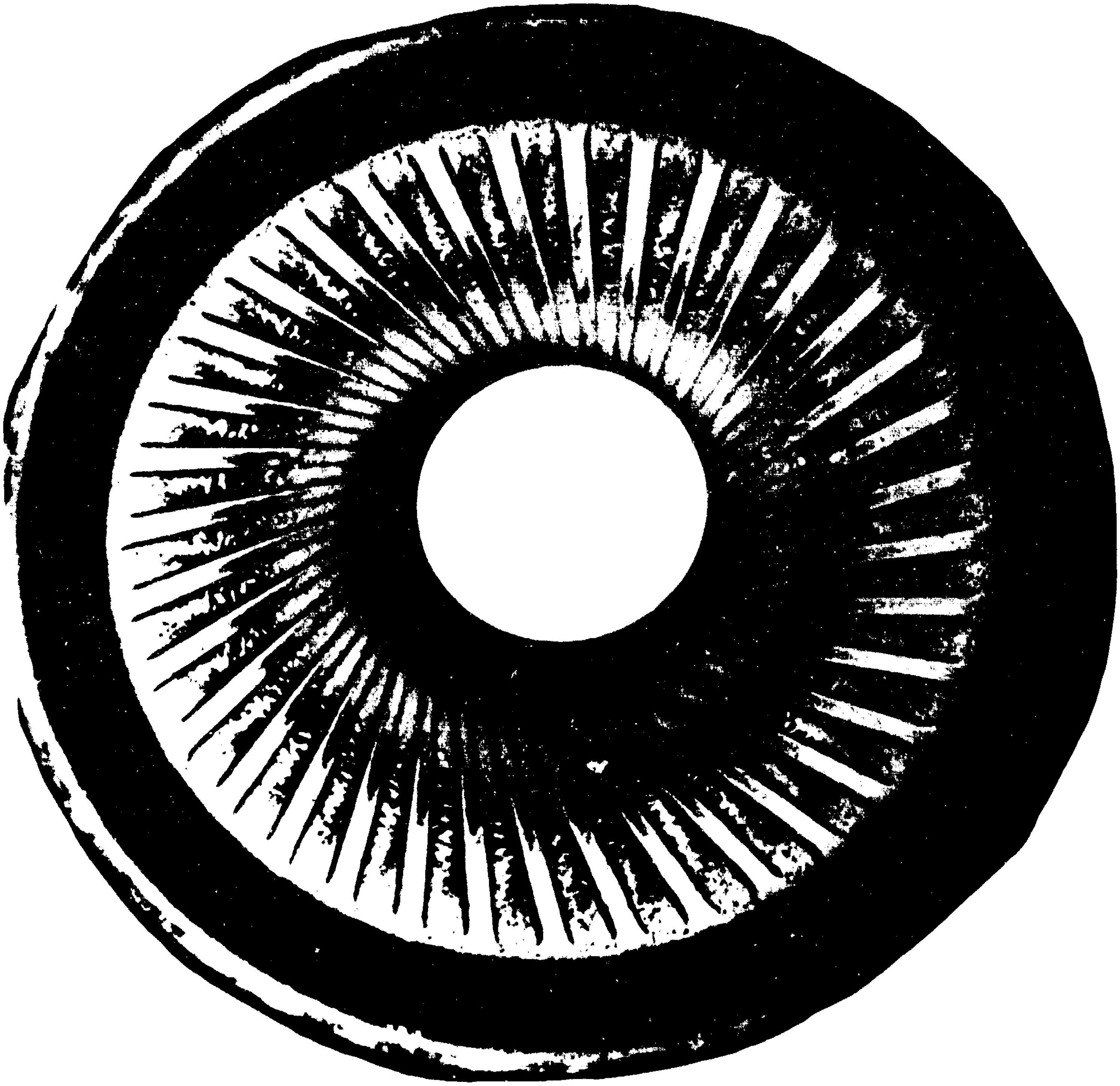


Figure 1. Bore photograph of tube No. 5 showing condition of bore from rear face of tube after firing 506 rounds.

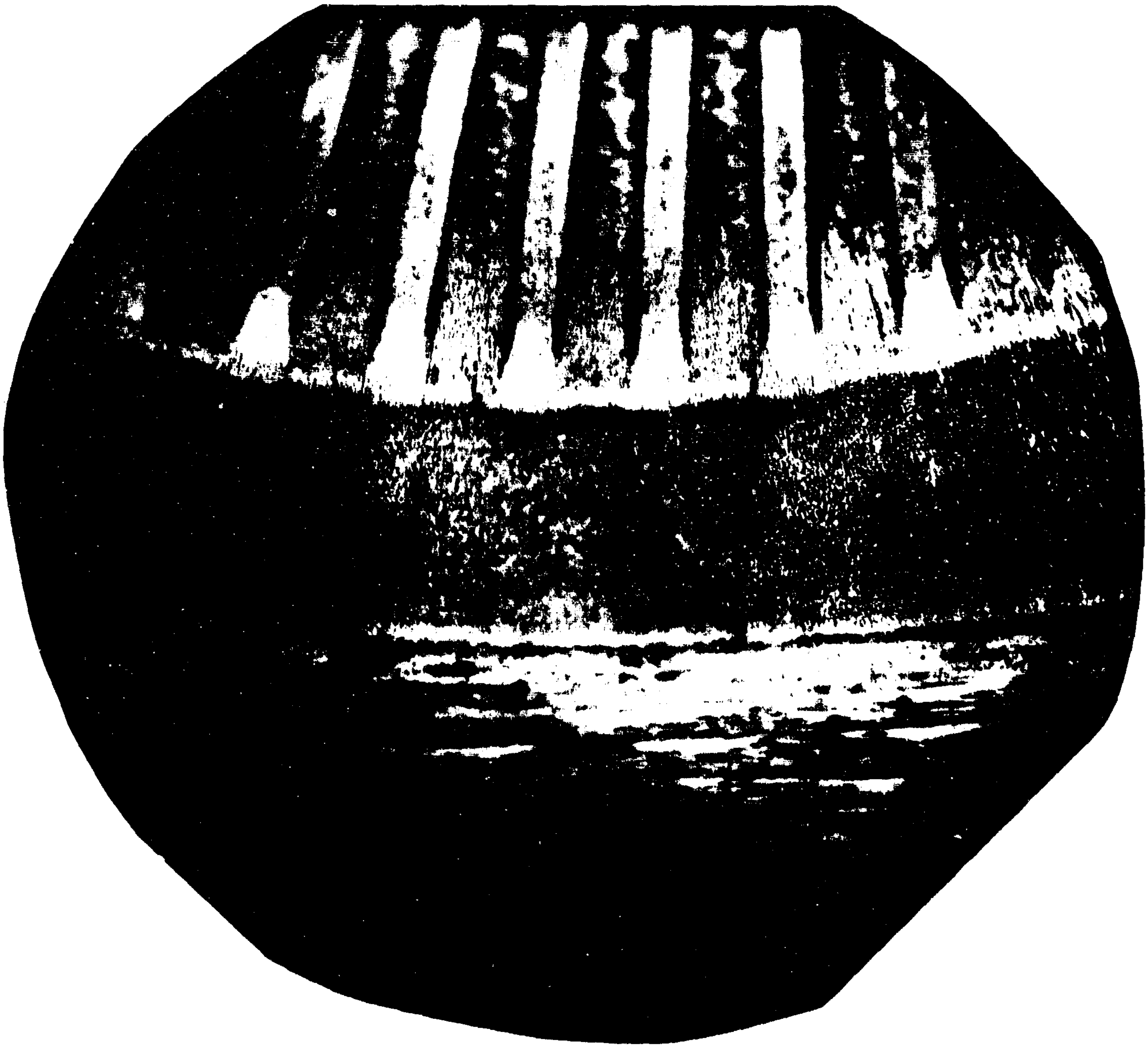
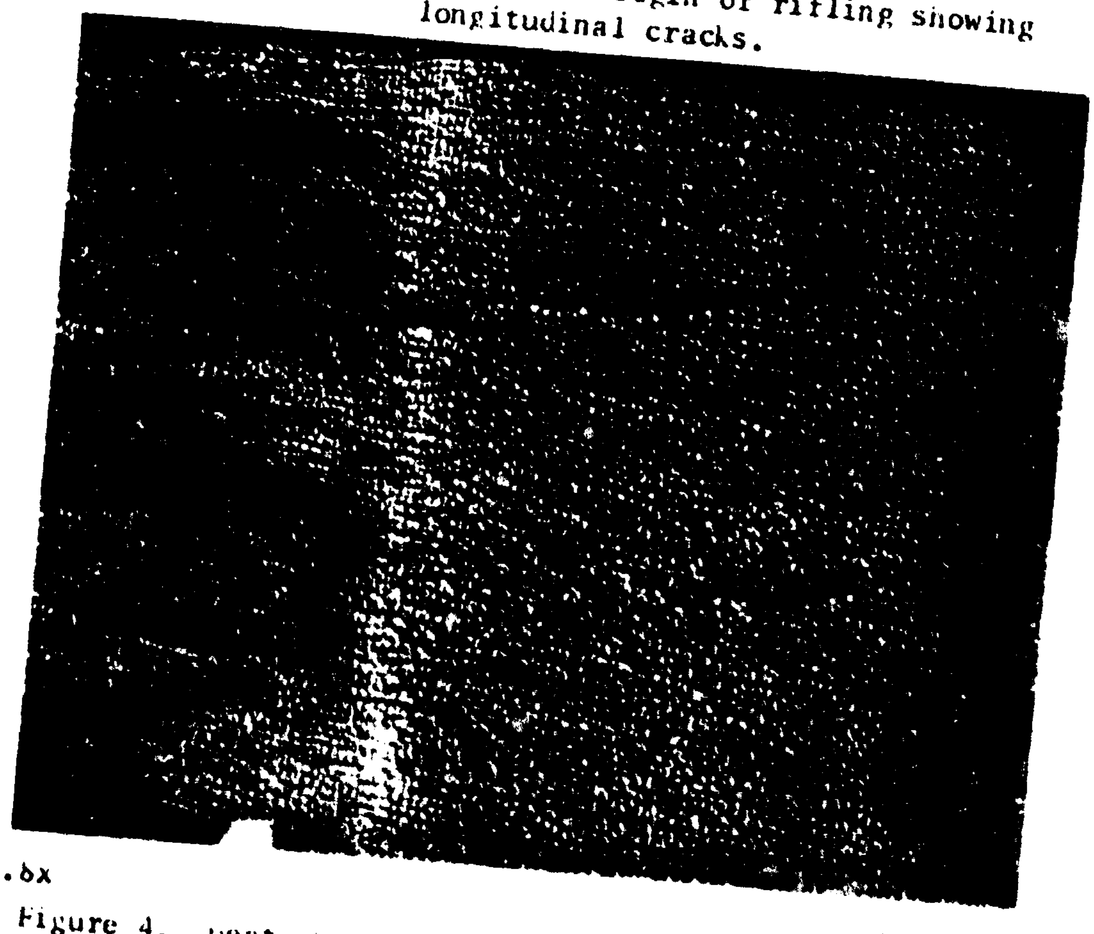


Figure 2. Bore photograph of Tube No. 3 showing condition of bore after firing 506 rounds.

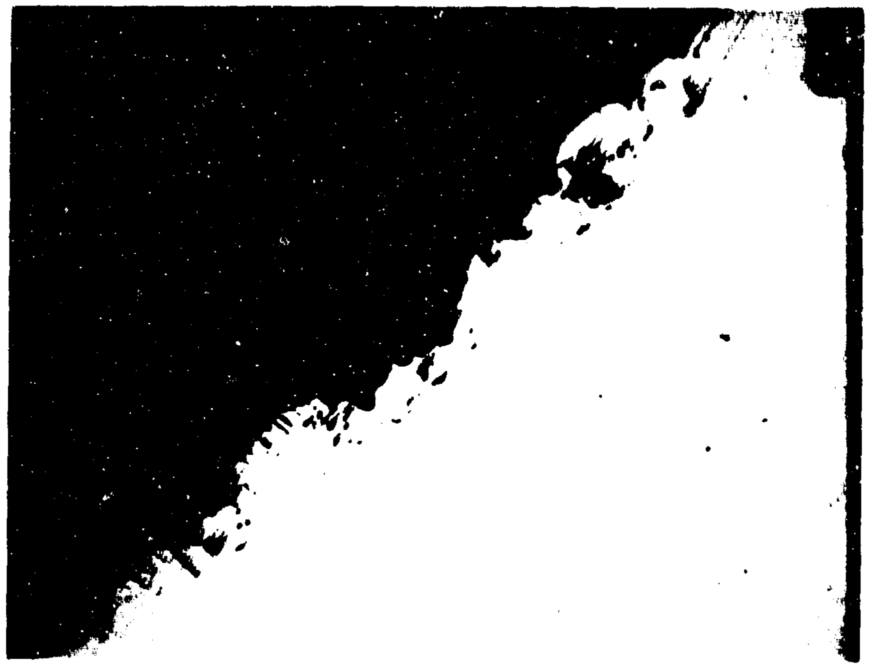
2x

Figure 3. Heat checking at origin of rifling showing longitudinal cracks. Unetched



3.6x

Figure 4. Heat checking at origin of rifling showing longitudinal cracks. Unetched



50x Unetched

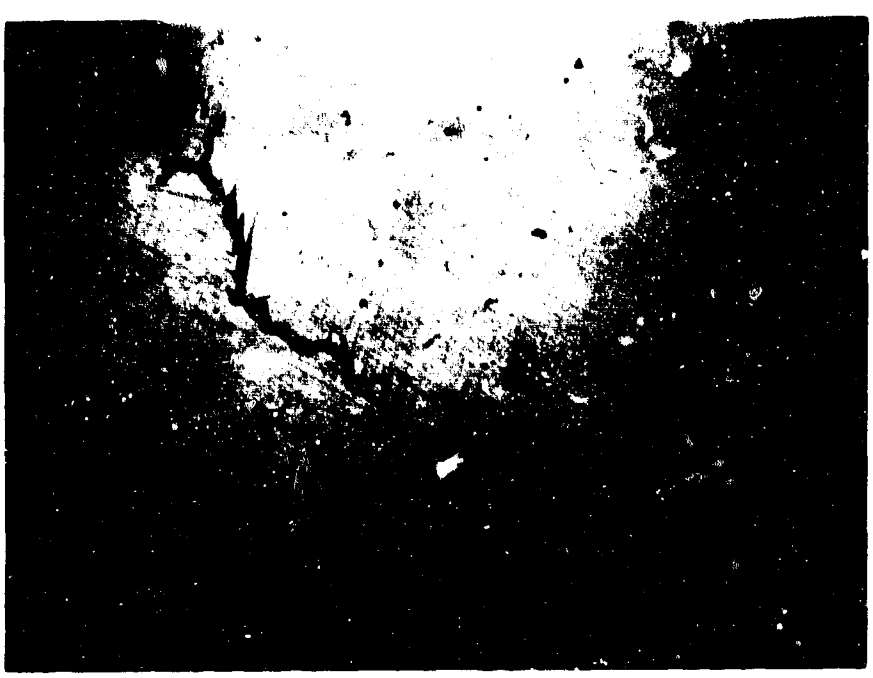
Figure 5. Cross sectional view of heat checked area.

200x 1% Nital

Figure 6. View of heat checking showing network of cracks.

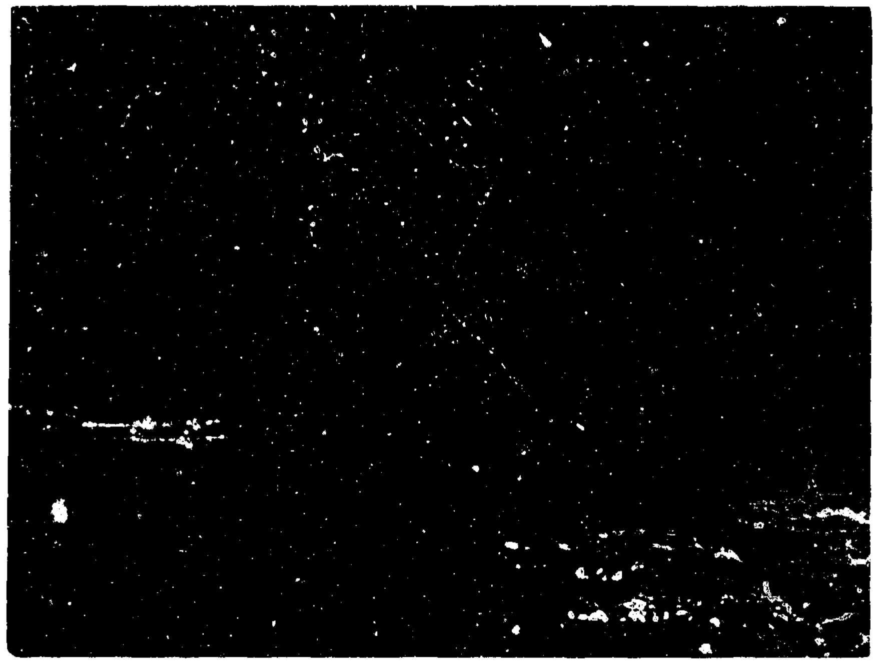
50x Unetched

Figure 7. Cross section of longitudinal crack.



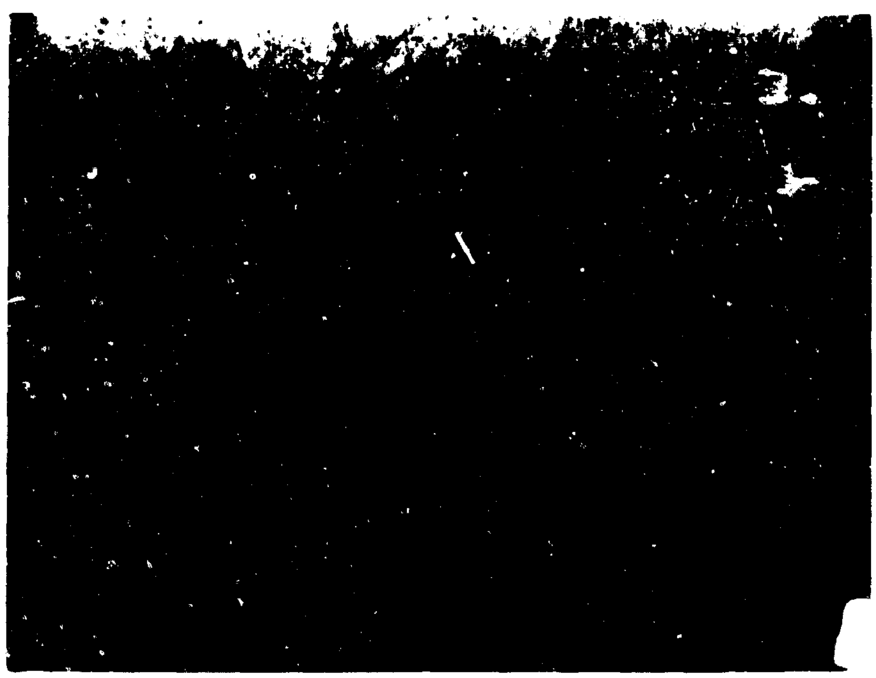
50x Unetched

Figure 8. Cross section of longitudinal crack.



100x 1% Nital

Figure 9. Cross section of longitudinal crack.



400x 1% Nital

Figure 10. Cross section of longitudinal crack.

1000x Modified Frye's Reagent

Figure 11. Photomicrograph showing intergranular nature of crack.

1000x Modified Frye's Reagent

Figure 11. Photomicrograph showing intergranular nature of crack.

500x Modified Frye's Reagent

Figure 13. General microstructure of both tubes.

500x Modified Frye's Reagent

Figure 14. Photomicrograph showing black rounded and white linear inclusion

2000x Modified Frye's Reagent

Figure 15. White regularly shaped inclusions, perhaps TiC

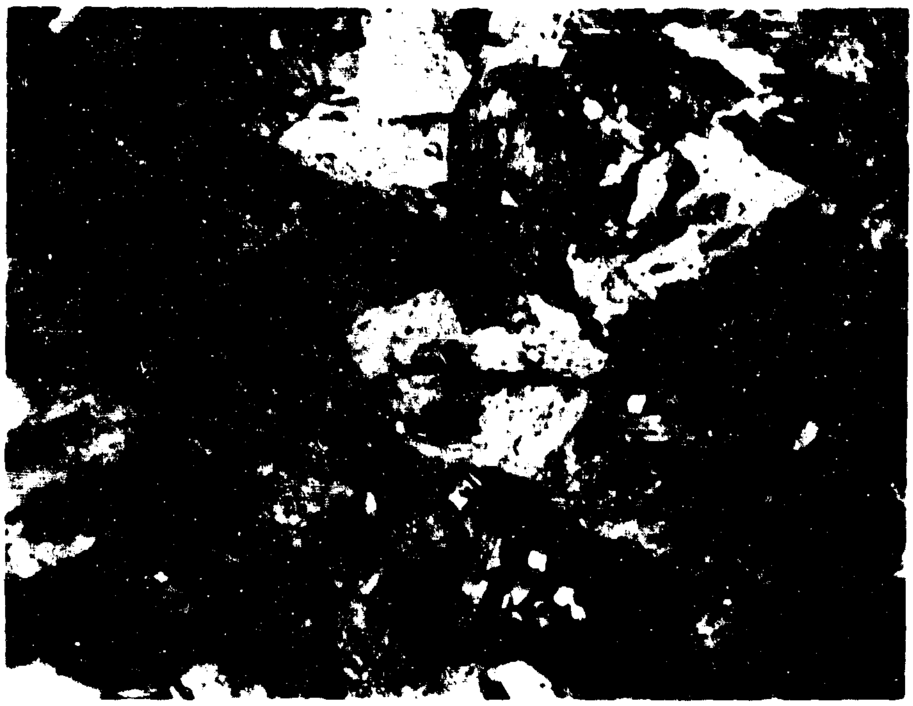


Figure 16. Photomicrograph showing white regularly shaped inclusions.

V. Colangelo: "EXTRUDED 90mm RECOILLESS RIFLE GUN TUBES"

I would like to speak about an extruded 90mm recoilless rifle gun tube. The initial engineering was done by Mr. McEwan of Process Engineering who acted as the liaison with the contractor and handled all the technical development end of the actual extrusion. My function has been simply to work out methods for testing these tubes. The status of the testing will be reported later.

I would like to give you a brief summary of the extrusion process, so that you will understand what we are working with. Lightweight gun barrels are ordinarily formed by ordinary machining methods from forged billets. The difficulty here, of course, is that the billet will ordinarily weigh from 3 to 10 times as much as the finished product. Generally, there is a lot of scrap, a lot of chips, and a lot of machining time. Extrusion was initially considered, therefore, for methods of economy to reduce machining costs and lead times, and essentially to lower the costs.

An extruded barrel should not require any major machining except where external contouring is necessary. The primary consideration for extrusion was for cost savings; secondary achievements, if extrusion was successful, would be the minimum use of critical alloyed materials such as nickel and cobalt. Also, the supply base would be broadened since you could produce gun tubes on equipment not ordinarily designed for gun tube manufacture; in this case, an extrusion press or extrusion presses.

After considering several companies in the field of extrusion, the Engineering Laboratories of Harvey Aluminum in Torrance, California, was selected to determine whether or not such a process was feasible. Their selection was predicated largely upon their demonstrated success in extruding very complicated shapes and extruding similar shapes in aluminum. Figure 1 is a photograph of a 75mm tube which Harvey Aluminum Company had produced in aluminum. For this reason they were selected to determine the feasibility of extruding a larger tube in steel. Figure 2 shows some other calibers with which we had some experience. These are aluminum and titanium. On the left is the 37mm, the center is the 50 caliber, and on the right a 2.75 inch tube.

Initially, three extrusion methods were considered. One was the direct extrusion of the rifling, that is, to extrude a tube with rifling already in it by means of spiral grooves in the original die and/or mandrel. This was the system used to produce the 75mm first shown.

The second method considered was to hot extrude the tube, to cold size the tube and then, by means of a rifling die or rifling button, to extrude the rifling by either forcing the tube through the die or drawing the button through the center of the tube.

The third method was to cold extrude to initial finish size with straight rifling and subsequently, go back into an induction coil, heat the tube locally and twist it.

After considering the engineering problems of the various methods, we selected the second as being the most promising. Additional development work was conducted on a 57mm tube of AISI 4340. Eight were successfully extruded and 3 were shipped to Watervliet Arsenal. All tubes exhibited essentially identical characteristics, e.g., (1) they were impact extruded from a hot blank with surface finishes of approximately 16 RMS, (2) the tube wall variation was about $\pm$ 1% of the wall thickness (this almost perfect wall characteristic is of fundamental significance in connection with the subsequent rifling) and (3) the tubes were successfully rifled after being heat treated to approximately 160 to 180 ksi yield strength.

The rifling depth and uniformity were consistent throughout the tube. A tube is shown in Figure 3. To recapitulate, this is a 57mm tube of 4340 material heat treated to approximately 160 to 180 ksi yield strength. Based upon the success of a 57mm tube, we decided to attempt to do this in an ultra-high strength 90mm tube. However, at this point, there was very little data on the impact extrusion and cold work characteristics in the 18% nickel maraging steels. On the basis of Harvey's experience and after consultation with representatives of International Nickel Company, a manufacturing process was determined. Fifteen maraging steel billets were procured to produce 12 completely rifled tubes. These billets were obtained from a single heat. With each billet they submitted a macroetched specimen. Harvey successfully extruded 11 billets at temperatures from 1450°F to 1500°F. They initially tried to extrude at higher temperatures since this would require less force, but at 1600°F and at 1700°F, the tubes had poor surface finishes. Consequently, the extrusion temperatures were reduced.

The big development problem was cold sizing and rifling in that they did not have a satisfactory conversion coating. Initially it had been intended to use a scrap compound, an organic soap. This was not adequate.

They finally used, after much development, a Parco Bond lube #234 applied over an organic salt, Parco Oxalate #70, along with a carbide rifling button. After developing this, they did not have any further problem with rifling.

I can give some of the processing data here just to give you an idea of the process. The usual rifling force is 40 tons. The total time to apply the rifling to the cold sized tube was 23 to 25 seconds, a fairly rapid operation. One thing developed which we did not anticipate. The hardness increased from Rc 28 to 30 in the solution treated condition to Rc 32 to 38 as a result of the cold sizing and rifling. We felt that on the basis of the published data that this material would not cold work to this extent.

This is extruded tube on the left. It is as it appeared when cold finished and rifled. Now the problem with thin wall tubes is how to test them. When you machine a tube from forged stock or bar stock you have sufficient material in the initial stock from which you can extract transverse mechanical property data. On an extruded tube, you no longer have material which is representative of the initial billet. How do you test this?

We are working on and considering methods of testing thin wall tubes. We are presently looking at precracked Charpy methods to determine whether or not they will give us data which can be useful for design purposes to predict what we can expect from the material,and from the processing used to form that material,because I don't think we can divorce the material from the process.

Another method is burst testing. We have done this on some tubes. We have here six specimens which were burst tested, three of which are 4340, three of which are maraging steel. When the tests are completed there will be three additional tubes which will be aged. These will be representative of the material as aged. Notice the lack of ductility with the maraging material. This will not be better with aging. With the 4340 we are getting a relatively ductile fracture. With the maraging steel we are at the point where we get relatively brittle failure.

This problem of brittle fracture and of fracture toughness in general is one with which we are seriously concerned. For this reason we intend to run precracked Charpy tests in the longitudinal and transverse directions. The longitudinal tests are fairly straightforward. However, extracting a transverse test from a tube with this wall thickness is going to be a problem. The present specimen design calls for end skirts to be electron beam welded to the test metal. We do not anticipate difficulty with the weld since the total heat affected zone is in the order of only .040".

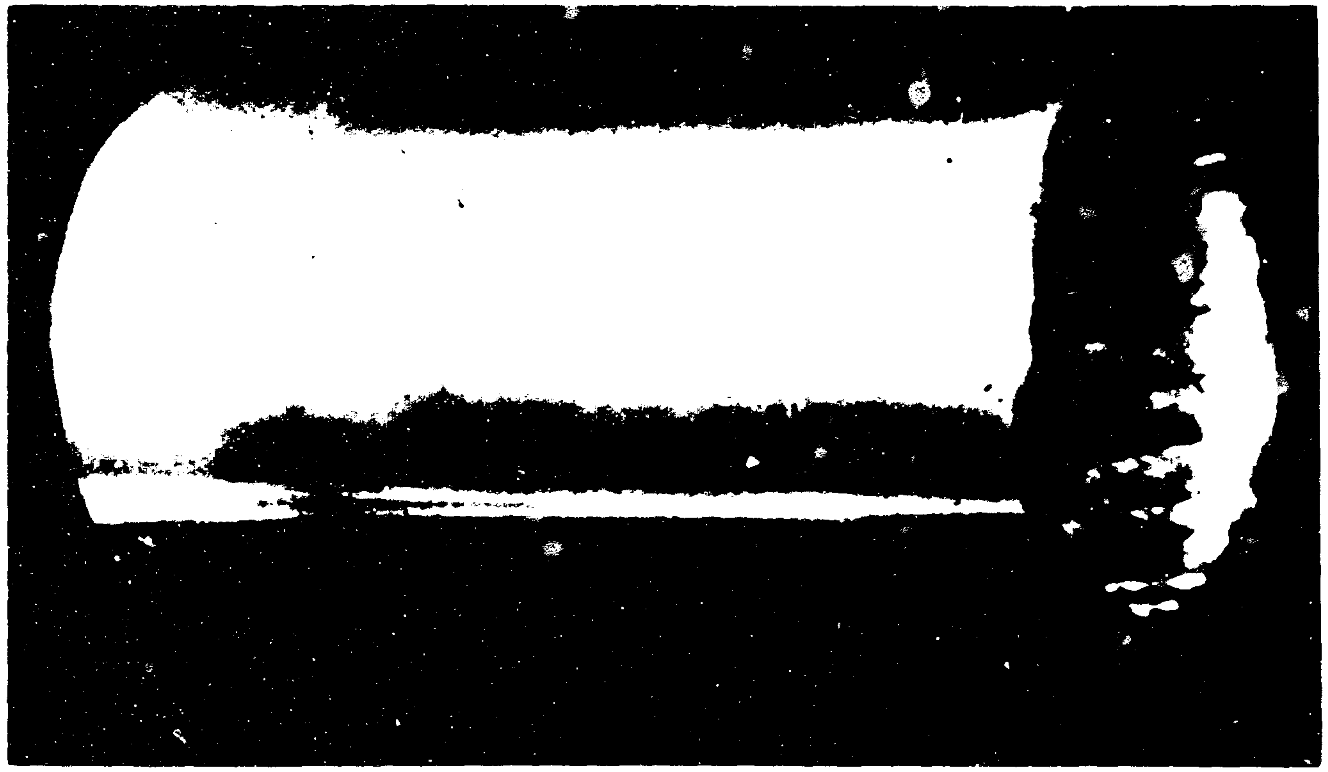
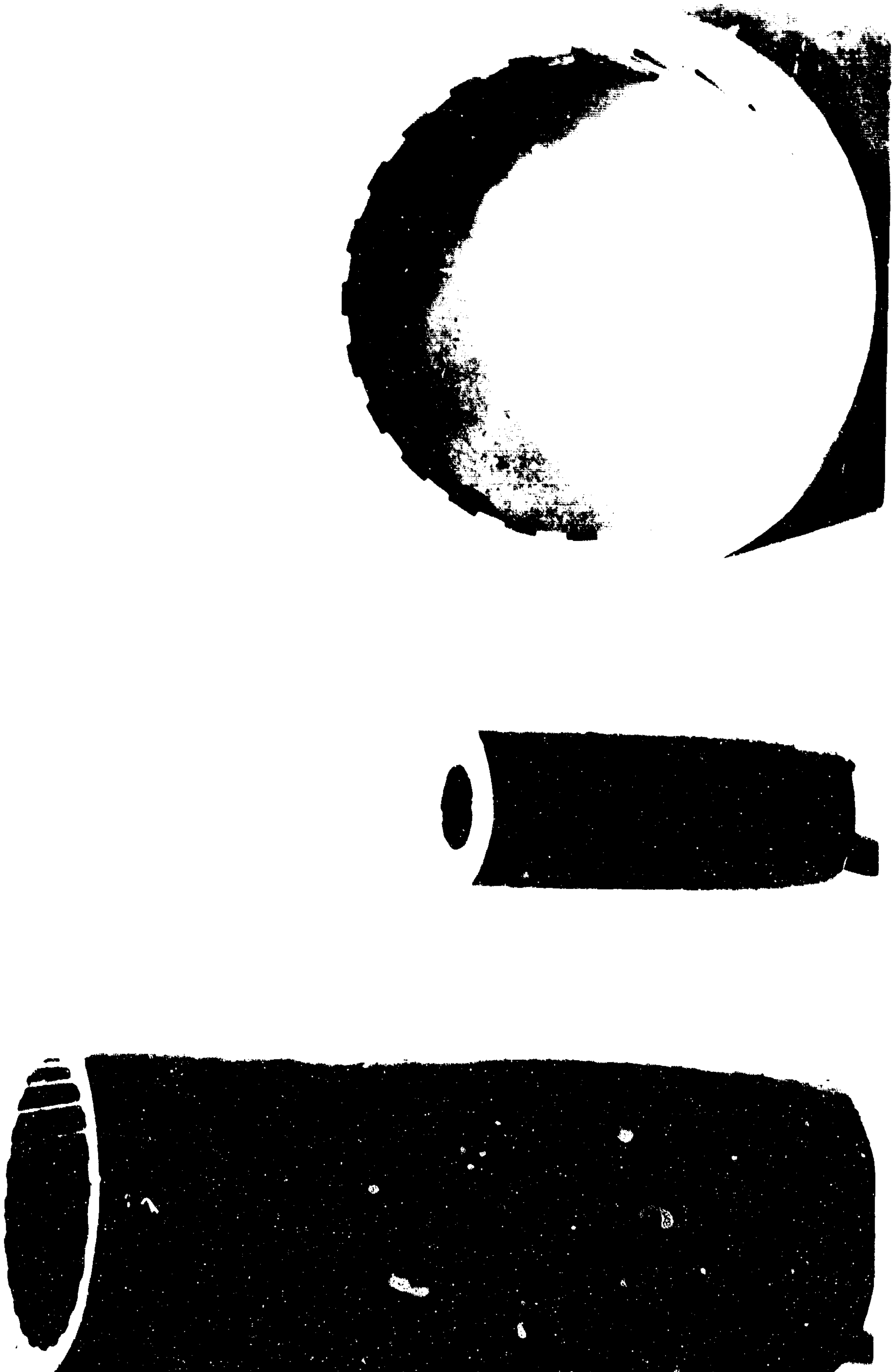


Figure 1. 75mm extruded aluminum tube.



2.75 INCH

CAL. 50

37 MM

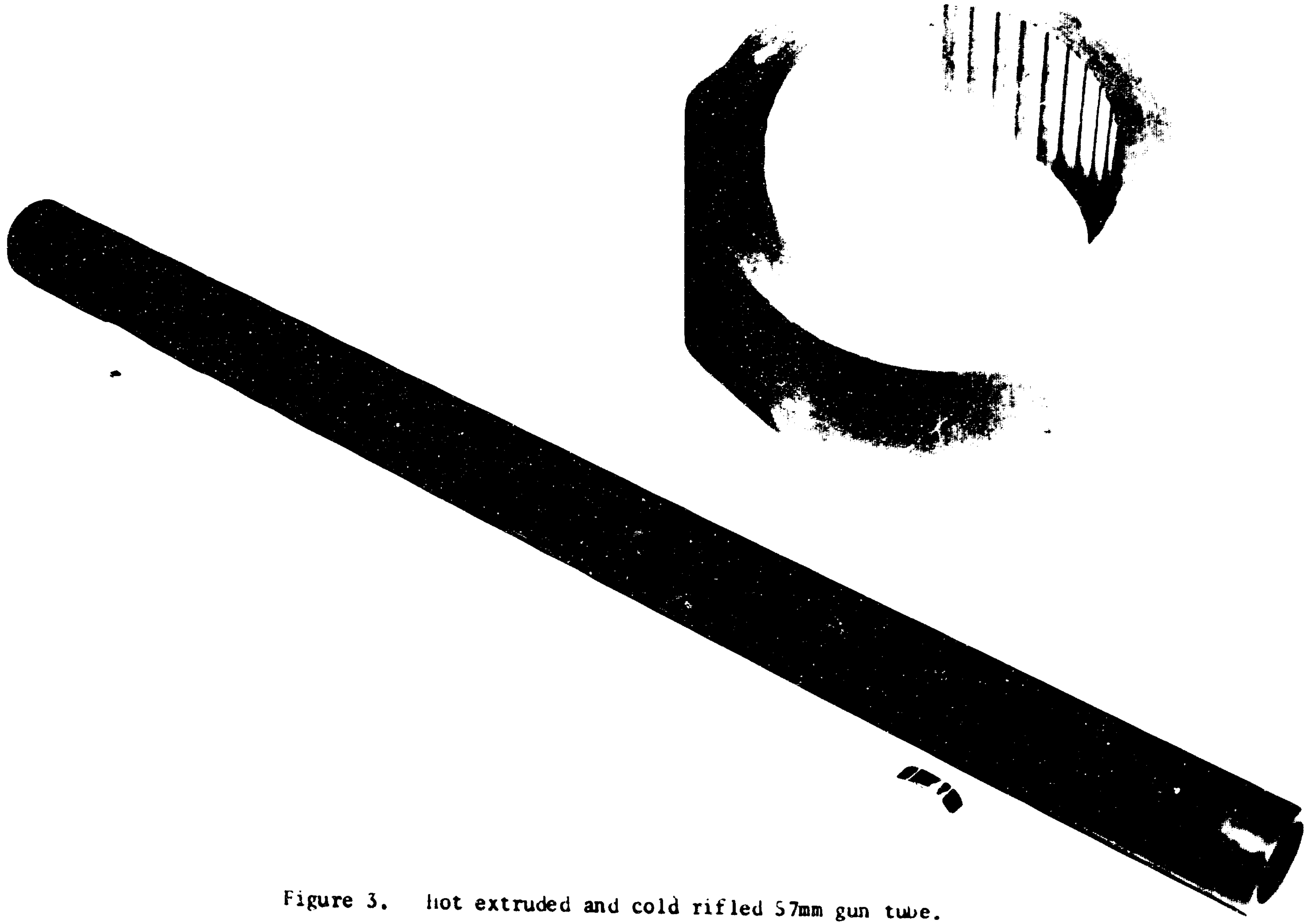


Figure 3. Hot extruded and cold rifled 57mm gun tube.

Discussion:

T. Landig: Were the tubes shown solution annealed or as processed?

V. Colangelo: They were as processed.

T. Landig: So there is a substantial amount of the cold work?

V. Colangelo: Yes, there is.

T. Landig: How much does the O.D. expand upon rifling?

V. Colangelo: I'd like to introduce Mr. William McEwan to answer that question. He is the project leader who actually conducted the development work.

W. McEwan: The question was how much expansion occurs in O.D. of the tube. None, the tube gets longer because you are restraining both the outside and the inside. This is a dual operation when you are rifling the tube.

T. Landig: You keep the I.D. and the O.D. the same but elongate the tube?

W. McEwan: Right. Actually there are three operations in the extrusion process. First, the initial billet is extruded, and subsequently solution annealed. Then it is reduced 23% and finally in the third operation it is reduced 5% and the rifling imparted.

R. Decker: What sort of subsequent processing do you anticipate? Do you plan on direct aging these or do you plan on solution annealing again and then aging? Have you decided what the processing will be?

W. McEwan: We have to perform some external machining on them and then inasmuch as the rifling is in, we want to try to go right into aging to insure maintaining concentricity and eliminating the possibility of scaling. There is one correction I would like to make. In the rifling operation where lubrication became a problem, Harvey was using a high speed steel mandrel. After two or three attempts and several tests of coatings, they turned to a carbide mandrel and were completely successful. We do not know how many types of lubrication would be available because the change in the mandrel material corrected the problem. We did not go any further into the lubrication aspects.

R. Decker: Was this rifling done at 1450°F?

W. McEwan: No. The initial extrusion is done at 1450°F, followed by a solution anneal.

R. Decker: Metallurgically, that 1400°-1450°F is not desirable. Is there any reason why they could not have heated to a higher temperature and then let it cool before it went into the press?

W. McEwan: It was on the recommendation of INCO on the West Coast that we use this temperature.

R. Decker: Yes, I know, but I was thinking of future operations.

W. McEwan: This was not considered at that time but could be in future operations.

T. Kucskar: "MACHINING OF PROTOTYPE GUN COMPONENTS UTILIZING MARAGING STEELS"

The maraging material which was furnished to the manufacturing shops in the Operations Division consisted of:

1. Four 107mm mortar tubes (Figure 1). The rough blank was a 6 inch diameter tube, 3 1/2 I.D. x 63" long. The I.D. finished up at 4 1/2 and the O.D. finished at about 4.62 inches, so there was considerable machining to be done.

2. The material size of the base plug (Figure 2) was 7 inches and finished at 5 inches. Again there was considerable material to be removed.

3. Two each of dynamic test 155mm howitzer rings (Figure 3) and blocks (Figure 4) were machined. It was furnished to us about 17 or 18 inches in diameter and finished at about 14 inches. It had a 9 inch trepanned hole in it. That trepanned slug was later used to make the obturator spindle (Figure 5).

The information I have on the machinability of these parts was furnished by skilled machinists in the shops. They are model makers working solely on prototype work. I think we can assume that their information is valid and accurate. It is pretty consistent with one exception which I will point out as I go along.

No machinability study was made as such. The material was given to the workmen in the shop. They were given a drawing to produce, and they had a schedule to meet. However, we had an interview with them later. They were able to furnish us with their observations.

In turning the tube material, an average surface speed of 150 surface feet per minute was used. Each of the four tubes reacted slightly differently. One in particular was tougher than the others. That one is still in the rifling machine. A carbide grade, Valanite VC-8, was used. It is one of the newer grades but is commercially available. No special tools were purchased for this material. All the tools were standard tools which are available in our tool cribs. A feed of .010 inches per revolution was used. Attempts to increase the feed to break the chip resulted in excessive tool wear. Consequently, feeds in excess of .010 inches per revolution were not used and the chips remained unbroken.

The finish produced on the material was excellent. All the machinists agreed it is easier to get a good finish with this material than with conventional gun steel. Incidentally, the conventional gun steels averaged 160 to 170 ksi yield strength, with a hardness range of Rc 37 to 40. The maraged material was about Rc 32 when we machined it. The coolant used in turning the tube was standard water soluble oil base.

On the mortar tube, there are three integral lugs which extend half the length of the tube. It is necessary on a prototype basis to make several passes down the tube with a mill. This was done with a cutter 4 inches in diameter, and an inch-and-a-half stub arbor about 4 inches long. The width of the cutter was 2 1/2", and the quill on the machine extended about a foot. To produce the radius, a special form mill of that type made of standard high speed steel was used. It was probably an M2 or T1 grade. The exact grade of the tool is not available. A standard cutting oil, a lard oil type, was used. Here we have one piece of information which is inconsistent. The machinist was able to use a feed of an inch-and-a-half per minute, whereas normally on alloy steel he can only go about one inch a minute using the same type of set-up. A 40 surface feet per minute speed on the tool was used. The finish was excellent and again easier to attain than on standard alloy gun steels. However, there was a slight tendency to burr. This may or may not be important but I think it reflects the fact that the material was extremely tough. In other words, when the machinist tried to blend two cuts, he wound up with a fine line down the length of the tube. This was not a mismatch. It was just a burr thrown upon by the pressure of the cut against the steel. Perhaps this could be overcome with a better coolant or a better grade of tool steel in the cutter. However, for these tubes a little benching was adequate.

In gun tube boring operations, we use a wood packed body 18 to 20 inches long, with two carbide tipped cutters. We use Wesson W-H cutting fluid as a standard grade. We generally use 150 surface feet per minute with a .020" feed on the alloy steel. This gives good performance, a straight hole, and breaks the chip satisfactorily. However, with the maraging steel we could attain only a speed of 120 surface feet per minute, and the feed had to be reduced to .008". If the speed were increased, the cutter broke down. At the .008" feed there was considerable trouble with chips. The chip was stringy. The machinists call them clock springs because of their appearance. However, I would like to repeat that these were standard tools used with standard chip breakers. No attempt was made to experiment or to improve the chip breaking characteristics.

In rifling, the speed, as with the other machining speeds, had to be reduced. Generally, whereas we normally rifle at a speed of 12 to 15 surface feet per minute, we had to use 9 sfm on maraged steel. The depth of the cut in rifling is .015" on the diameter. The rifling head is about 15 inches long. We started with a chrome plated head but had to replace it with a bronze head because the burr thrown up in the rifling groove cut into the head. This is not good with a chrome plated head because it is apt to snag the head in the bore. So we used a bronze sleeve on the head and allowed the bronze to be cut, which in turn allowed the head to pass through the bore without hanging up. There are 18 cutters per set. The cutter material was an N-44 molybdenum high speed steel at Rc 70. This worked quite well. The edge held up well and the finish was excellent once again. The lubricant used was a light lard oil, 40% base, 60% kerosene. The only problem was that at the end of the pass, the chip clung to each individual tooth on each rifling cutter. Each was removed individually.

In addition to the burr problem mentioned earlier, there was a second burr problem. As the cutter left the bore it rolled over the edge of the tube. The face of the tube was damaged very slightly and required benching which is not otherwise required.

In honing and grinding, there was no appreciable difference noted between this type of steel and the conventional alloy steels. The machinists indicated that the former heats up more, but they really did not have enough material to make sufficient tests to prove the point.

A base plug was made for each of the tubes previously described This screws on or into the gun tube depending on the design. These parts were turned using Valanite VC08 once again.

For those areas which required machining with high speed steel, Vasco Hypercut was used. Attempts to utilize conventional M2 or M3 high speed tool bits were unsuccessful. The edges wore rapidly, causing friction and work hardening in the piece.

In turning the threads with a single point tool, Vasco Hypercut was used again with no trouble. When conventional tools were tried, the edge rolled. The thread could not be finished with conventional tools.

The base plug was furnished as a 7 inch diameter round and sections were cut on a band saw. It tool 7 hours on a band saw using a conventional M2 blade. The initial surface speed was 150 sfm and the pressure 150 lbs. This is normally used on alloy steels. It was necessary to turn the work piece because the saw cut ran out. Finally, the speed was reduced to 100 sfm and the pressure to 100 lbs. It was then possible to cut through and reduce the time to 4 hours.

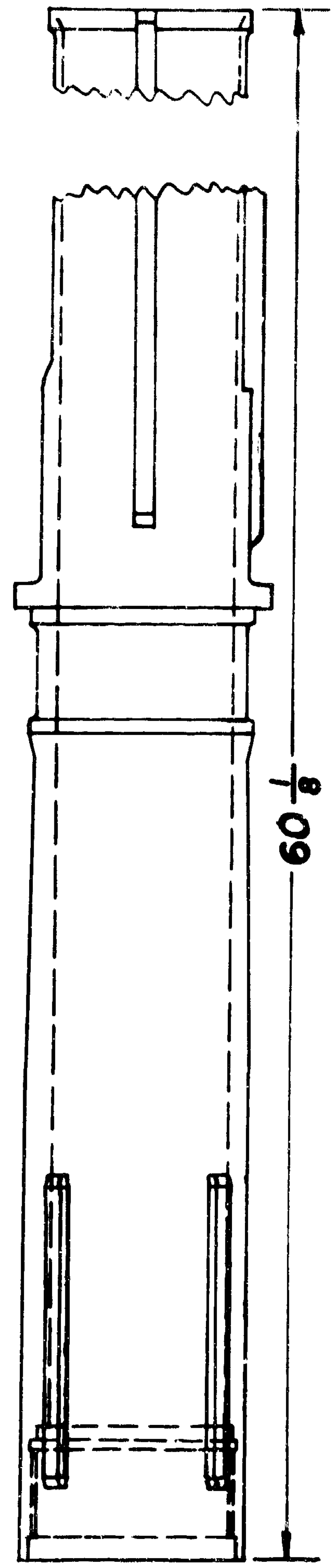


Figure 1. 107mm Mortar tube.

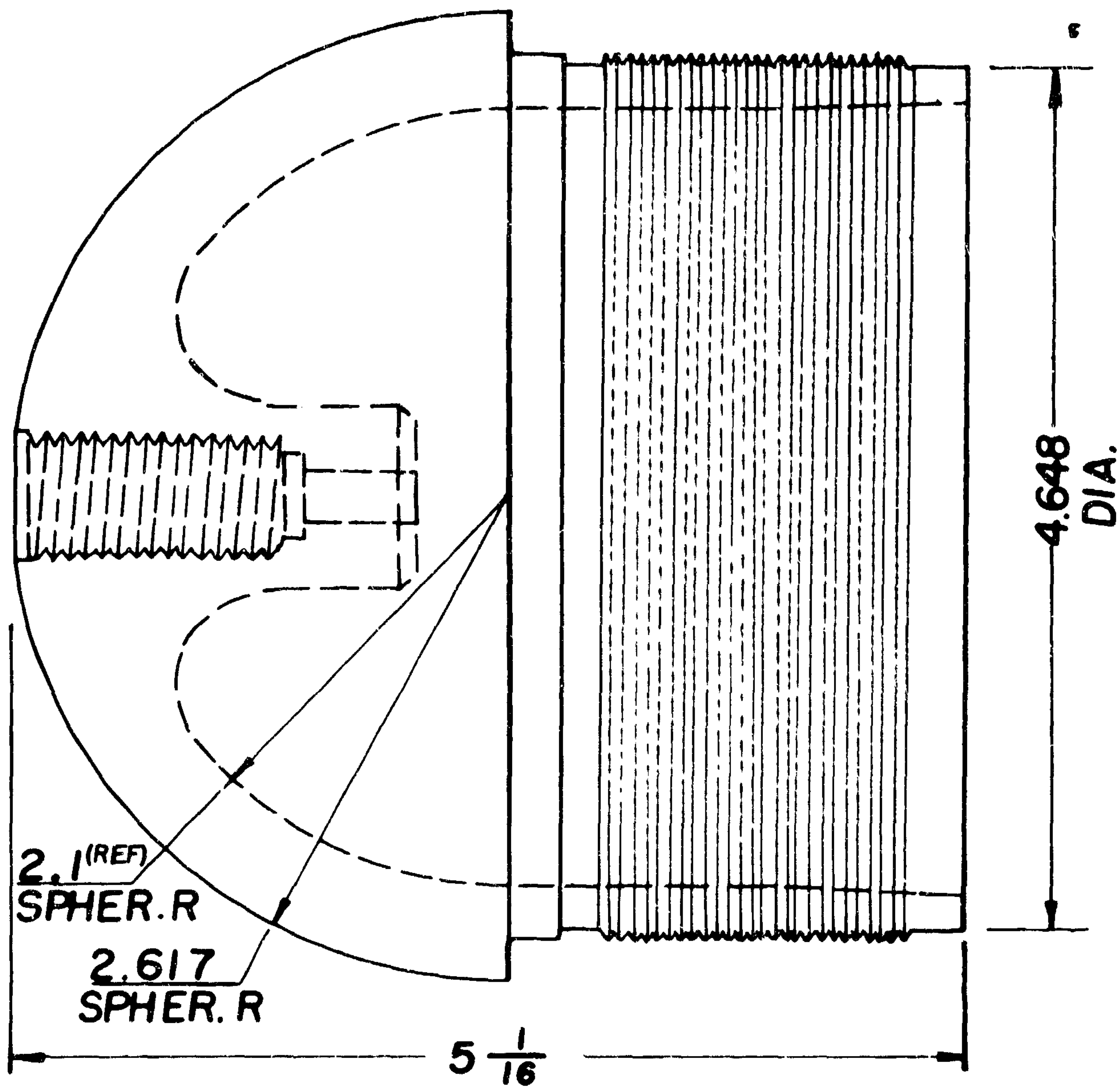


Figure 2. Baseplug

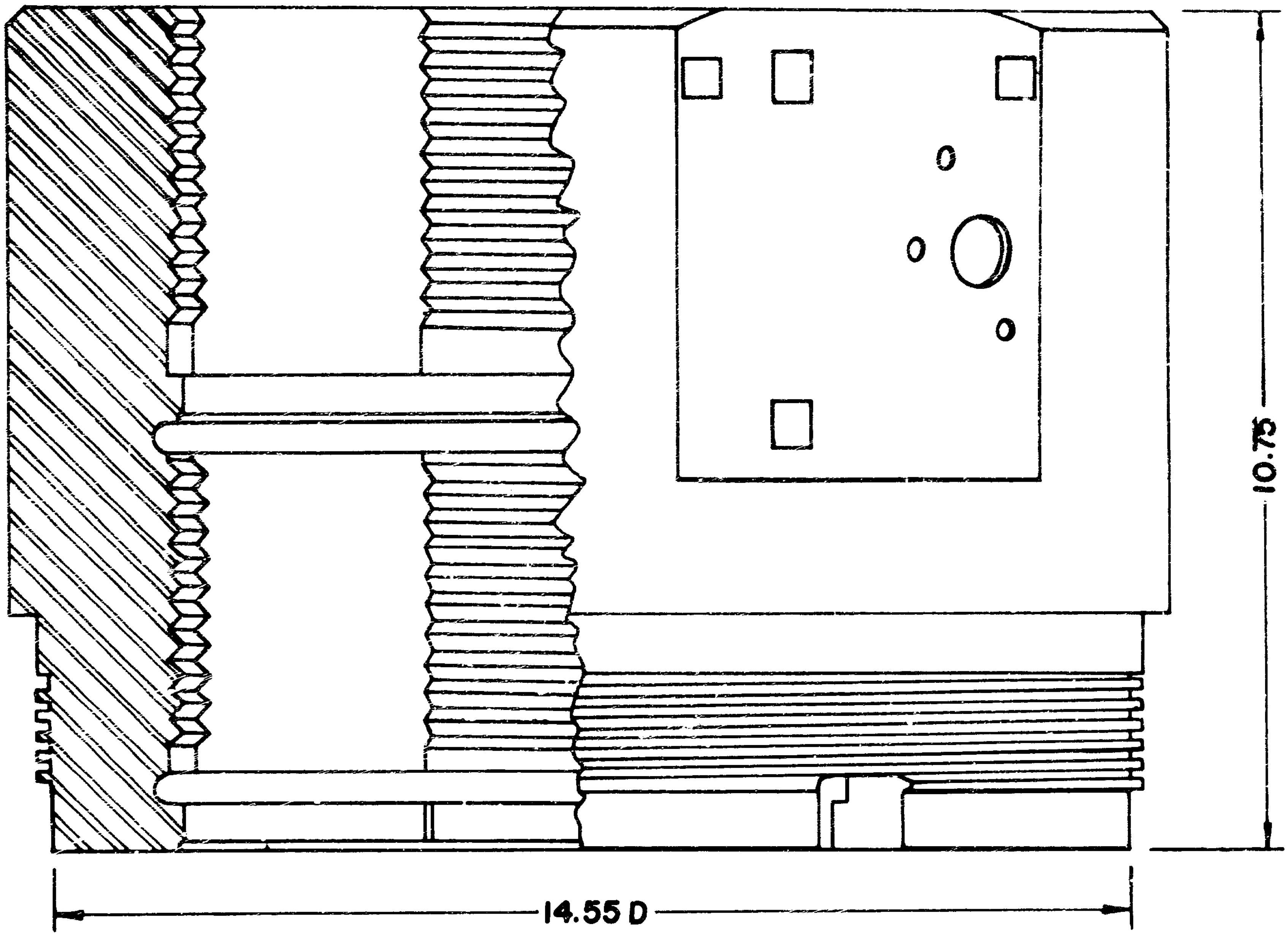


Figure 5. Breech ring.

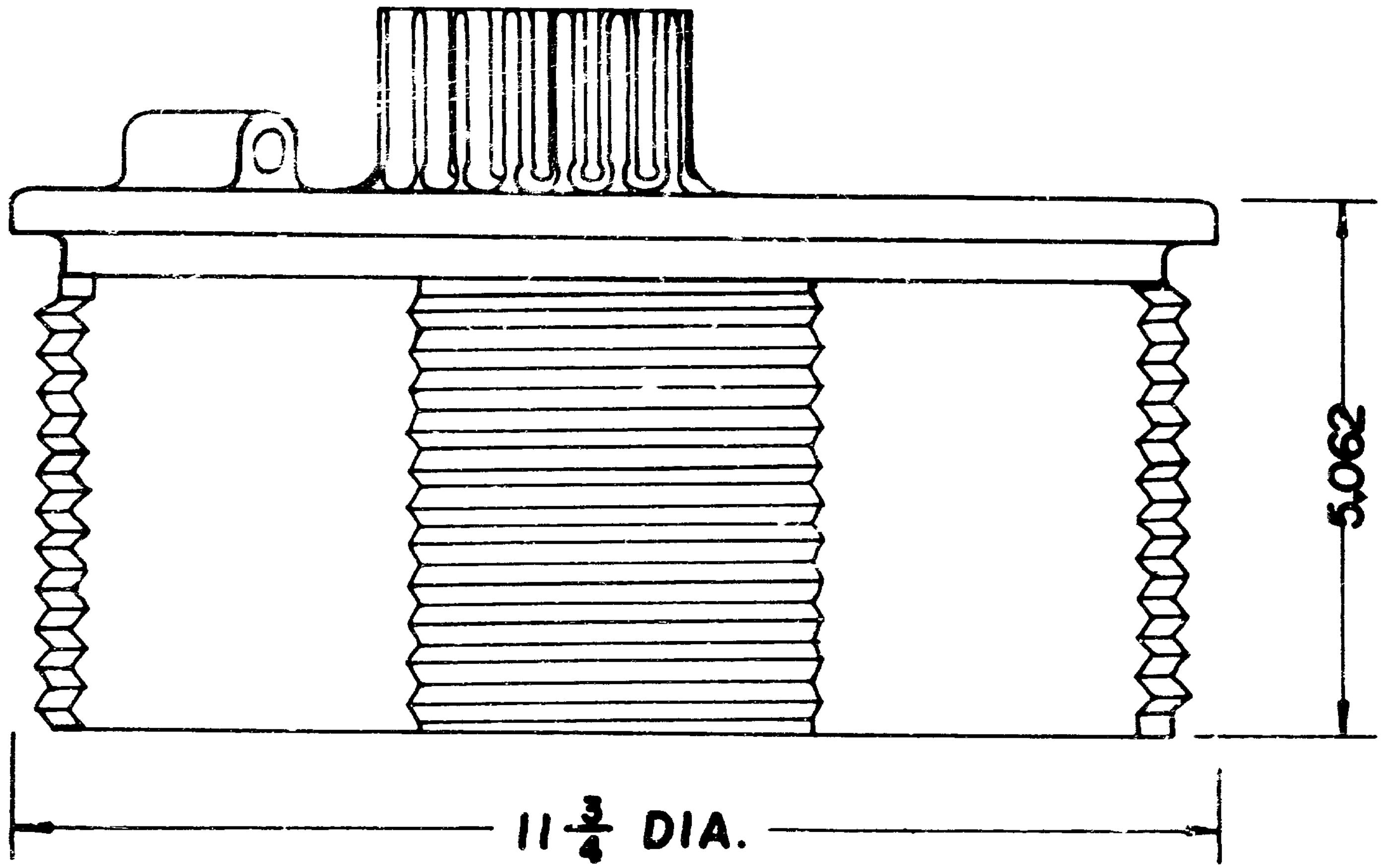


Figure 4. Breechblock.

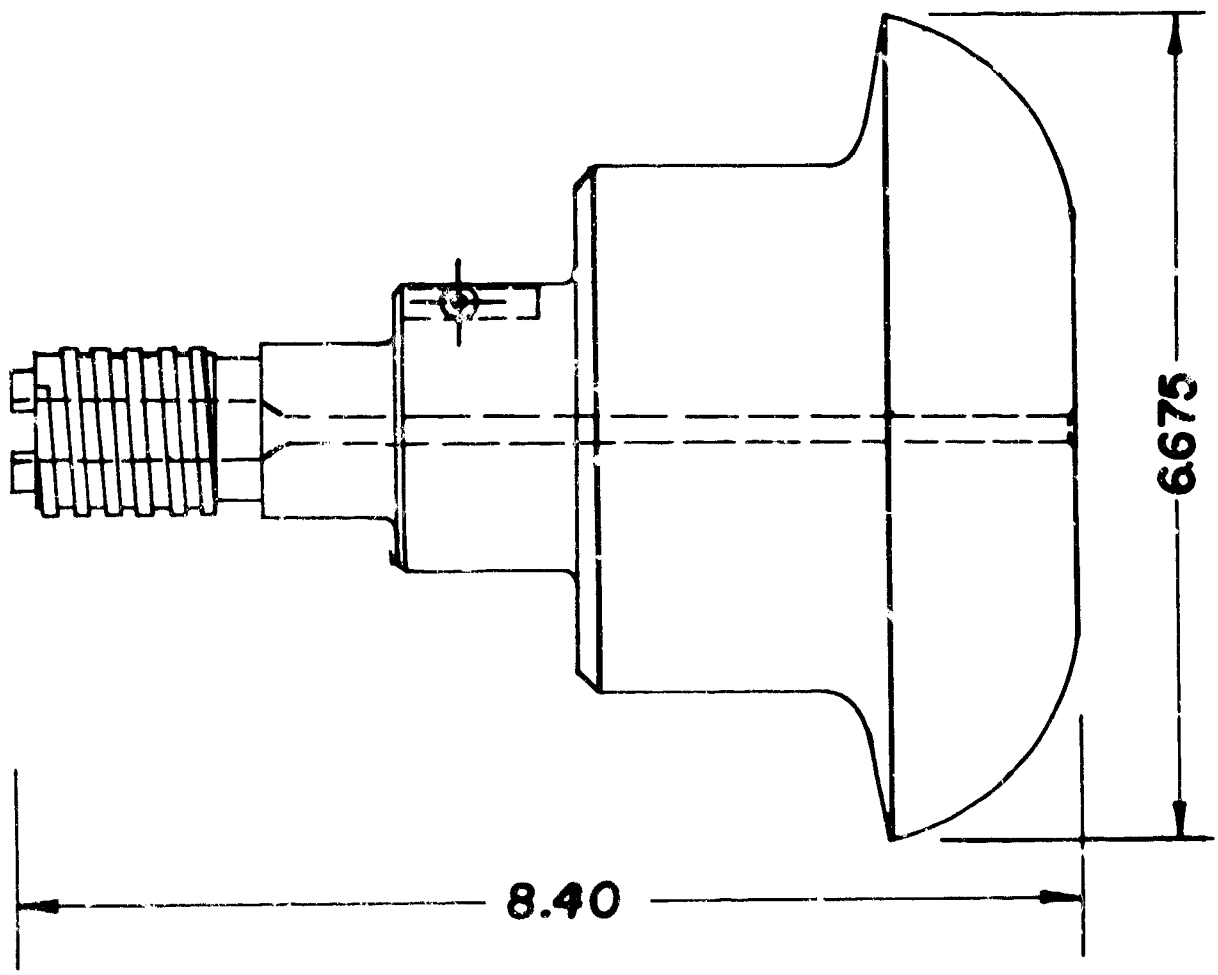


Figure 5. Obturator spindle.

There is a tapped hole in that base plug. The machinists found that with conventional M2 and T1 taps, they could at best get one hole per tap. They could get no holes from a helical tap. Perhaps if taps were made of a special material and rake angles and helical angles were specially controlled, this might be improved. With the available taps they could get only one tap per hole. Nitriding the taps did relieve the situation.

To summarize, the general consensus of all the machinists seems to be that maraging steel can be machined quite satisfactorily with the following precautions:

1. Use a high hardness (Rc70) high speed steel cutting tool of the Cobalt type. A soft tool will not only dull quickly but will cause work hardening and cause additional trouble.

2. Use an extreme pressure additive lubricant, with a highly sulphurized, chlorinated mineral oil content to prevent welding of the tool to the chip. The welding would build up on the edge of the tool and destroy the cutting effectiveness of the tool.

3. Do not use high speeds.

4. Do not force the feed.

<u>D. Kendall</u>: "STRAIN RATE EFFECT IN MARAGING STEELS"

I would like to present a brief summary here on some work we have been doing on strain rate effects on high strength alloy steels, one of which is a 300 type maraging steel. We have developed a high speed tensile testing machine which will develop 60,000 lbs. force in approximately 1 millisecond. This will produce a strain rate on the maraging steel of approximately 10 inches per inch per second. We are interested in these high strain rates because the strain rates in a typical gun chamber are in the order of 1 inch per inch per second.

Generally, the consensus is that high strength steels are not strain sensitive. This has generally been proven to be the case. However, they are not completely insensitive to strain rate. In some cases where we are concerned with 5 or 10% in our design safety factors this could be a critical factor.

For the maraging steel, when .2% Y.S. was plotted versus the strain rate on a log-log scale, a linear relationship was obtained. At a strain rate of 10^{-4} in/in/sec, the yield strength was 270 ksi. At 10 in/in/sec, this increased 10% to 295 ksi.

For comparison, here is the data for a few other materials: On Vasco-jet 1000, a modified H-11 type, the yield strength increased from 250 ksi at 10^{-4} in/in/sec to 270 ksi at 10 in/in/sec. The difference with this material is that the response was not linear. The material did not show any appreciable strain rate effect until a strain rate of 10^{-1} in/in/sec is applied. Then it increases rapidly. This is also the type of reaction you get with mild steel.

The other material which we considered was 4340 bar stock material. This shows very little strain rate effect. You start at 158 ksi at 10^{-4} in/in/sec and increase to 165 ksi at 10 in/in/sec. This also showed a linear response although the change was so slight that little deviation from linearity was noted.

B. Schaaf: "EFFECT OF COMPOSITION & PROCESSING VARIABLES ON MARAGING STEEL"

The first point that I would like to briefly cover is the effect of composition variables on the mechanical properties of the maraging steels.

Nickel provides the tough ductile martensitic matrix. As a strengthener it does have a contribution perhaps in the order of 500 psi per 0.1%. If nickel content does become excessive, that is, beyond the range usually specified, there is the possibility of retaining austenite. If this becomes appreciable, it causes a loss of strength because austenite does not marage. It is the martensite which marages.

Cobalt and molybdenum are the principal strengthening elements in maraging steel. Over the permissible range of these two elements, the strengthening effects are 900 psi and 2000 psi per 0.1% respectively. Of course, there is a synergistic effect, meaning that the total contribution of hardening of these two elements is greater combined than each individual contribution. Excessive amounts of cobalt and molybdenum produce strengthening at the cost of toughness. I should mention in passing that cobalt has a unique effect in that it is the only strengthener in maraging steel which raises instead of lowers the martensitic transformation range. By so doing, it allows higher contents of molybdenum and titanium.

Titanium is a very potent strengthener. Its contribution is the order of 10,000 psi per 0.1%. Less than the recommended titanium, therefore, will have the effect of producing an alloy which has less than the desired strength. On the other hand, too high a titanium level causes a loss of toughness.

At this point I might add that both titanium and molybdenum, particularly titanium, are well known for their segregation tendencies. Conditions which aggravate segregation, i.e., insufficient homogenization or excessive molybdenum or titanium, can produce segregation with the result that there are alternate light and dark bands, in etching.

Aluminum is added as a deoxidizer primarily. However, it does have a strengthening effect similar to titanium. In its deoxidation capacity aluminum increases the Charpy impact strength by the order to 5 ft-lbs at the 0.1% level.

Boron and zirconium have little effect on mechanical properties and are added to enhance resistance to stress corrosion.

Silicon and manganese levels are set on the basis that excess silicon and manganese impair impact strength. For some reason, a higher annealing treatment will tend to reduce this impairment of impact strength.

The interstitials, carbon, nitrogen and oxygen in solution have a very detrimental effect and are therefore maintained at minimal levels. Carbon in excess of the .03% maximum actually weakens the alloy by tying up titanium and molybdenum as carbides and thereby keeping them from performing their strengthening function.

Sulphur is by far the most detrimental element. The .010% maximum limit was established primarily on the basis of being a reasonable level to reach. Even at this level, there is some impairment, particularly of transverse properties of large billets and forgings. There is directionality, the primary loss being in the transverse direction based on the distribution of titanium sulfide. These platelets are so oriented as to be primarily detrimental in the transverse direction. A calcium addition is made to reduce the sulphur concentration.

Phosphorus and antimony at levels considerably greate· than those which cause embrittlement in low alloy quench and tempered steels are tolerated with no problem in the maraging steels. We don't know what the maximum levels are, though.

Consider the effect of section size and forging reduction together. Table I shows the mechanical properties of a 20 inch diameter ingot reduced successively to 10 inch, 8 inch, 6 inch and 5 inch diameter bars. The 10 inch diameter bar is about a 75% forging reduction. The 5 inch diameter represents approximately a 94% forging reduction.

The strength does not change, but transverse elongation, reduction of area and Charpy V-notch strength progressively improve as the bar is forged down. For instance, the 10 inch bar has 1.4% elongation, 8.8% reduction in area and 7.0 ft-lbs. At the 5 inch section size, these figures have increased to 6.4%, 27.0% and 13 respectively.

Since these are round bars, the short transverse direction does not occur. We would expect, in general, that the short transverse direction is the worst.

Table II shows some comments on the etch discs. The grain size goes from 0 to 1 in the ten inch disc to 5 in the five inch diameter disc.

There is a dendritic pattern at the central 5 inches of the 10 inch diameter bar, the central 2 inches of the 8 inch bar, but none in the 6 inch bar.

Some banding persists from the 10" bar to the 6 inch bar, but is absent in the 5 inch diameter bar. Also, there is some titanium carbonitride segregation present in the 10 and 8 inch bars only.

These data certainly illustrate an effect. I think it makes a point that you do get an improvement of properties as the material received greater reduction. But the question not answered is what part of this transverse property improvement is attributable to forging reduction itself and the corresponding microstructural improvement and what part is attributable to section size variation per se.

Processing Variables

A continuing study at the Inco Research Laboratory is concerned with effects of hot processing variables on resultant toughness and ductility. It was prompted by the observation that in commercial heats wide variations in transverse ductility and toughness could not be explained by banding, segregation of nonmetallic compounds, chemical composition or heat treatment variables.

This work has been confined principally to product from an air melt 18 Ni 250 heat in the form of 5/8" plate but the general observations apply to many other heats studied, both commercial and laboratory heats, either air or vacuum melted. In general, the embrittling tendencies observed were common to all heats of the standard 18 Ni 200, 250 and 300 types and only some low strength heats of approximately 180 ksi yield strength seemed immune.

Table III and Figure 1 summarize the experience on the most widely investigated heat. Basically, if the as-received material is subjected to a grain coarsening treatment at 2200°F, the study shows that relatively short time isothermal holding at 1300°F-1800°F (or slow cooling through this range) induces a reaction at austenite grain boundaries which, upon subsequent aging following cooling to room temperature, results in marked impairment of ductility or toughness. For example, reduction of area decreases from 49 to 13% and Charpy value from 20 to 10 foot lbs. with a 30 minute hold at 1400°F. The grain boundary precipitation that is responsible can be redissolved and original properties achieved but only at high solution temperatures of 2000°F or higher.

Figure 1 (isoembrittlement Charpy curves) shows in fact two separate temperature regions where the reaction occurs most rapidly (at 1500 and 1650°F) so perhaps there are two separate phenomena involved in the overall observed effects which have been called "C" curve embrittlement.

The 2000°F treatment, causing grain coarsening, accentuates the degree of subsequent embrittlement. This treatment was deliberate to permit more accurate definition of the effects of subsequent isothermal holding treatments. The study suggests several factors that should be considered in the stages of hot reduction of maraging alloys.

1. For reheating preparatory to final hot working, restrict temperature to 2000°F max. (In forging, some of best properties have been achieved with 1850°F heating temperatures and actual hot working at 1750°F.)

2. Finish hot working at as low a temperature as possible.

3. Cool as rapidly as possible following hot working.

4. In heavy sections (where cooling rate is low) restrict annealing temperatures to the minimum required for recrystallization.

5. Avoid prolonged annealing treatments at temperatures below 1700°F regardless of section size and cooling rate.

DISCUSSION:

L. Slawsky: You mentioned banding disappearing in the 5 inch bar. If you went up to higher magnification would you find your banding again? What I'm after is a firm definition of banding.

B. Schaaf: Banding is segregation. It's the old thing that we have been living with for a long time in other materials. To try to answer your question, I think the answer is "no". It's a pretty coarse thing. It shows up readily at 50x or 100x. There is no reason of going any higher.

T. Davidson: Are there any effects of banding on properties?

B. Schaaf: I am sure that they would have an effect particular in a short transverse direction.

T. Davidson: Has this been determined?

B. Schaaf: George Pellesier of United States Steel touched on this subject at the Third Maraging Review. I do not recall what test he ran but the indication was that the properties were the least in the short transverse direction. This was a heavy plate that he was looking at.

T. Davidson: Do you attribute these properties to the banding?

B. Schaaf: I think the segregation phenomena is the main cause there. I am sure there are other considerations too, but that is the principal one and certainly the most obvious.

V. Colangelo: Do you have evidence that this segregation is affecting transformation and causing retained austenite?

B. Schaaf: For the very most part it's all martensite. It's just that some areas have become enriched in titanium and molybdenum and etched darker while the other will be relatively light by comparison.

J. Sliney: To what do you attribute the disappearance of the banding in the smaller section?

B. Schaaf: I think it's just a matter of homogenizing the material by further work.

T. Davidson: Is anything being done to break up the banding in the larger section?

B. Schaaf: I'm sure that the producers are all working along this line. I know that the contract that Republic Steel has with the Air Force is aimed in this direction. Certainly we are very interested in this at the INCO Lab too, but it's not the sort of thing that we can contribute to. They are working on it, I am sure.

T. Davidson: Have they had any success as yet?

B. Schaaf: I'm quite sure they have. I know of three specific programs from three different producers that are pretty much completed. The only one I've heard back from directly was successful. They are no longer having problems with banding.

L. Slawsky: On isothermal holding at 1400°F after a solution of 2200°F which reduced your impact properties from 20 ft-lbs. to 6 ft-lbs. Have you investigated this at lower solution temperatures?

B. Schaaf: At about 2000°F you tend to pretty much get out of this area.

R. Decker: This was intended as a simulation treatment to get a coarse grain size such as you might have with a forging and to simulate some of the cycles that would go on during heating for hot working. This study did indicate that 2000°F would be about optimum as far as a reheating temperature for working.

V. Colangelo: Does this constituent resemble anything that was shown this morning?

B. Schaaf: We have been working on this a long hard time and we certainly have ideas, but they are not well enough formulated to talk about at this time.

R. Decker: It definitely would not be seen in photomicrographs at 1000x. It takes electron miscoscopic and fractographic analysis primarily.

B. Schaaf: The next area is one that is in the producer's area and not in the developer's area, namely, the effect of ingot size on properties. I know this is being studied by the producers. As far as specifications are concerned, this is something between a producer and a user. I will say, however, that the specification in connection with the 107mm mortar tube, is very good and fairly tough. (230 to 260 ksi, 0.1% yield strength, 18% reduction in area and 12 ft-lbs at -40°F.

J. Penrose: Do you think those are reasonable requirements to make?

B. Schaaf: I think it's a tough specification with respect to the impact strength. With the reduction in area, it's still pretty good when you are talking about large sections.

J. Penrose: If we write a procurement document (or specification) we do not ordinarily relate to section size.

B. Schaaf: With the present state-of-the-art it's tougher to get these transverse properties in large sections than it is in smaller sections. That is something you might want to consider. Another thing that was of interest to me in your specification was the .008% sulphur and phosphorus limitation. I think that is a very good point, particularly in connection with large sections because where you have a larger section you have more opportunity for segregation.

L. Slawsky: With that specification, are we talking about the same material that you people published all your data on?

B. Schaaf: You are talking about limiting cases which are the large sections. What I am saying is that you can do better when you get in bar stock where you just have a longitudinal test and in plate, where you have more reduction. Where you are dealing primarily with large sections, you have the tough problem. The producer has to produce this material.

V. Colangelo: Doesn't this seem to impose undue penalties on the material because of the producer's inadequacy? What I'm trying to say is that it appears there are really two different grades of maraging steels: Those which are capable of yielding an impact strength in the order of 20 ft-lbs in the transverse direction, and those which are capable of yielding much less than that. The difference between the two seems to be associated with composition, melting, such as consumable vacuum melting and its associated effects, processing, and synergetic effects when all these variables are combined.

B. Schaaf: Are we talking about two different materials? Not really. Certainly the producers have a problem. They have progressed a long way and it's a matter of working with them.

P. Rummel: On this specification business, what progress has been made by other users in developing and obtaining material specifications? Have you any experience or comments from the producers concerning thick sections? Have you any knowledge of other specifications successfully used in materials of 1 inch thick and over?

B. Schaaf: I think you will have to go a little higher than that in thickness before you start getting into thick sections which are troublesome. I still point out that ASTM has a task group working on maraging steel specifications. They are presently presenting a specification to the membership of the subcommittee at large.

P. Rummel: Does this specification cover plate?

B. Schaaf: Yes, this is a plate specification. However, in regard to the forgings, I have to say that we cannot really recommend the very heavy sections at this time. Some producers are going very well while others are not. Variations of this type must be expected.

J. Penrose: We do know that other people are working with heavy sections. Pratt-Whitney, for example, requires about 12 ft-lbs in a 4" section. Do you know who is supplying this material to Pratt-Whitney?

B. Schaaf: I know the people who are supplying the material to them. Whether they are meeting the specifications, I don't know. This is something that I'd rather not talk about.

F. Heiser: This is perhaps away from thick large sections, but I understand that some people are requesting from Vanadium Alloys that they provide precracked Charpy data.

B. Schaaf: Yes, Thiokol is getting into this area now. This requirement applies to anyone supplying material to Thiokol.

F. Heiser: Do they have a set requirement?

B. Schaaf: Yes, they do. I haven't seen the specification myself so I cannot pass on to you the values that I heard. These values, however, do reflect the difference between longitudinal and transverse direction.

V. Colangelo: Has there been data of any extent generated on vacuum degassed material? Has there been any experience with either vacuum degassed materials or materials melted by a Hopkins type process?

B. Schaaf: We have had some reports back on this. I don't think I can put myself in the position of commenting on them. I think you could find out pretty easily which company could produce such products.

R. Decker: You can tell us something on the Firth-Sterling data.

B. Schaaf: I think some of their data has been very outstanding. To put it this way, for instance, they talk about Charpy V-notch strengths of 45 and 50.

V. Colangelo: I haven't seen any of their data. I know that consumable electrode melting has been sold as being considerably cleaner. This is true in that it would not have the titanium oxides and nitrides that would be present in air melt but I also know that other problems occur, for example, freckling. To what extent is freckling a problem with consumable melted maraging steels?

B. Schaaf: There is no proper melting process I know of. Does that tell you anything?

V. Colangelo: This is the reason that I was looking for data on other methods.

B. Schaaf: There is data on materials based on various methods.

T. Davidson: Getting back to the problem of specifications. Do any of the other large users of maraging steel have a micro cleanliness specification? Secondly, how do the suppliers feel about this? Finally, what are they using as a basis for their micro cleanliness requirements?

B. Schaaf: Vanadium Alloys has actually added another category to the JK inspection for titanium carbo-nitrides. This is in addition to the conventional ratings A through D.

T. Davidson: Are many large users specifying a micro cleanliness for large sections? Are they basing their micro cleanliness requirements on what they have learned from other materials or do they actually have experimental data backing up their requirements?

B. Schaaf: Probably some of both.

J. Penrose: Can you explain the cracks that Mr. Heiser described this morning on howitzer gun tubes?

B. Schaaf: We can talk a little about it. I'm not sure how much we can explain. It looks like stress corrosion cracking to us since fatigue is usually transgranular as well as intergranular but this is strictly intergranular. The carbon content and nitrogen contents are triple in the surface layer which is austenite. This might suggest that maybe there is some corrosive agent within the powder gas which could be causing the corrosion.

J. Penrose: Can we expect that in other gun tubes?

B. Schaaf: I don't know, it's hard to say because I've looked at only one of the gun tubes. I think on any one test you must be cautious.

R. Decker: It certainly is going to help if you get a fine grain size. That was a coarse grain size in the ones we looked at.

B. Schaaf: You can postulate this carbon and nitrogen going in on the grain boundaries and causing an embrittling formation of carbo-nitrides at the grain boundaries. There are any number of possible mechanisms here.

C. Nolan: Would you say that 18% reduction in area represents a segregated billet?

B. Schaaf: No, I don't think this would be a valid assumption.

R. Decker: The C-curve embrittlement we discussed previously represented unsegregated material. We have seen material that looked banded and yet it had very good short transverse toughness. So the occurrence of banding per se, cannot always be bad. The C-curve embrittlement can be independent of that and it seems to be the major problem with short transverse properties.

F. Heiser: Where is the dividing point between thin wall sections and large wall sections?

T. Landig: You have to know in more detail what the producer is doing. This is an area in which we have very little control. In terms of general numbers, when you get in sheet below 100 mils, your elongation begins to decrease. You reach an optimum at about 3/8 of an inch. Then you get into the heavy section problem in the range from 1 inch to 3 inches. Over 3 inches, you definitely have a heavy section problem.

B. Schaaf: There are some very good properties on 9 inch billets, however, so it's hard to generalize. At one time one producer was talking about 25 square inches as being the difference between a large and small section as far as properties were concerned.

V. Colangelo: Wouldn't this depend on the prior processing history?

T. Landig: This is a processing history dependent problem. Actually, we are talking about what a businessman would call product differentiation, that is, the different producers realize varying degrees of business success on their ability to control a process. Different producers will develop from time to time, optimum sequences in their processing cycles which give them the best properties. So, pretty soon the business goes in that direction. Our approach is to try to develop in the lab the principles whereby you can control this process. We are prepared to talk in some detail about the principles, like C-curve embrittlement, but not in terms of anything other than general principles. I'm afraid we are in an awkward position to put quantitative numbers on this sort of thing.

Each forge shop has different facilities. They have different ingot sizes and methods. We cannot specify quantitative numbers but we can talk about the principles, e.g., what temperatures one should use in heat treatments. We can do identification work on the intermetallic compounds that are precipitating. In terms of the details of mill processing, I suspect that you are in a better position to obtain these data than we are.

L. Slawsky: Then we cannot use a maximum value for wall thickness as design criteria since it depends on each individual producer.

T. Landig: There is a heavy section problem. We think it's solvable but it's solvable in terms of a processing technique which will be peculiar to different producers and which you will have to work with them on. We stand ready to advise and to do work with the principles which will govern the selection of a processing sequence.

B. Schaaf: For instance, this work on embrittlement. This was primarily designed to assist the producer in understanding some of the fundamentals. How he applies that information, of course, will depend on his individual facilities.

L. Slawsky: I think my whole point is that you talk about the heavy section problem. It could be a thin section problem too, depending on processing.

T. Landig: I think what we are trying to say is there is an optimum of about 3/8 of an inch. If you get very far below that you can get into a problem, and if you get very far above it you can get into a problem. We are trying to work out the principles of what are the factors that have to be put under tight process control to get the kind of properties that we believe are inherent in the material.

B. Schaaf: I would like to generalize just a little further. This is sheet and plate mostly with this 3/8" limitation. I think it's nearer 25 square inches for billets.

J. Sliney: Is this banding type segregation inherent in the alloy system?

B. Schaaf: It's not inherent. Certainly molybdenum and titanium tend to segregate, and so have an opportunity for segregation. The point is to arrange a processing to minimize the opportunity for segregation, to homogenize sufficiently for a given ingot size, or to reduce ingot size such that you don't get it.

R. Decker: Any high strength system that you are going to use is based on an alloy design principle in which you are trying to increase the disorder in the material. Whether you are trying to harden steel, aluminum, or titanium, whenever you get up into high strength materials, you are putting a lot of different kinds of materials (different atoms) into the system.

Whenever you do this, you run the danger of segregation and banding, and the property differences which are created by the presence of these elements. In all the systems, there are methods which you can utilize in order to put at your control the inherent advantages of the material.

C. Nolan: Specifically, on what paths do you proceed to put it under control?

B. Schaaf: For one thing, we used a 30# ingot which minimized any segregation problems.

R. Decker: A rather substantial contribution has been made by the work on the C-curve embrittlement. For the heavy section problem the conclusion you can draw is that, first, the cooling rate is very important. If you cool slowly enough so that you enter these C-curves, this is bad. It is a grain boundary problem, so your processing must be selected to move boundaries off any precipitates that form during cooling. You should use as small an ingot as possible, because this means your cooling conditions are going to be better. There are principles you can work out based on the discovery of such an effect as C-curve embrittlement.

F. Heiser: I have two questions relative to banding. Is it really a grain boundary segregation? This infers that it occurred during solidification. Next, if this banding were mechanically separable from the rest of the material, what shape would it be?

R. Decker: It depends on the thermal history. I think you stated the problem very well. It's something that primarily occurs on solidification and, then, depending on the hot processing that is given to it, it will create the banding in whatever shape the hot processes dictate.

B. Schaaf: Once again, I think you ought to make the point that this embrittlement and banding are two separate things. They might both be in part due to some sort of segregation, but I don't think you ought to confuse the two.

F. Heiser: Are you saying that this C-curve embrittlement occurs as a result of the solution anneal or does it occur upon solidification from the original melt?

B. Schaaf: It occurs in the original working, where you are cooling down from a temperature of up above 2000°F in the order of 2200°F.

F. Heiser: You are not talking about freezing from the melt?

B. Schaaf: No, if you were to freeze from the melt and check your ingot properties you would see the same thing because you would go through the same cycles.

F. Haiser: It would not occur if you came up to this temperature?

Table 1

(1) Mechanical Properties vs. Ingot Reduction
(2) Ma-18 (250) Steel

(All Air Cooled) Property (Room Temp.)	Direct Age: 1500F-1 hr - (Prod), 900F-3 hr - (Lab) — Center	Direct Age — Mid-Radius	Double Solution and Age: 1500F - 1 hr - (Prod), 1500F - 1 hr - (Lab), 900F - 3 hr - (Lab) — Center	Double Solution and Age — Mid-Radius
A. Bar Size 10" rd. (≈75% Red. of Area) Transverse Direction				
Ten. Str. (ksi)	249.3	253.4	253.3	258.3
Yield Str.(.2% ksi)	245.1	244.1	247.2	251.3
Elong.(% in 1.4" or 4/D)	2.8	2.8	1.4	2.1
R. of A. (%)	6.2	3.4	8.8	11.5
V-Notch Charpy(ft-lbs)	7.0	8.0	7.0	10.0
B. Bar Size 8" rd. (≈84% Red. of Area) Transverse Direction				
Ten. Str. (ksi)	250.3	253.3	256.3	256.3
Yield Str.(.2% ksi)	246.2	245.2	251.3	249.3
Elong.(% 1.4" or 4/D)	5.7	5.0	5.7	2.1
R. of A. (%)	19.2	14.1	21.7	14.1
V-Notch Charpy(ft-lbs)	8.0	8.0	8.0	9.0
C. Bar Size 6" rd. (≈91% Red. of Area) Transverse Direction				
Ten. Str. (ksi)	250.3	252.3	254.3	258.3
Yield Str.(.2% ksi)	244.2	251.3	249.3	251.3
Elong.(% in 1.4" or 4/D)	5.7	7.1	8.6	7.1
R. of A. (%)	26.6	29.0	36.7	26.6
V-Notch Charpy(ft-lbs)	9.0	10.0	10.0	10.0
D. Bar Size 5" rd. (≈94% Red. of Area) Transverse Direction				
Ten. Str. (ksi)			254.0	255.0
Yield Str.(.2% ksi)			250.0	252.0
Elong.(% in 1.4" or 4/D)	None	None	6.4	7.9
R. of A. (%)			27.0	30.0
V-Notch Charpy(ft-lbs)			13.0	14.0
E. Bar Size 5" rd. (≈94% Red. of Area) Longitudinal Direction				
Ten. Str. (ksi)	246.0	245.0	250.0	251.0
Yield Str.(.2% ksi)	230.0	232.0	240.0	240.0
Elong.(% in 1.4" or 4/D)	11.4	11.4	10.0	11.4
R. of A. (%)	57.0	57.0	41.0	55.0
Hardness (Rc)	48	48	48	48/49
Grain Size (ASTM No.)	7-8	7-8	7-8	7-8

(1) All bars produced from 20" rd. VAR ingot
(2) Heat R-411

C	Mn	P	S	Si	Ni	Mo	Co	Ti	Al
.030	.08	.005	.004	.08	18.05	4.53	8.20	.36	.11

Abbreviations:

Ten.	Tensile
Str.	Strength
Elong.	Elongation
R. of A.	Reduction of Area

Table II. Internal Quality Characteristics of 18% Ni Maraging Steel

MA 18 (250

BAR SIZE (in)	Macro-etch (1)				Micro Cleanliness (2)				Grain Size Mid Radius (ASTM No.)	Remarks
	A	B	C	L	A	B	C	D		
10 Rd.	1	1	1	0	0	.5	0	2	0 to 1	Fine center dendritic pattern (5" rd) - Micro Ti segregation - Ti(C,N) stringer .002" x .020". Inter dendritic banding.
8 Rd.	1	1	1	0	0	.5	0	2	1	Fine center dendritic pattern (2" rd) - Mid-radius Ti(C,N) segregation - intergranular Ti carbides.
6 Rd.	1	1	1	0	0	0	0	1.5	5	Uniform macroetch edge to center. Evidence of slight micro structural banding.
5 Rd.	1	1	1	0	0	0	0	1.5	5	Uniform macroetch edge to center. No evidence of banding.

(1) Rated by MIL-STD-430

(2) Worst Field Jernkenteret (JK) Rating - all ratings are thin, no heavy types.

Table III. "C" Curve Embrittlement Data

Commercial Air Melt Heat, 5/8" Plate

CHEMICAL COMPOSITION %

C	Ni	Co	Mo	Ti	Al	P	S	B	Si	Mn
.02	18.4	7.8	4.8	.37	.07	.006	.006	.0026	.09	.12

MECHANICAL PROPERTY DATA

Standard Heat Treatment - 1500°F - A.C. + 900°F - 3 hrs. - A.C.

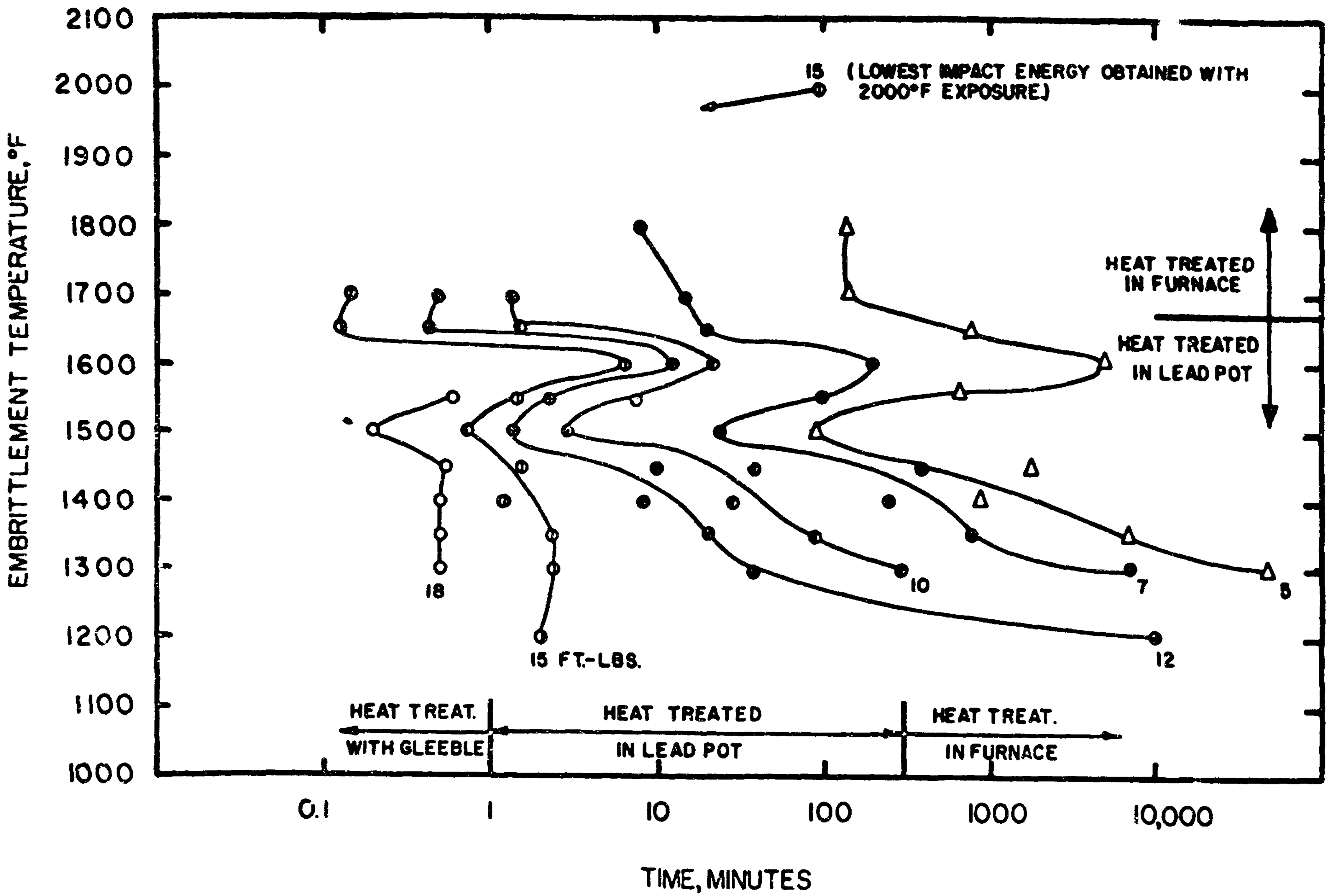
Y.S. ksi	U.T.S. ksi	% El in 2"	% R.A.	Charpy V-Notch Ft. Lbs.
249	259	10	50	20

Grain Coarsening Treatment - 2200°F - 1 hr. - W.Q. + 900°F - 3 hrs - A.C.

Y.S. ksi	U.T.S. ksi	% El	% R.A.	Charpy V-Notch Ft. Lbs.
235	250	11.5	49.5	20

EMBRITTLED @ 1400°F FOR VARIOUS TIMES

Y.S. ksi	U.T.S. ksi	El %	% R. A.	Charpy V-Notch Ft. Lbs.	Embrittlement time
243	258	4	13.5	10	30 min.
244	260	3	10.0	8.5	1½ hr.
241	258	3	6.0	6.5	5 hr.



SPECIMENS WERE SOLUTION ANNEALED 1 HR. AT 2200°F, DIRECTLY EXPOSED AS SHOWN, AND AGED 3 HRS. AT 900°F. CURVES SHOWN REPRESENT "ISO-CHARPY V-NOTCH ENERGY" LEVELS.

Figure 1. Embrittlement curves for 250 k.s.i. 18% Ni Maraging steel (Alloy 1).

B. Schaaf: It would not occur.

J. Sliney: Has the Nickel Company increased their knowledge in recent months along the line of strengthening mechanisms?

R. Decker: As of a year ago we knew there was a molybdenum precipitate, Ni_3Mo. There is a cobalt effect, probably to increase the quantity of the precipitate Ni_3Mo. There is also a secondary unidentified precipitate, probably Ni_3Mo.

J. Sliney: Actually, there is very little knowledge on the ordering aspect. Is that correct?

R. Decker: That's right. Actually, there is little knowledge on the cobalt. No one has established it yet. Our largest advance on the transformation end is the C-curve embrittlement. As far as the hardening mechanism is concerned, I would say "no".

B. Schaaf: We have done more work here than has been reported. This is something that seems fairly firm. I think it would be six months before this data regarding embrittlement is released.

R. Decker: We have a microfractography study underway. It is the most potent technique we are studying. As I mentioned, at 1000x you can't see it but by microfractography using extraction replicas of the fracture surface, you can do a very good job of studying the C-curve embrittlement.

T. Landig: "MECHANICAL PROPERTIES OF MARAGING STEELS"

In Figure 1 is a stress-strain diagram showing the true stress-true strain characteristics of the 200, 250 and the 300 maraging steels. The major feature that we want to show is that the slope of the plastic deformation region of these curves corresponds to a strain hardening exponent of about .03. This is a relatively low strain hardening exponent indicating a low rate of strain hardening in the material. We would like to put this deformation characteristic of the maraging steel in perspective by referring to a plot, after Holloman, in which the strain hardening exponent is plotted versus stress at a particular strain (Figure 2). Holloman showed that a straight line resulted which corresponded to the strain hardening exponent's being proportional to the reciprocal of the stress. This straightness then created a family of curves depending on the carbon content. The point he made was that it was the carbon content which was determining, at different strength levels, the strain hardening exponent. To get a high strain hardening rate one had to have a high carbon content.

At the .03 carbon level of the maraging steel, there is really very little data. At the low strength level we have .03 carbon deep drawing steel, and at the high yield strength region we have the maraging steel family. If we look at Figure 2 rather loosely we see that at the .03 carbon level we do get a general sort of picture which fits into the Holloman analysis. The main point I want to make is that at this low interstitial level of carbon, it is expected that we will get a low strain hardening rate.

In the design of a tough steel, we must decrease our carbon content because at any particular strength level, the lower the carbon content, in general, the greater the toughness. This principle is inherent in the design of the maraging steel.

Figure 3 shows tensile strength plotted versus notched tensile strength. The maraging steels exhibit very good fracture toughness properties by this analysis.

There are a number of other things evident here also. We have, for bar stock, a ratio of about 1.5. We find in looking at the three maraging steels, that the more notch tough material, i.e., the 200 and 250 grades, fall well within the 1.5 and 1.25 region. But when we get up to the higher strength material, i.e., the 300 grade, we do drop below the 1.25 level. Some data, however, are transverse data in large forgings and are responsible for dropping the scatter band below this 1.25 level.

For sheet, the ratio for steel is about 1.0. The maraging steels fall well within this region, although there is some data that has fallen into this lower region of a ratio of .75.

DISCUSSION:

V. Milligan: On your shee aterial, what Kt do you have?

T. Landig: The Kt for this data covers a rather large range but most of it is for a Kt of about 12. The data are so voluminous and cover so many different investigators that I have not shown a Kt.

In Figure 4 Charpy V-notch data versus test temperature is plotted. This shows, in general, a Charpy impact behavior in which there is a very slow decrease in the impact energy as we go to lower and lower temperatures rather than the sharp impact transition temperatures which are characteristic of body centered cubic material.

While the notch tensile test and the Charpy V-notch impact test are very useful techniques for measuring fracture toughness, the stress analysis technique in which one produces K_{I_C} values, the so-called plane strain fracture toughness, is an excellent method whereby one can rate and also use for design purposes, the fracture toughness of the material. In Figure 5 are plotted a number of alloys at different yield strength levels with their K_{I_C} values. In the maraging steel, K_{I_C} values are 100 to 160, 90 to 150, and 80 to 130 at yield strength levels of 200, 250 and 280 Ksi respectively. These values compare very well with the other high strength materials listed.

T. Davidson: What type specimen did you use?

T. Landig: These are NASA type specimens for all materials.

T. Davidson: Is this data from different investigators or your own data?

T. Landig: They are from different investigators.

T. Davidson: Are they all using the NASA type sample?

T. Landig: They are all using the same type of sample and testing technique. These materials are all being tested primarily for missile cases. So the type of sample they are picking is for sheet of thickness from 6 mils to 200 or 250 mils. There are differences from investigator to investigator in the thickness of the sheet tested, but this is my attempt at summarising the data that are available.

F. Heiser: Has the spread in values been correlated with anything?

T. Landig: This is a correlation I have not attempted to make, but I suspect that it's related to processing history. Some of the earlier data has very wide swings to it, but some of the more recent data on the 300 grade from Curtiss-Wright has values above 100. I think we have a learning curve here in the producers. It is very difficult to categorize data of any type on these steels while we are on the learning curve of how to process this material in order to obtain the inherent characteristics of the material in various products.

T. Davidson: Is this data for large sections also?

T. Landig: I'm not in very good shape on bar data. Most of what I have been looking at is on sheet and plate.

R. Decker: Some of that data is one-inch plate.

J. Sliney: At Watertown, Dr. Kula and I have just finished an investigation of the plain strain fracture toughness of the 250 material. I think I might have a comment that might answer one of the earlier questions. Regarding the spread, it might come from the variation in thickness. K_{Ic} does decrease with decreased thickness. The materials that we started with had an original thickness of about .135. We tested three increments down to approximately .040. Our data correlated very well with the range that you specified for 250 grade material.

T. Landig: We are very glad to hear that we are beginning to get some consistency in results from place to place.

F. Heiser: As I interpret fracture toughness, the higher the fracture toughness, the less likelihood for fracture to propagate. Is this the proper interpretation?

T. Landig: Yes, that is one of the interpretations you can make.

F. Heiser: How then can you account for the complete shattering of our 155mm breech ring?

T. Landig: Shattering is something that I suspect has not so much to do with fracture toughness per se but with energy dissipation. In the maraging steels because one has a low strain hardening rate and therefore an inefficient device for dissipating energy, you first form a crack. This crack opens and puts a complexity of stresses on the system. Because of the great amount of energy which it must dissipate, it starts secondary cracks going and the thing breaks into many pieces rather than forming a simple burst. Because we have a very high strength material that requires a large amount of energy to initiate fracture, when fracture does start it then begins to go in many different directions in order to dissipate all this stored energy.

B. Schaaf: That's the general picture, Tom, but the material used for the breech ring would not seem to possess adequate fracture toughness from the outset. The 22" diameter section would certainly seem to be highly susceptible to the type of embrittlement that we discussed earlier.

T. Landig: I believe the next figure will help me clarify that point. We have plotted in Figure 6, the gross section stress versus crack length in inches for 250 and 300 maraging steel, 4340, H-11 and D6AC. These data were not calculated from the K values. These are partial thickness crack determinations of what the critical crack size will be. These data are from various investigators, some of whom record their data as crack length and others as crack depth. We have normalized the data to crack length by multiplying the width data by 2 since most of these cracks are elliptical in nature and that is a pretty good approximation. For the 300 grade material we find that the critical crack length is about .10". We then get a gradual fall off of the gross section stress as we go to larger crack sizes.

If I calculate a critical crack size from the K_{Ic} value, I get a value of 50 to 100 mils. This is less than what we empirically determine by the partial through thickness crack method. The 250 material will tolerate a crack in the range of 200 or 300 mils before we begin to get decrease of the gross section stress because of the growth of the crack.

Presumably the designer will use a steel depending on the ability to detect cracks of this size and eliminate them or design to them. If he can't eliminate cracks larger than this value, he will have to lower his design stress.

In comparing the maraging steels to the conventional low alloy high strength materials, however, it is evident that the maraging steels have a rather substantial advantage in terms of preventing crack propagation. I think this might help answer some of the earlier questions on

K_{I_c}. There is reasonable agreement between the plane strain fracture toughness values and these particular data.

T. Davidson: The data indicates that in applying high strength steels to gun tubes we would have a problem due to heat checking. These high strength steels leave rather small critical crack lengths. On this basis then, the critical crack length could be in the same order of magnitude that we normally get in heat checking. This also means that we have to look extremely closely if we are using this high strength material.

T. Landig: There's a big step in using data like this and applying it to a physical situation like a gun barrel. What you say is true in general, but I would worry more than anything about the chemical environment. You have carbon and nitrogen to diffuse into the material and change its inherent characteristics, in addition to heat plus other combustion products which would have a corrosive effect on the material.

We had demonstrated earlier that on the basis of the number of laboratory measurements, Charpy, notch tensile and fracture toughness measurements including partial crack thickness measurements, the maraging steels were unusually tough for a high strength material. The proof of this is to transfer these laboratory measurements to a prototype test. One of the most convenient ways of doing this is by means of a burst test. Figure 7 is a summary of the data on burst tests with both full scale and sub scale maraging steel pressure vessels.

The first data point is on 18 nickel 300 maraging steel with a wall thickness of .144 to .148 inches in a 65 inch diameter missile case in which the uniaxial ultimate tensile stress was 296,000 and a burst test 342,000 for a biaxial improvement of 16%. This is an excellent biaxial improvement value. This particular data point came from Curtiss-Wright who have been doing experiments on other high strength low alloy steels. Their biaxial improvement values are definitely below that. This is for a spun missile case with a girth weld.

Without going into the details of the other examples, the biaxial improvement values are all in the range of 16% to 19% which is an excellent example of a fracture tough material.

Even though we obtained this tremendous biaxial improvement and we have a fracture tough material, the missile case broke into many different parts. All the fractures in terms of fracture appearance, were representative of a ductile material. Therefore, we are really not worried that it ends up in many pieces after the completion of the test, after having shown such biaxial improvement values. The conclusion that we draw is that we have an unusual high strength, ductile material that has substantial fracture toughness, although, because of the low work hardening rate, the mode of failure is such that after initial failure occurs it breaks into a number of pieces.

With that we will leave the fracture properties and discuss fatigue. Figures 8, 9 and 10 summarize the fatigue data with respect to rotating beam, tension-tension and low cycle fatigue respectively.

Figure 8 shows the rotating beam data. The top band is for smooth bar and the bottom band is for notch bar data. The smooth bar data once again show that the 300 material has the highest endurance limit, with the 250 material falling into a wider band in the general range of 100-120,000 psi at an endurance limit of 10^8 cycles. The notch bar data fall in the lower range at the level of about 40 to 60,000. We have very limited measurements in terms of short transverse rotating beam data but we see a further decrease in the fatigue life in short transverse directions. It borders on the lower range of the band. Going to sharper Kt values, we also get a slight lowering of this band for the rotating beam test.

J. Barranco: What was the RPM used in the rotating beam test?

R. Decker: It was approximately 3500 RPM.

T. Landig: Figure 9 shows the tension-tension results. All we have for the smooth bar data are the results for 300 material, and for notch data, the 250 material. The 250 notch data is a shade below the 300 results as one might expect if you assume the relationship that the higher the yield strength, the higher the fatigue strength.

Figure 10 is a plot of low cycle fatigue data. Here we have the strain range plotted versus cycles to failure. The lower curve represents the point of observation of a 3/16 inch crack and the upper curve represents the point at which failure occurred. The point here is that once a large crack has occurred, rapid crack propagation resulted and failure ensued in a small number of additional cycles.

T. Davidson: What specimen geometry did you have?

T. Landig: This is on a flat plate sample.

T. Davidson: At what frequency?

T. Landig: The frequency is 200 cycles/min.

The endurance limit plotted versus ultimate tensile strength in Figure 11 results in a straight line relationship. The ratio of the endurance limit to the ultimate tensile strength approximates 50%. We find that for normal steels we begin to get a deviation from this 50% ratio at about 200,000 psi for polished specimens. The upper curve represents very rare cases of steels which held to the 50% ratio for a much longer time. This curve incidentally is from "Fatigue of Metals" by Forrester.

I have plotted on this curve the three maraging steels to show that their fatigue endurance limit is above the normal of other high strength steels. The fatigue life of the maraging steel is really very good. It's just not outstandingly better than other materials. We are so used to speaking in superlatives about this material that when it isn't off the curve somehow we get conservative. When you put it into context, the total picture of the fatigue strength versus the tensile strength looks very good as these three maraging steels indicate.

The next area we will discuss is the effect of machining on fatigue life. There was some work done in England and confirmed in our laboratory that finish machining practice had a significant effect on the fatigue life of maraging steels, i.e., if you finish machined after aging you got improvement in the fatigue life. Figure 12 demonstrates that point. We are plotting maximum fiber stress versus cycles to failure. The upper curve represents finish machining last on 18 nickel 200 maraging steel and the lower curve represents aging last. We are quite sure that this is a significant effect. If one is trying to optimize the fatigue life it would be a good idea to put compressive stresses in the surface of the material. Such things as shot peening and finishing machining will certainly enhance the fatigue life.

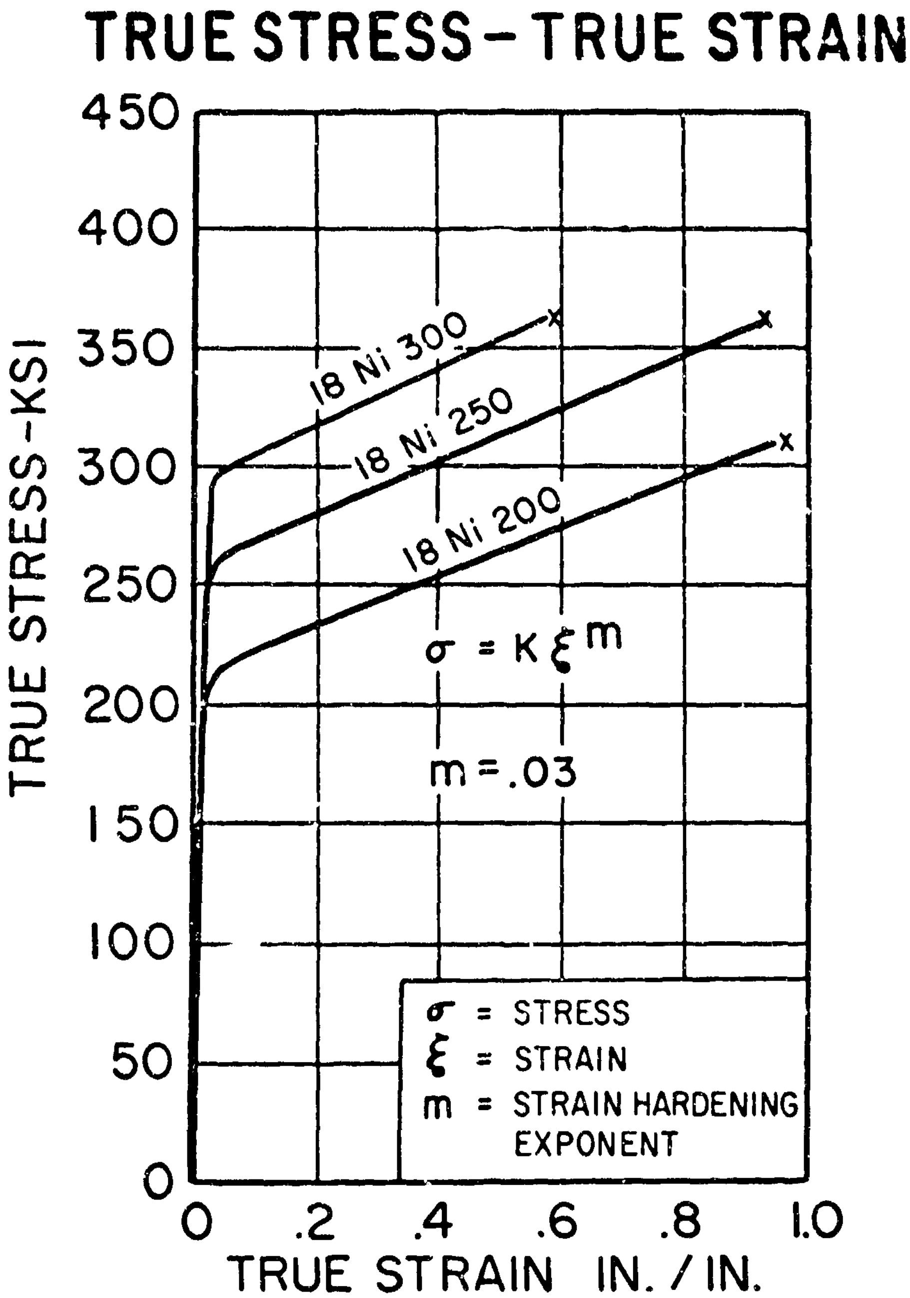
There have been a few experiments in our laboratory in which the effect of nitriding on fatigue life has been examined. With nitrided specimens which were prepared by General Electric, the nitriding effect was negligible. This may simply be that they hadn't been nitrided to a sufficient level of hardness to generate the compressive stresses that are desirable in order to enhance fatigue life. Anyway, the effect has not been shown in nitriding.

T. Davidson: You have to be careful in interpreting the data. Our primary interest is in low cycle region. While there is an improvement at 50,000 cycles, our interest is in the region of 10,000 cycles and down. As far as its effect of machining is concerned, it's converging very rapidly. This would probably be negligible in the region that is of primary interest to us.

T. Landig: This also brings up another point. I think that having a good fracture tough material will play a role at the low cycle fatigue end, but it will have a negligible effect at the higher cycle end of the curve.

T. Davidson: Do you know of anyone who has done very low cycle work by strain amplitude control on maraged steel?

T. Landig: In addition to this work, Messrs. C. M. Carman and Catlin of Frankford Arsenal are working with Mr. Daris of Lehigh on this low cycle fatigue problem.



THE TRUE STRESS-TRUE STRAIN TENSILE CURVE FOR THE 18 NI 250. THE LOW STRAIN HARDENING EXPONENT AND STRAIN HARDENING RATE APPEAR TO CORRELATE WITH THE LOW CARBON CONTENT OF THE MARAGING STEELS AS SUGGESTED BY HOLLOMON.
TENSILE DEFORMATION
TRANS. AIME 162, 268-290 (1945)

Figure 1. True stress, true strain.

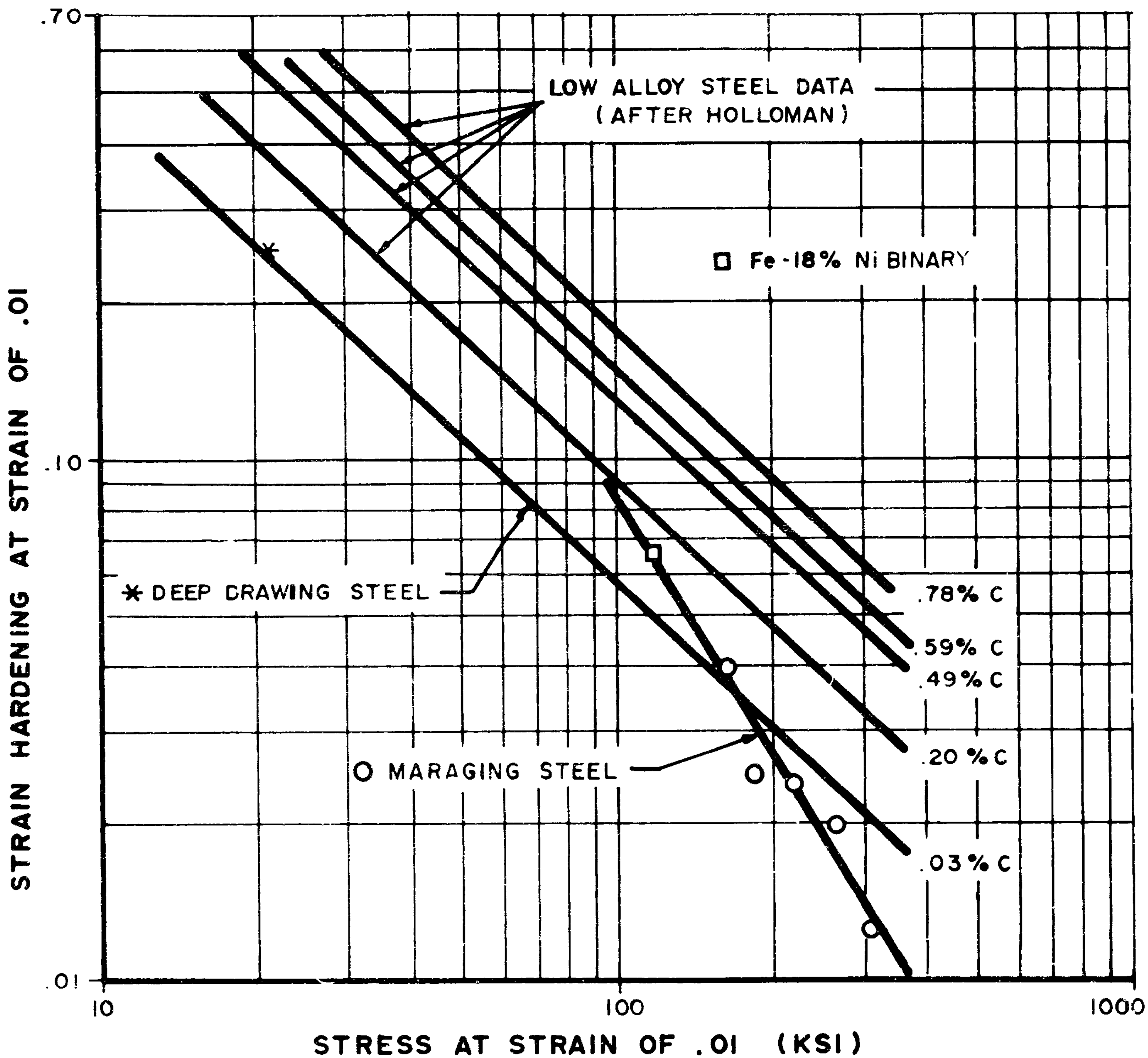


Figure 2. Comparing strain hardening exponents of maraging steels with other steels.

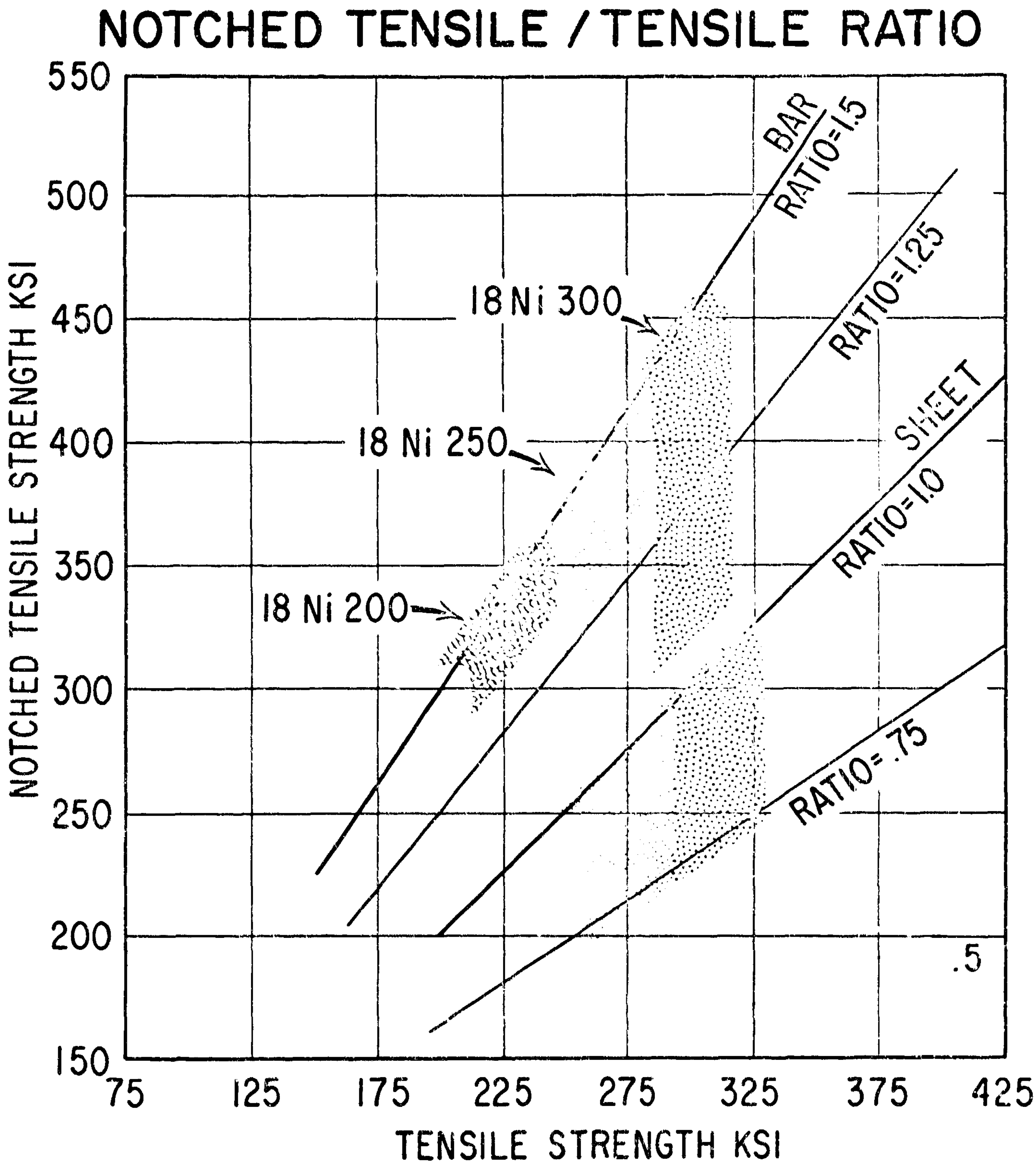


Figure 5. Notched tensile/tensile ratio.

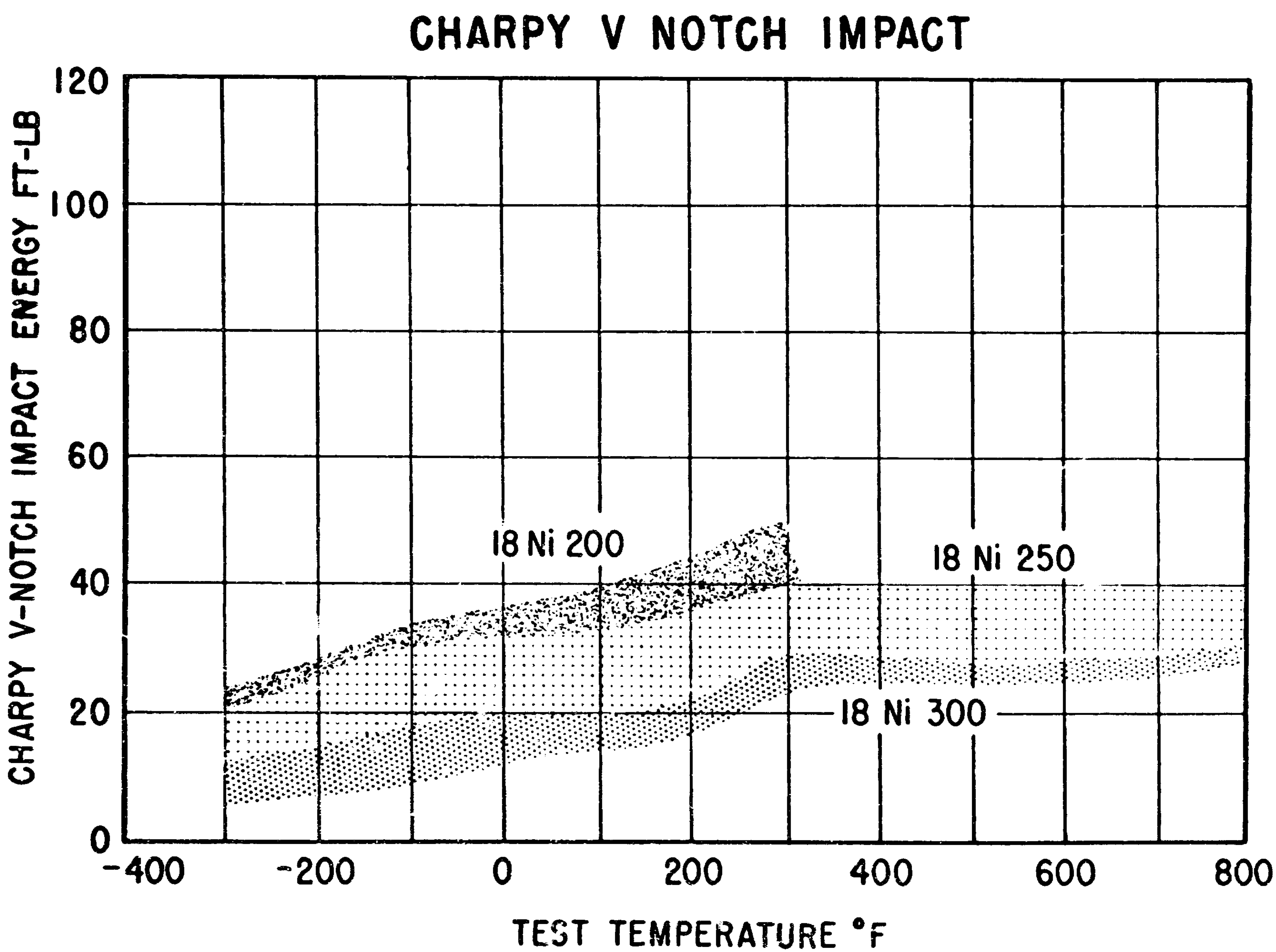


Figure 4. Charpy v notch impact.

ALLOY	YIELD STRENGTH KSI	K_{I_c} KSI in
18 Ni 200	200	100-160
18 Ni 250	250	90-150
18 Ni 300	280	80-130
D6AC	200	80-90
H - 11	260	60-65
AISI 4340	260	55-60
AMS 6430	220	55-65
Titanium-16V-2.5AI	170	45-50
Aluminum 7075.T6	60-70	35-60

Figure 5. Plain strain fracture toughness.

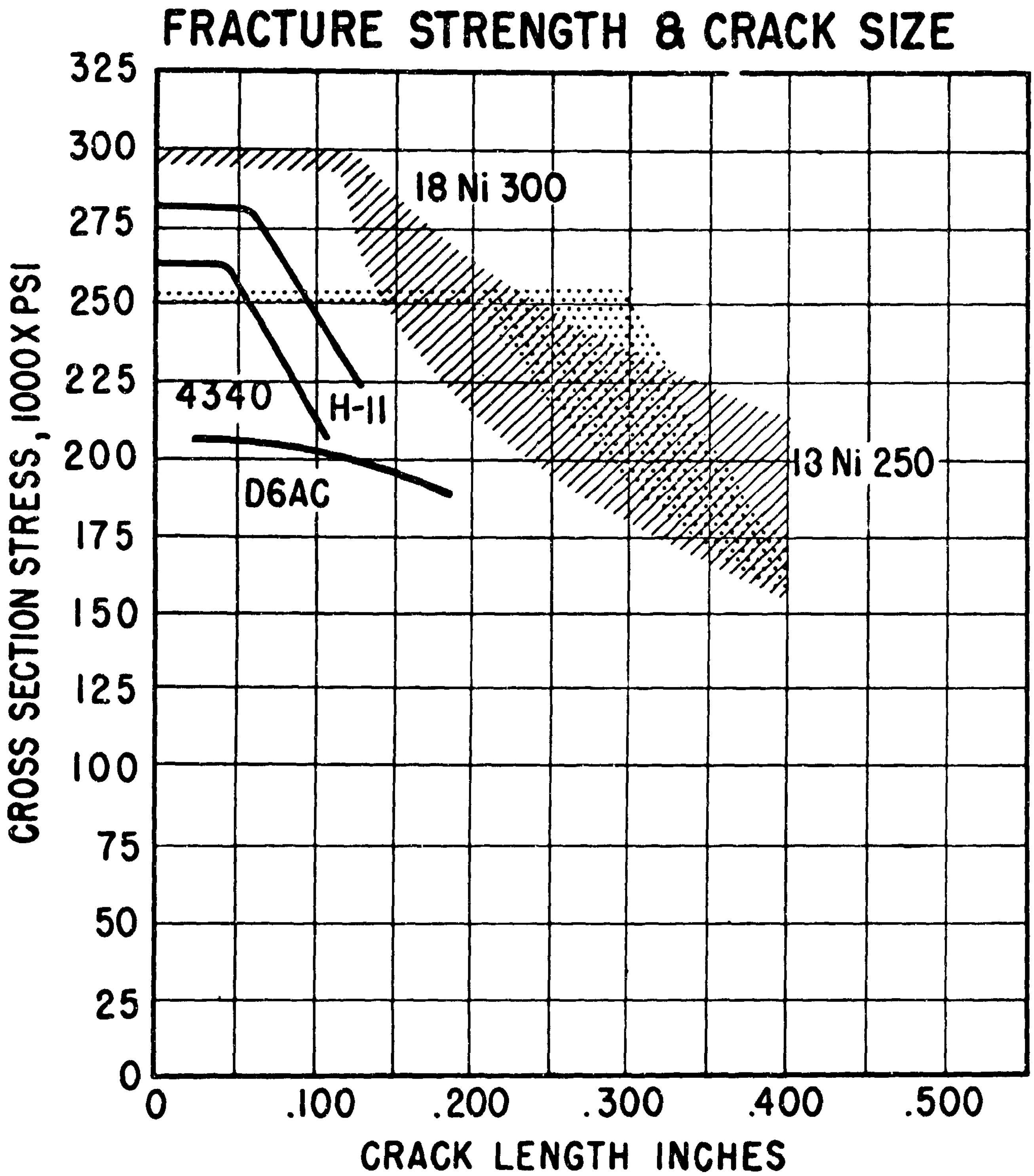


Figure 6. Fracture strength and crack size.

TYPICAL BURST TEST DATA FULL SCALE AND SUBSCALE

Material	Wall Thickness	Diameter of Case	Uniaxial UTS	Biaxial UTS	Burst Stress $\frac{Pr}{t}$	Biaxial Improvement In UTS
18 Ni 300	.144"/.148"	65.5"	296,000	-	342,000	16.0%
18 Ni 300	.090"	40"	290,000	-	342,000	17.0%
Forged, machined, cut and Welded 18 Ni 300	.070"	6"	284,000	327,000	335,000	16.2%
Forged and machined 18 Ni 300	.070"	6"	291,000	338,000	345,000	16.2%
Shear spun 18 Ni 300	.070"	6"	299,600	358,000	350,000	18.9%

Figure 7. Test data.

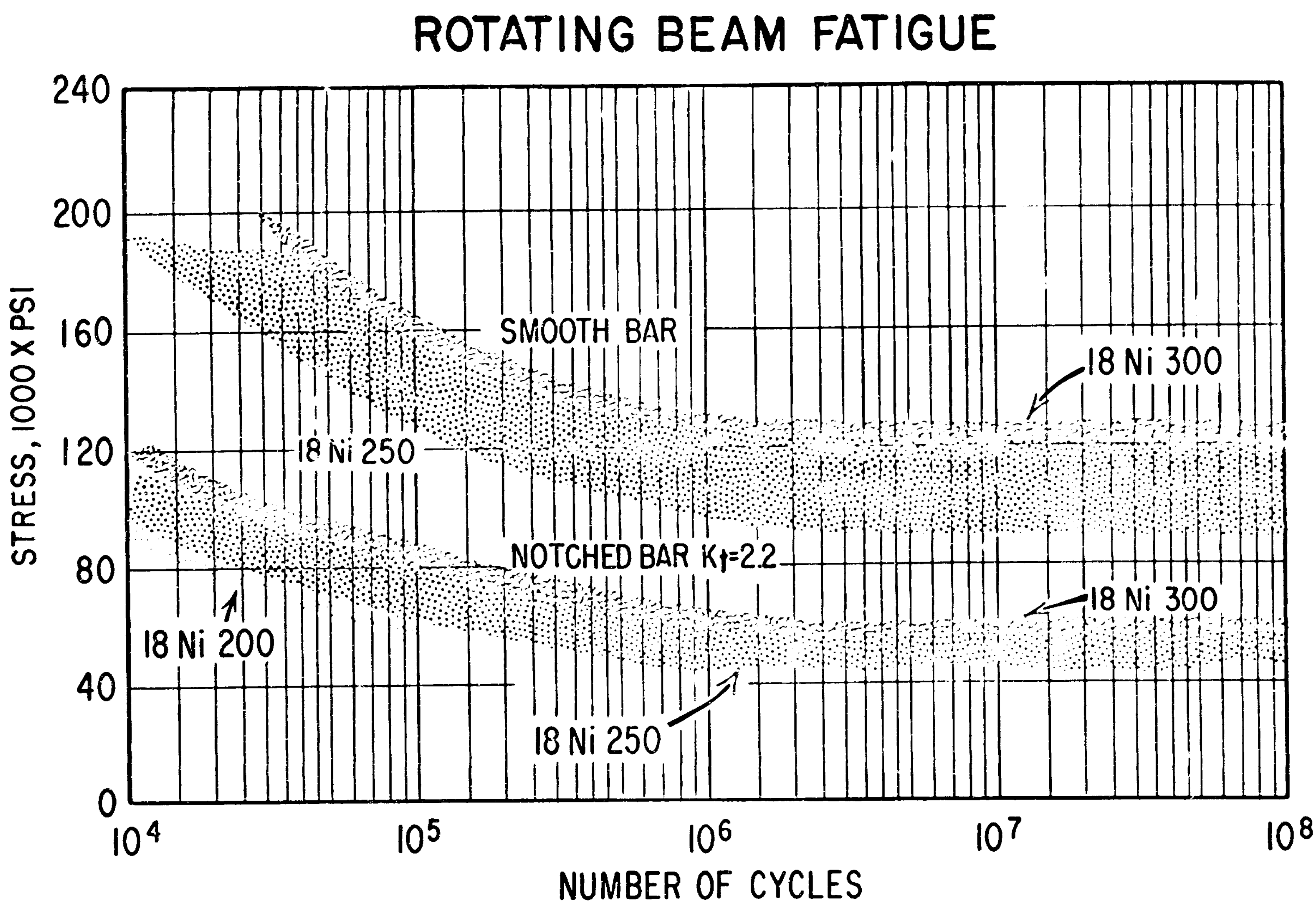


Figure 8. Rotating beam fatigue.

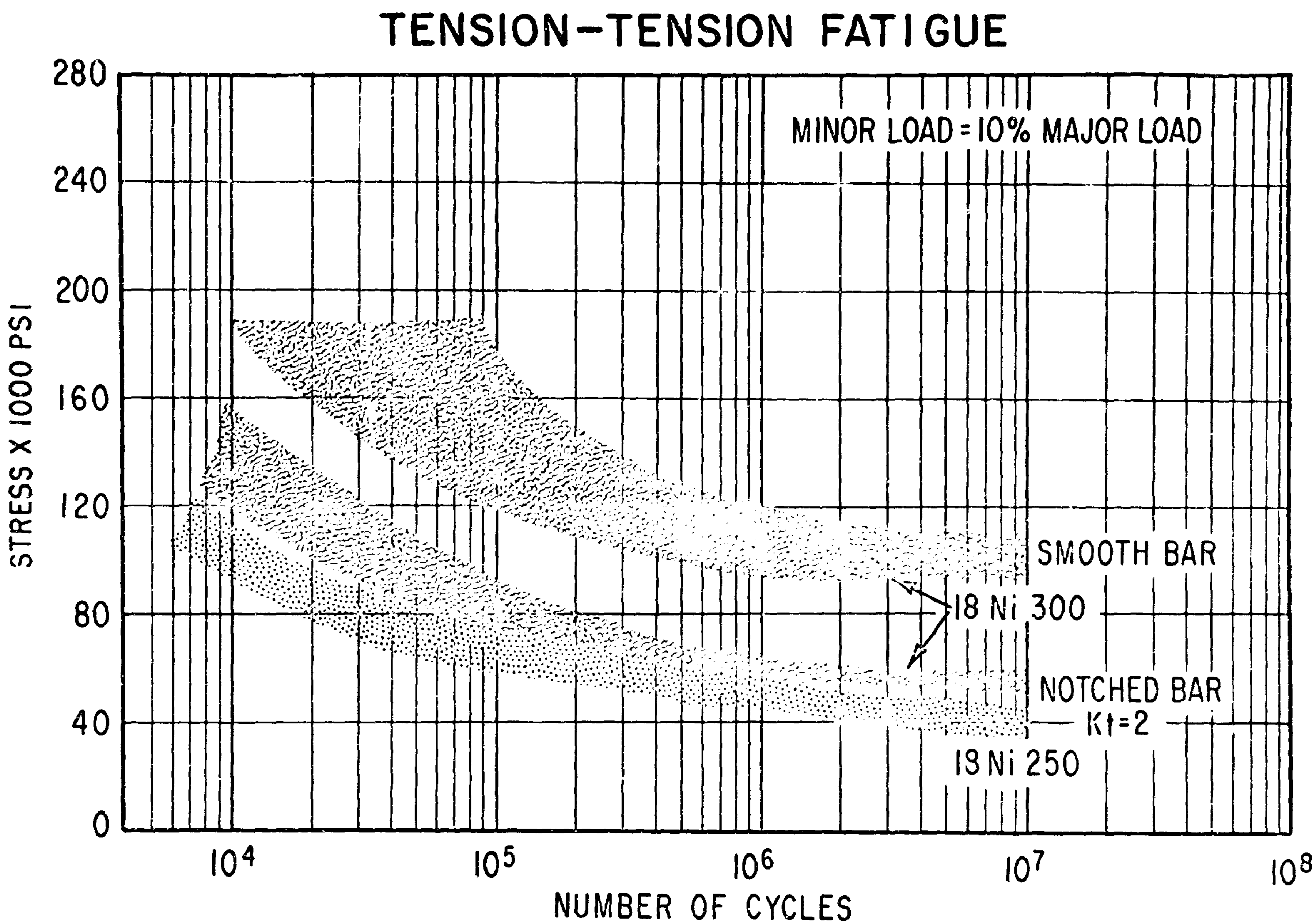


Figure 9. Tension fatigue.

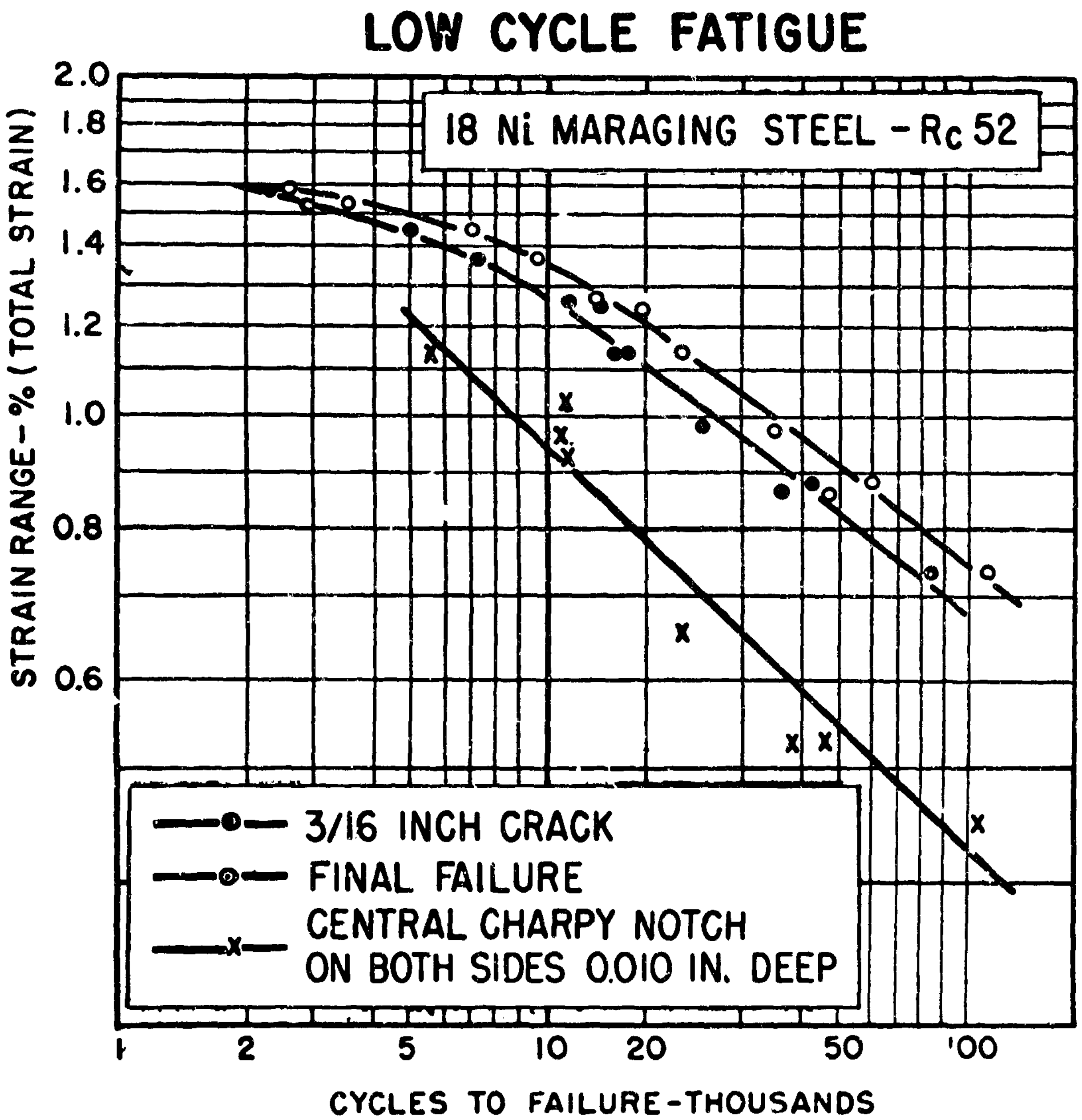


Figure 10. Low cycle fatigue.

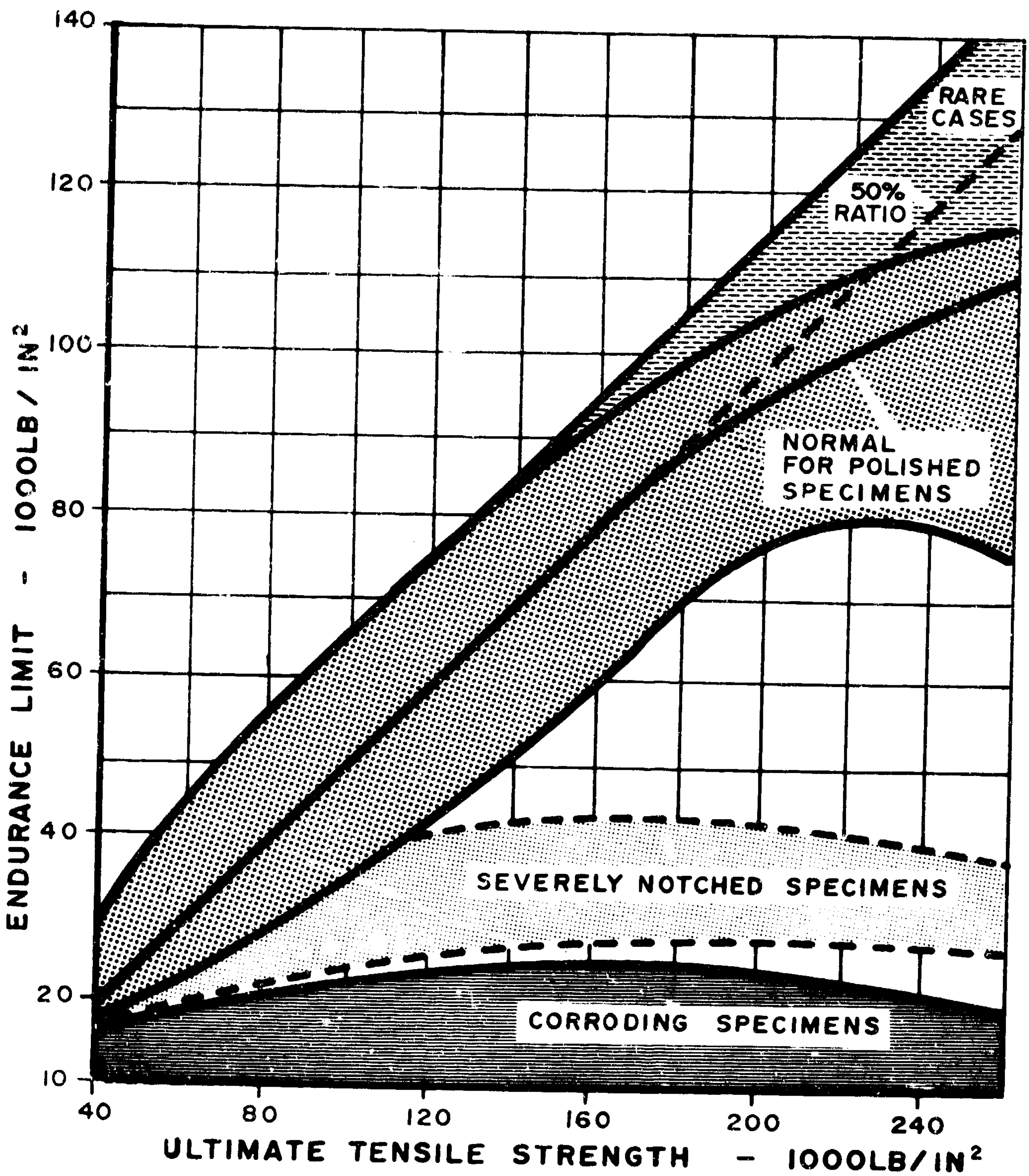
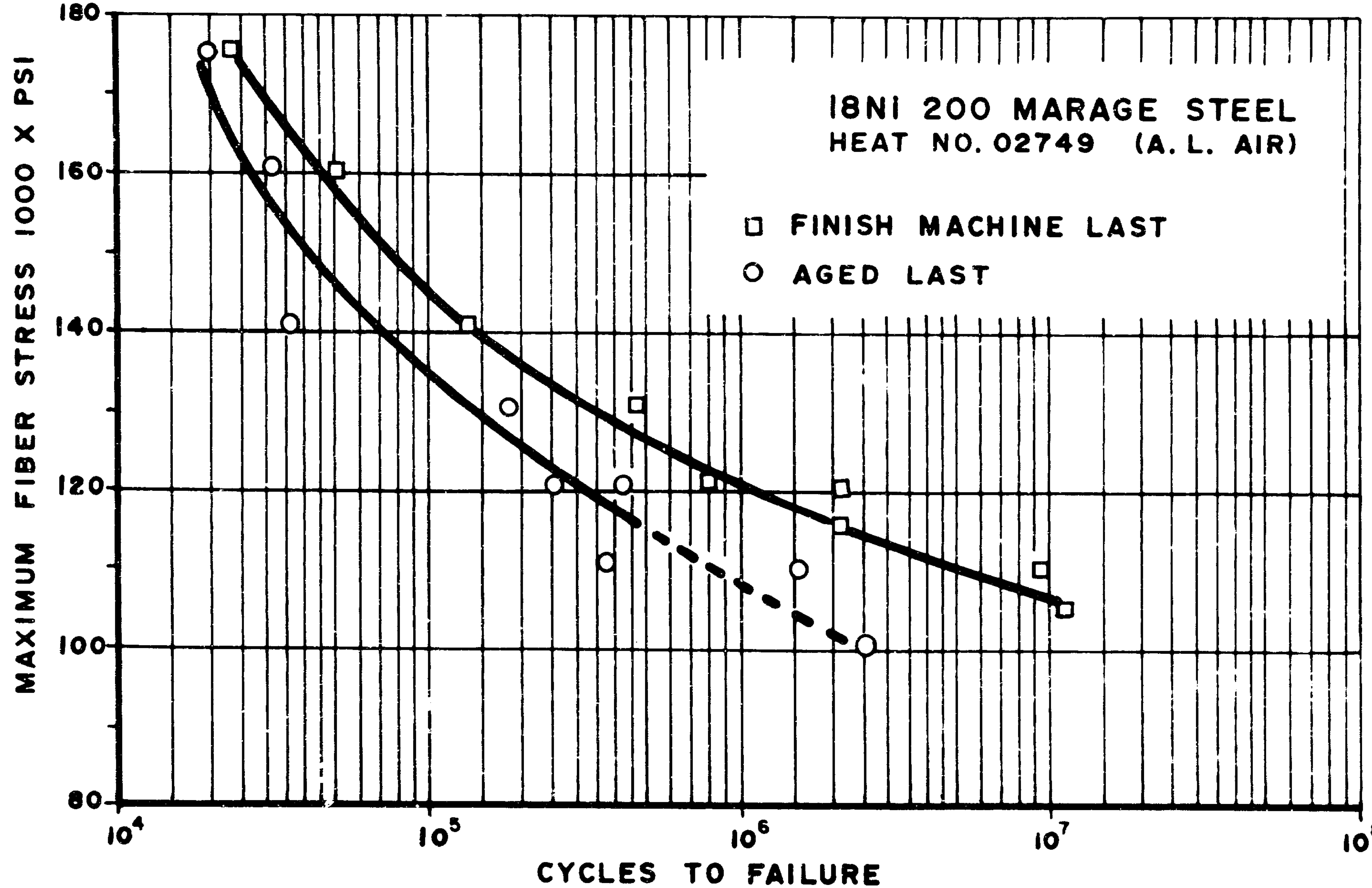


Figure 11. Endurance limit vs. tensile strength.



ROTATING BEAM METHOD

Figure 12. Effect of finish machine practice on fatigue life (single tool point).

E. Fowler: "MACHINING CHARACTERISTICS OF 18% NICKEL MARAGING STEEL"

The comments I will make relate to some work we did at Pratt-Whitney Company on machining the 250,000 tensile strength material, coupled with field experience on machining the maraging steels and other materials. Our determinations resulted in the fact that annealed and hot rolled material had essentially the same machinability. The material in the maraged condition, although of higher hardness, still has very excellent machinability in comparison with other materials.

Figure #1 is a tool life curve of the annealed material machined with various carbide tools. This was developed by machining approximately 26 square inches of material and determining tool wear. Here we see the type C50 carbide tool which is a 370 Carboloy tool, showing the highest tool life.

The next curve, Figure 2, shows the same thing for maraging material. The C2 grade 883 Carboloy, positive rake showed the least amount of flank wear. However, this was a positive rake tool and we chose to recommend the C70 or grade 350 negative rake because in general this would usually be used in the field for machining cuts greater than .100 inch deep and it would be more versatile.

Figure #3 is a tool life curve of machining the maraged material with single point lathe tools.

Figures #3 and #4 show the tool life for carbide tool materials as a function of cutting speed for the annealed and maraged materials. The annealed material gives considerably better tool life than does the aged material.

Figures #5 and #6 show the same type of tests conducted with high speed steel tools. The aged material gave somewhat lower life with these tools, also.

Figures #7 and #8 show the obtainable surface finishes on annealed and on maraged material at various feeds. Figure #9 shows the similar data for a reaming operation.

A compilation of data on various machining operations is included in the appendix.

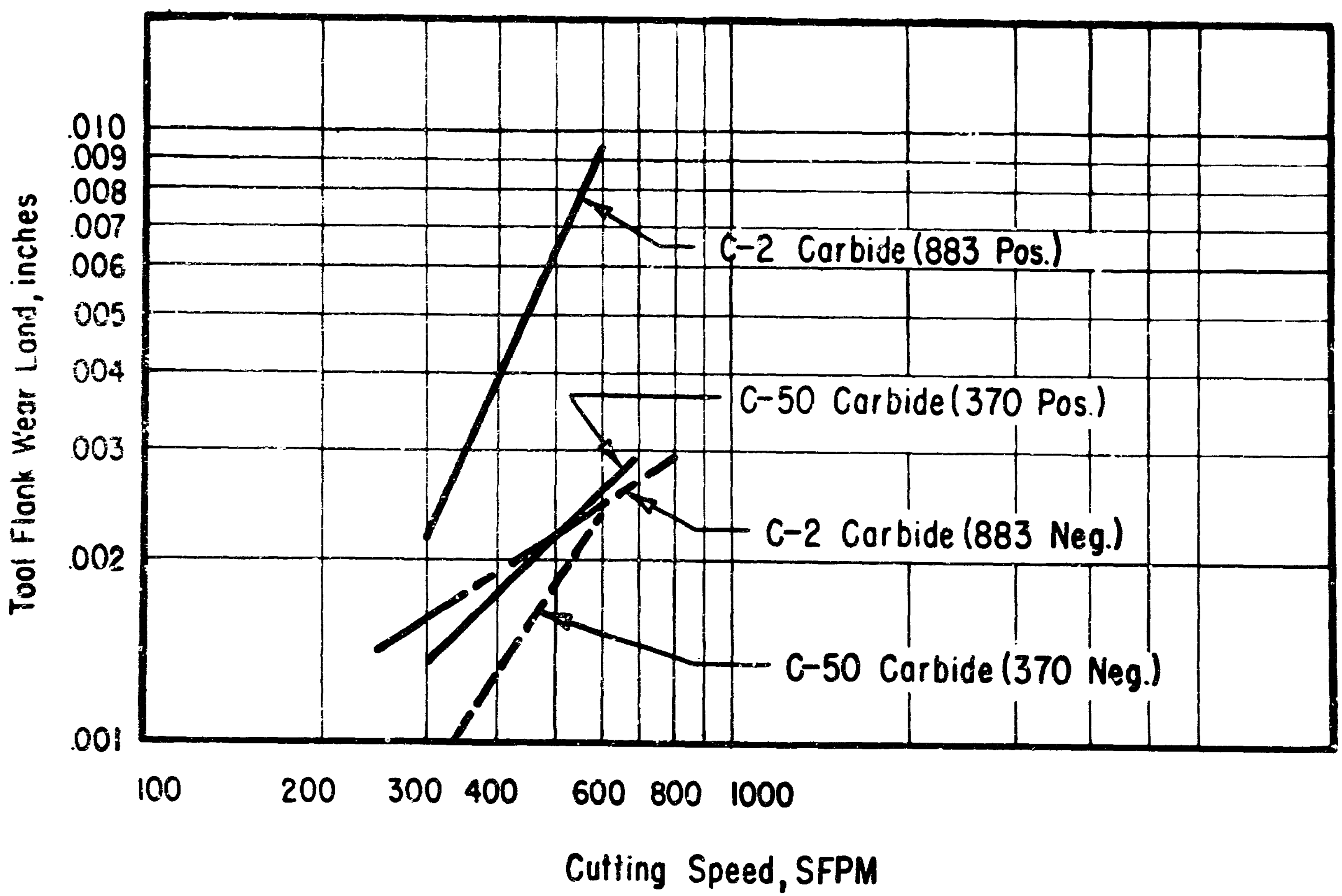


Figure 1. Annealed material, tool wear/cutting speed.

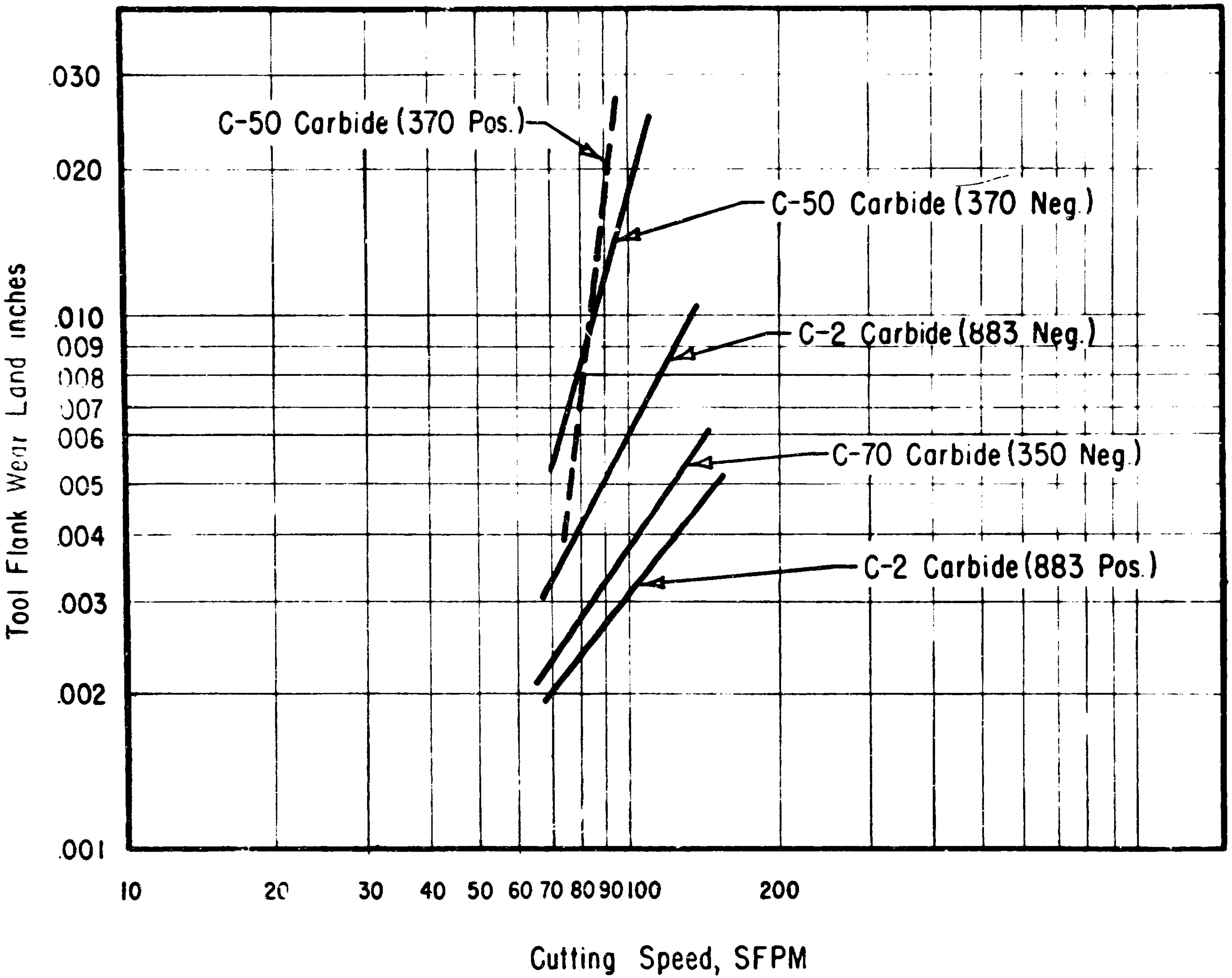


Figure 2 Maraged material, tool wear vs. cutting speed

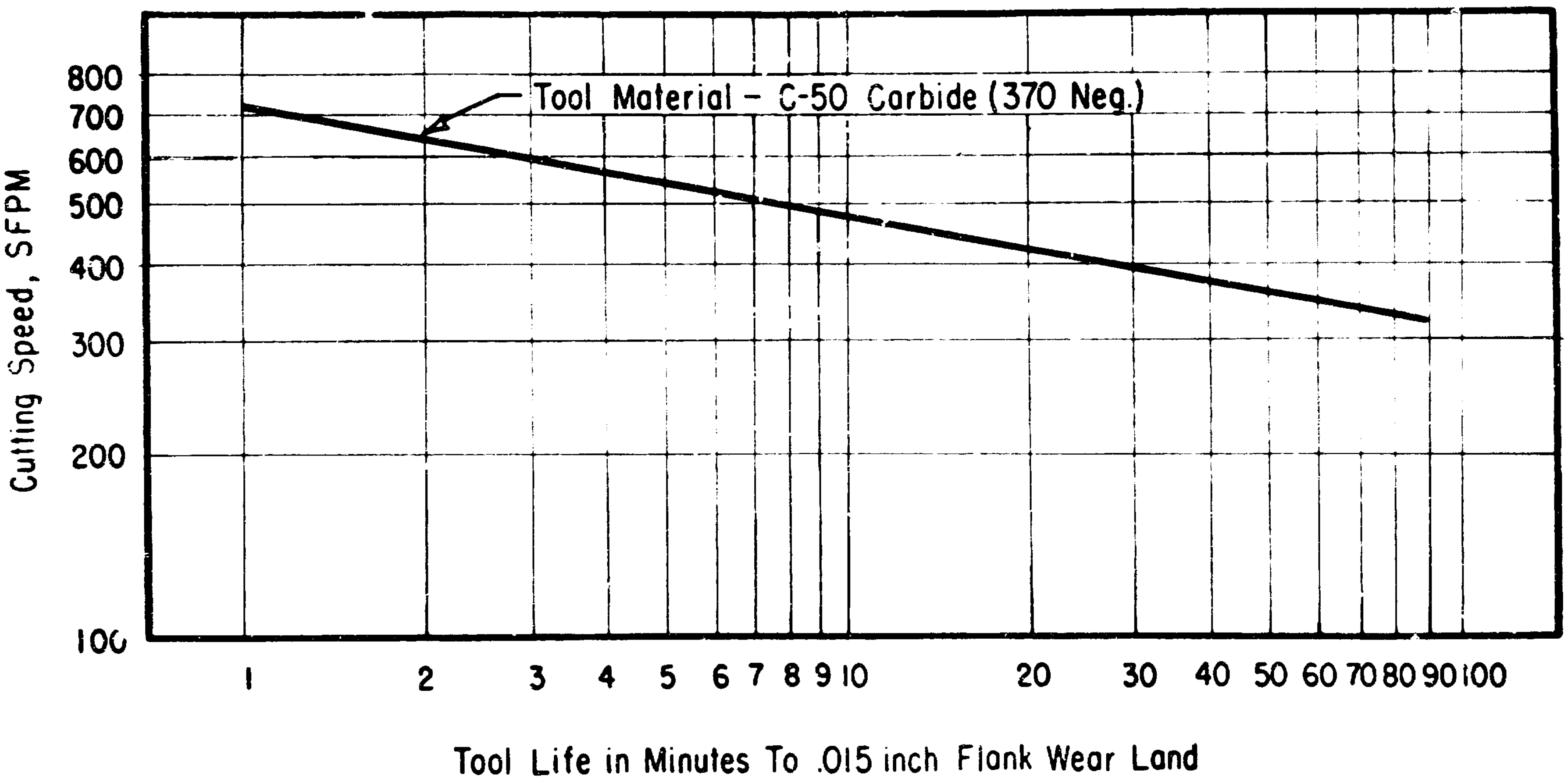


Figure 5. Annealed material, cutting speed vs. tool life.

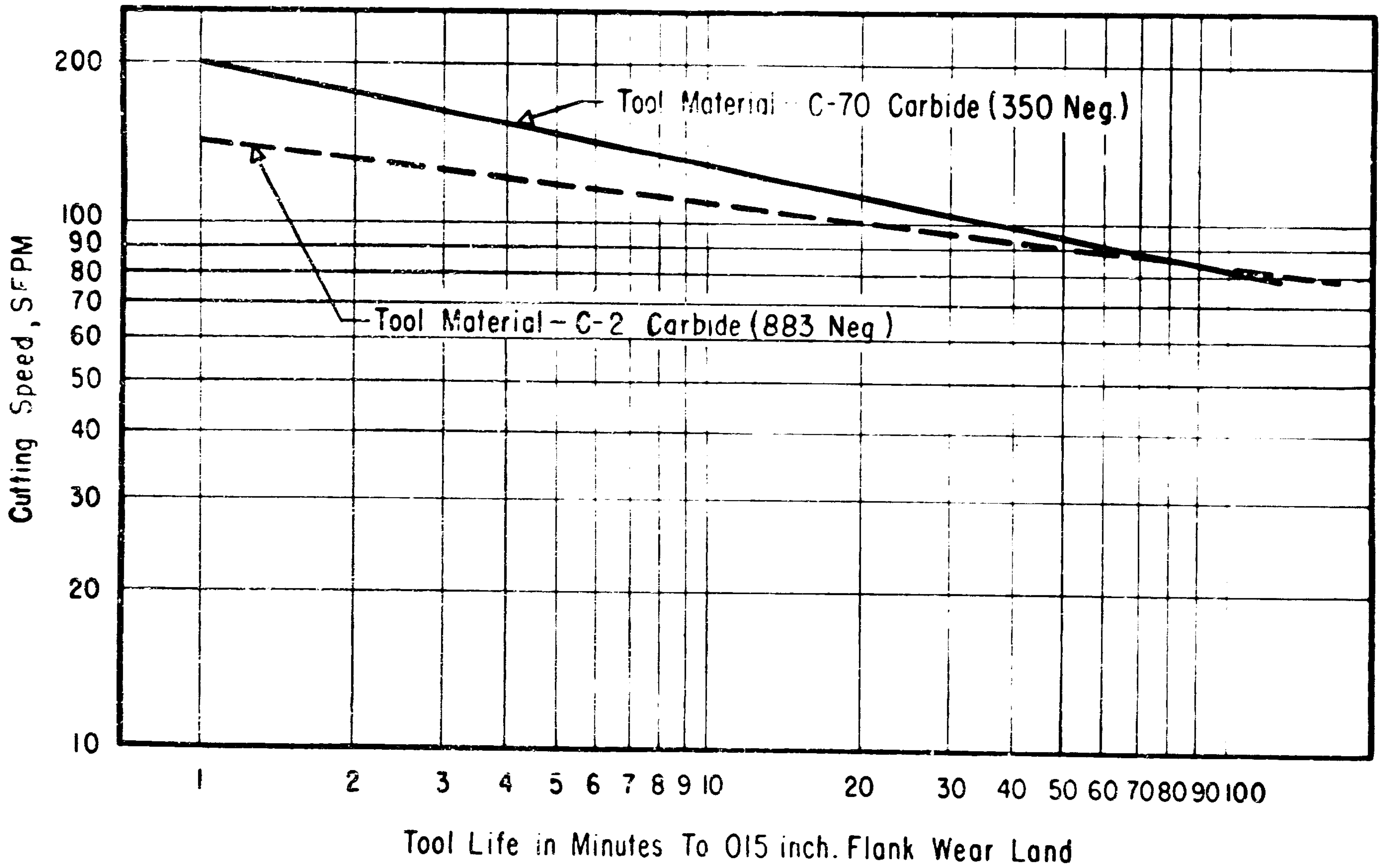


Figure 4. Maraged material, cutting speed vs. tool life.

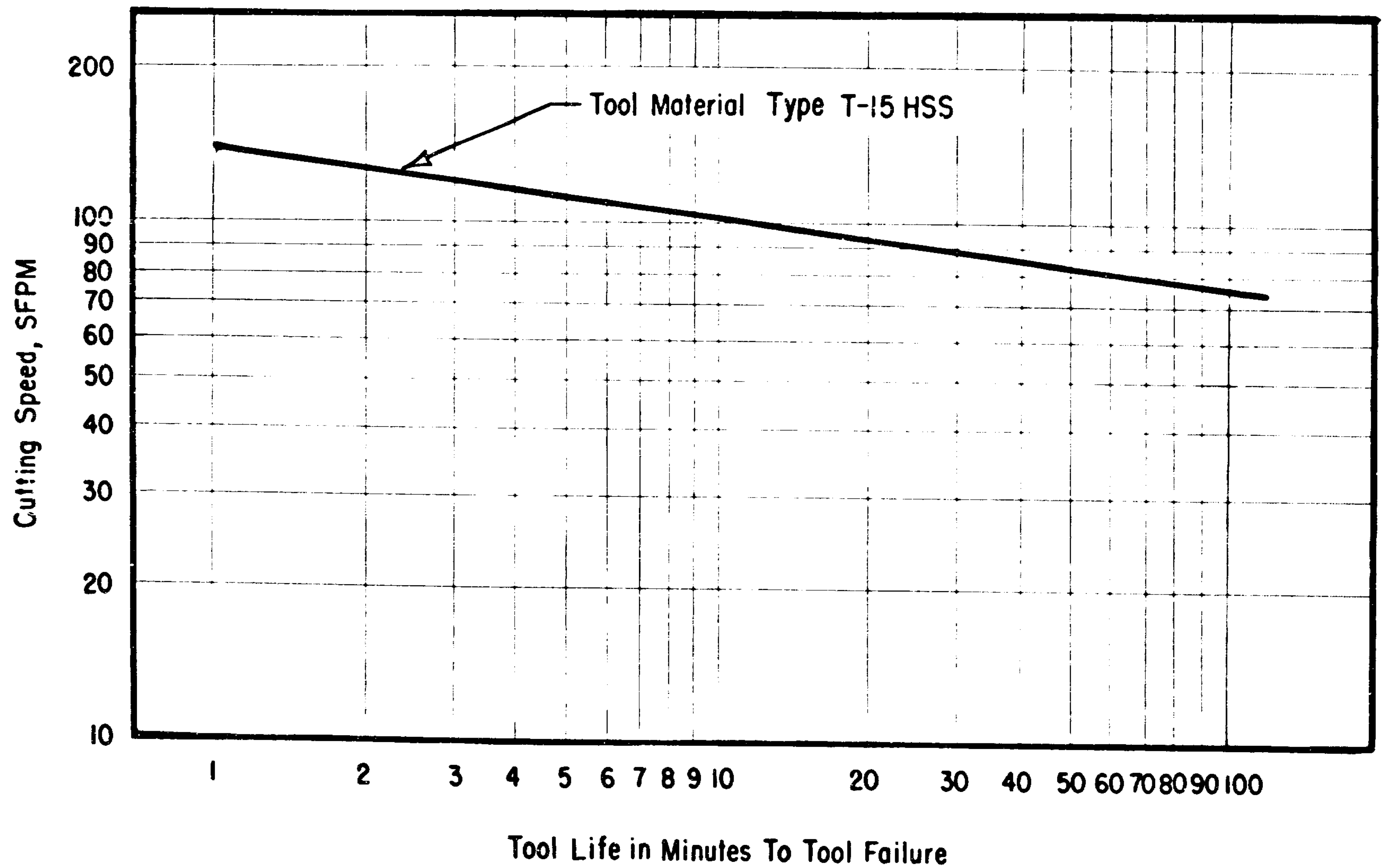


Figure 5. Annealed material, cutting speed vs. tool life.

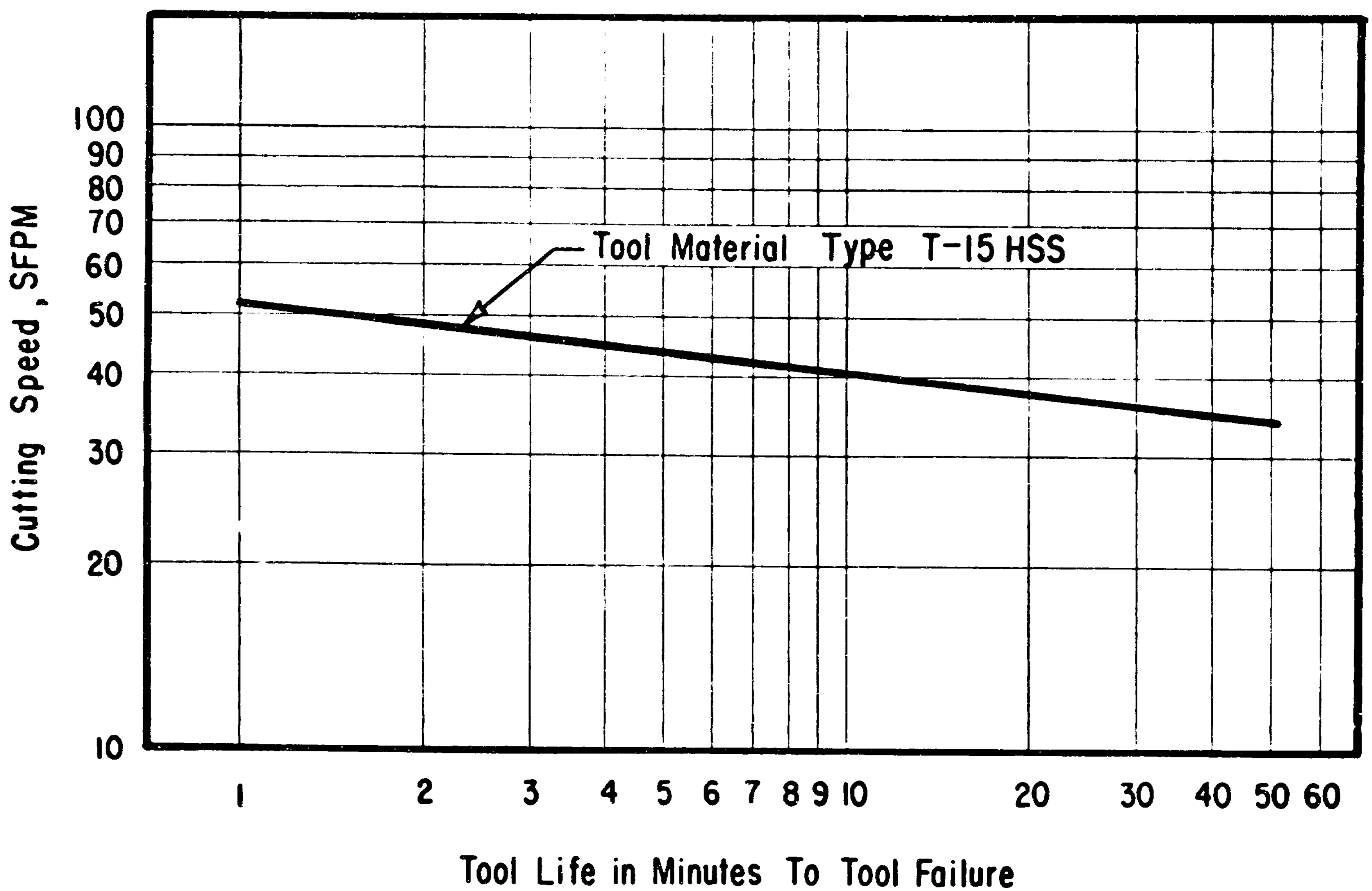


Figure 6. Maraged material, cutting speed vs. tool life.

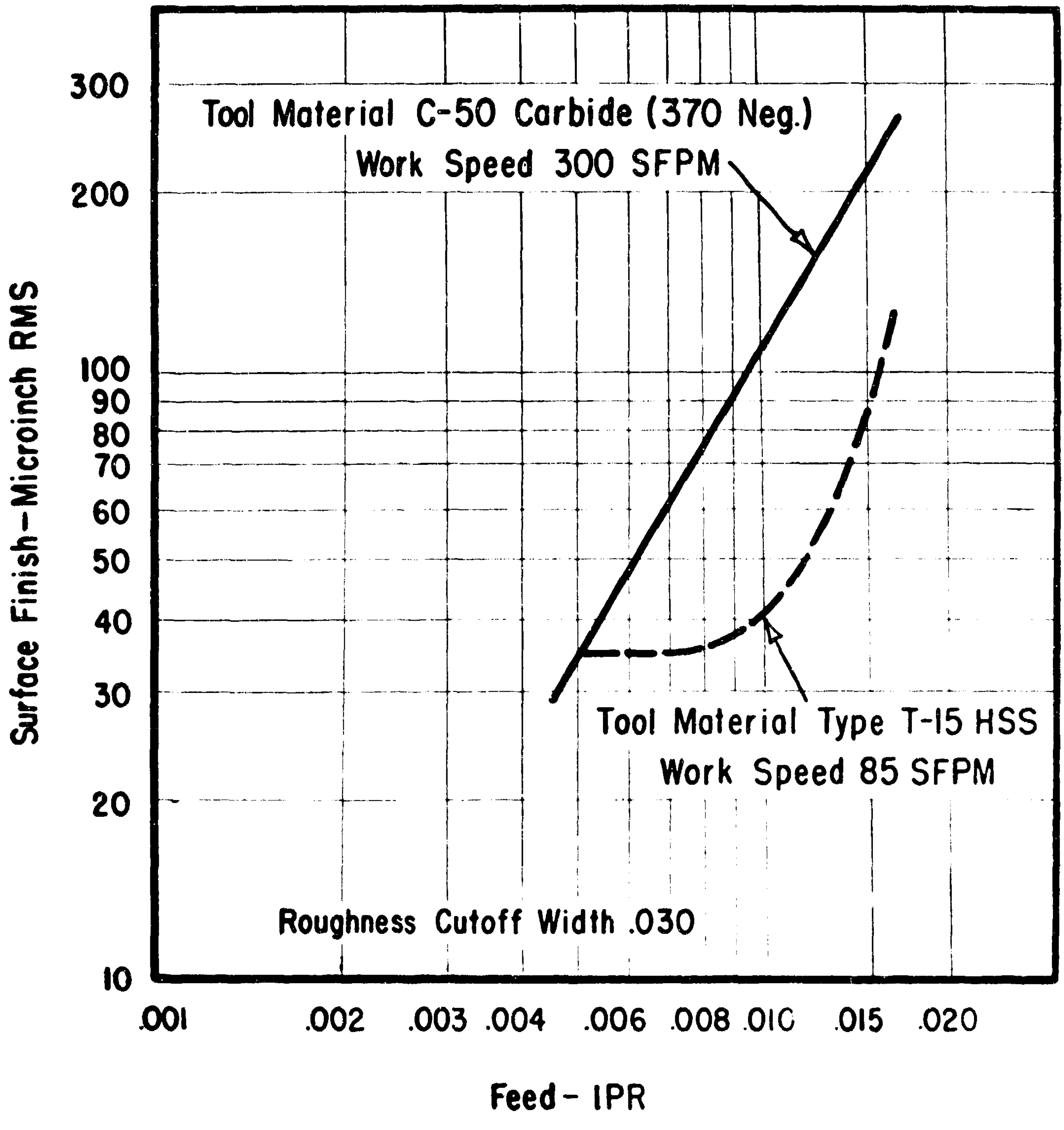


Figure 7. Finish single point turning, annealed material surface finish vs. feed.

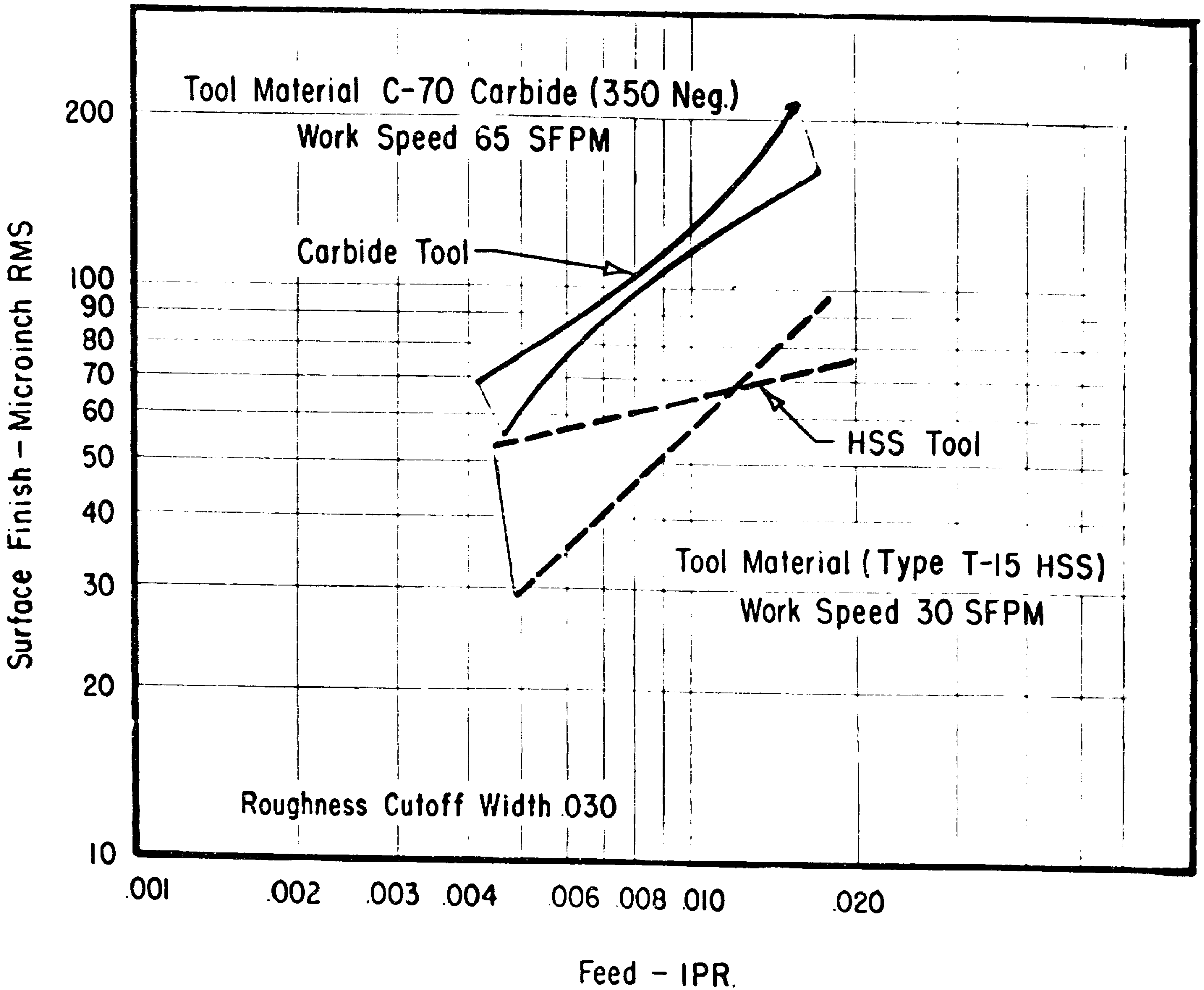


Figure 8. Maraged material, surface finish vs. feed finish single point turning.

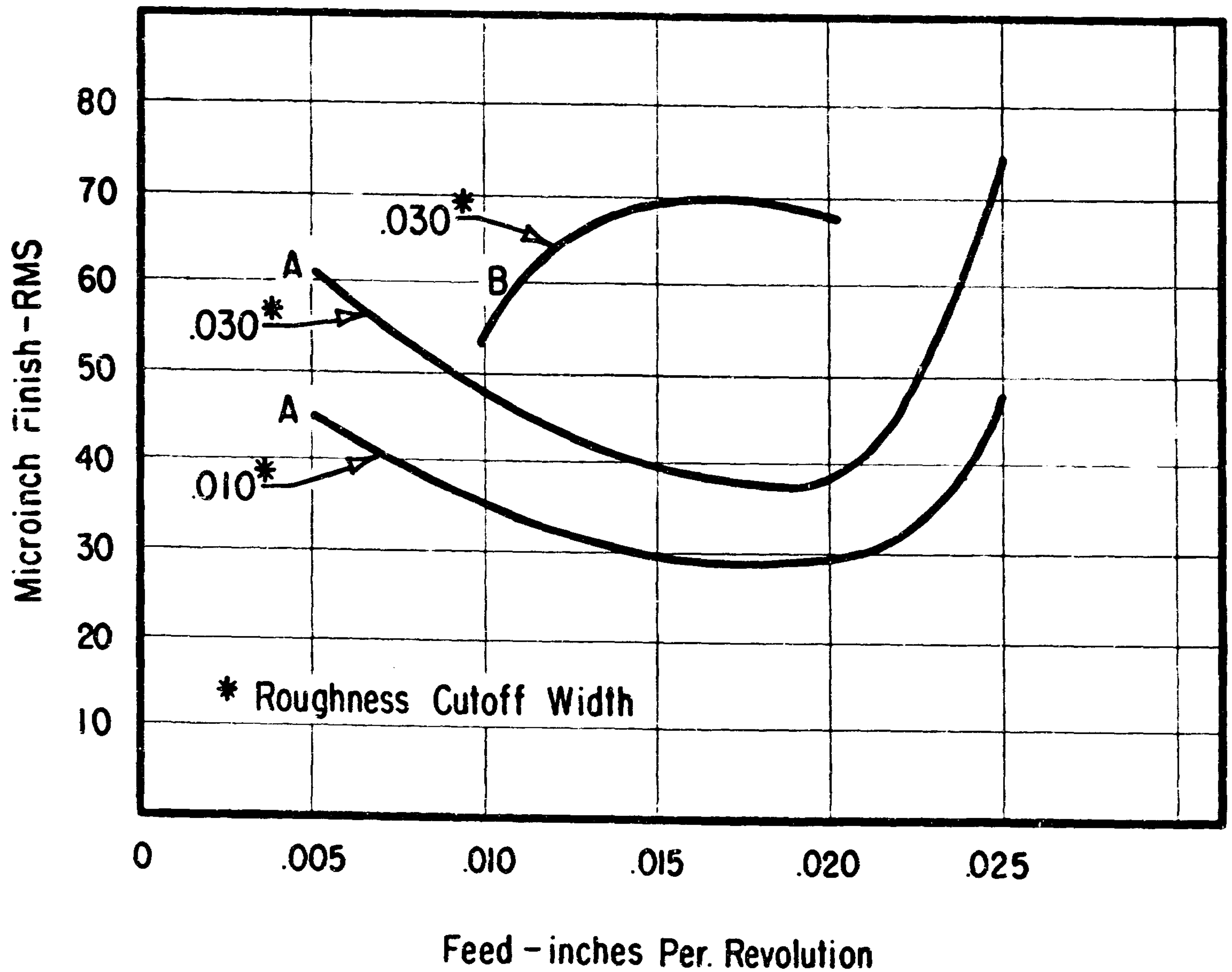


Figure 9. A. Hot rolled material.
B. Maraged material, finish vs. feed.

N. Matthews: "SUMMARY OF PRESENT STATUS OF MARAGING STEEL"

We recognize the problem that Watervliet deals mainly with heavy sections and that transverse properties are of primary importance. Since the beginning of the maraging steel commercial experience, we have recognized the tendency towards segregation and other phenomena that detract from transverse ductility in forging billets. As a result, there hasn't been much emphasis on forging applications.

There is, however, at Republic Steel Corporation, under Air Force sponsorship, a program to try to optimize processing methods to achieve maximum transverse ductility and toughness.

Republic Steel is well along in a program that will run close to two years in total duration. They are already in the large heat size. Reports are out on this. We expect within another two or three months, to obtain definitive data on the results of their most recent efforts by optimum control of heating and hot working processes to get good properties. We have heard qualitatively that they are getting very good results on both air melted and vacuum arc remelt product.

We know that other producers limited to air melt facilities are going to extremes in hot working procedures to try to break up the structure and achieve better properties. For example, the upsetting of ingots and the subsequent hot working through normal methods are being practiced. The value of that has been demonstrated. It is a possibility with a large diameter billet to upset the ingot, draw it out again, upset it again and so on. This is a way of getting hot work into the material which will certainly help transverse properties.

However, the embrittling phenomena can occur independently of hot working per se, so you must be careful. Temperatures used, cooling rates and other effects must be controlled to realize the maximum improvement from some extraordinary hot working process.

Another Government supported program is the Navy's program with U.S. Steel Corporation. Here the work is directed at a lower strength material for hull plate primarily and is not limited to maraging steels. In the maraging steel area, their efforts seem to be narrowing to the thorough investigation of a new alloy system that our laboratory pioneered for lower yield strength where an extreme amount of plastic deformation must be withstood without fracture. In other words, we are talking about a material at maximum yield strength that will give a minimum of perhaps 50 ft-lbs.

We have supplied quite a few small heats to the Navy from which they have drawn an expectancy curve that represents perhaps near optimum results. It is up to U.S. Steel to see if they can reproduce these results in products from large ingots. They undoubtedly will have their problems, such as we have encountered with the higher yield materials, as section size and ingot sizes increase.

From these two programs there will be a lot of information. This will ultimately become available to all producers and certainly should influence the understanding of the phenomena that are affecting properties in not only plate but also billet form.

INCO has a program at Brown University under Dr. Findlay to investigate biaxial fatigue in heavy wall cylinders. This work was directed primarily at commercial applications like high pressure polyethylene systems, but will be generally applicable to gun tube problems also. Wall ratios of 1 1/2" to 2 1/2" approximately will be involved. Initially, the work is being confined to 250 yield strength material. Ultimately it will be possible to factor in any other type of maraging steel that is of interest for high pressure autoclaves, gun tubes or other types of applications.

With respect to the howitzer application, we were dismayed at the results. I would say that the evidence we have to date would indicate that despite the fact that this material wasn't optimum, this is probably an application we'd have to think about before the arsenal invests any more money. I think there is something happening that we don't understand. Certainly the performance is very poor.

We talked a lot about fatigue today. Although the fatigue properties in maraging steels are not poor considering their yield and tensile strength, they certainly are not outstanding either. This whole subject is getting attention in our laboratory now. If we had to guess today we would suspect that we probably can't do too much about the work hardening exponent without damaging notch toughness or some of the other desirable characteristics.

In conclusion, I would like to say that we recognize that Watervliet has a unique problem in that you are only concerned with heavy sections. We think you will probably have to await further improvement of technology for the distribution of the optimization results that we hope will come out of the various programs. Until this knowledge becomes common to all the producers, there will always be a difference in capability among manufacturers.

D. Cassidy: "AVAILABILITY OF STRATEGIC MATERIALS IN MARAGING STEELS"

I have been asked to discuss the availability of nickel, Cobalt and molybdenum. Actually, when people ask you about availability, one of the easiest answers I think is to say that there is a stock pile of critical and strategic materials. There is also a continuous assessment by the experts that are running this thing, of the political situation, of what is to happen with regard to possible war and semi-war, and on these assessments are based the amount of materials in the stock pile, balanced against the needs.

I am not going to go much further than that. What I'll do briefly is list some figures that are given in the public press for these areas and will make very little other comment.

First, with regard to nickel, the present free world consumption amounts to approximately 525 million lbs. annually. Half of this consumption is in the United States, give or take a little, and half in all of the rest of the free world. Against this consumption, the present free world production capacity is listed at 640 million lbs. or some 150-120 million lbs. in excess of consumption. Of this total free world capacity, the capacity of North American Mines is 530 million lbs. or a little bit more than the entire free world requirement. All of these figures, of course, are for peacetime consumption and again, as I say, the critical and strategic stock pile is supposed to take care of other eventualities. The best figures we have for estimated nickel in the stock pile is 450 million lbs. or a little less than present peacetime free world supply.

The situation with Cobalt is similar. The present free world consumption of Cobalt is approximately 33 million lbs. Of this, the U. S. consumption runs about 9 million lbs. or slightly more than 25%. Against this consumption, the production in Katanga, Africa, largest single production area, is approximately 18 1/2 million lbs. or a little more than half of the present free world consumption. The present U. S. production is 2,600,000 lbs. and Canadian production is 3,400,000 lbs. Between them they produce 6 million lbs. or two-thirds of the U. S. consumption. In a marginal situation but available if needed, is a production capacity between the U. S. and Canada of 12 million lbs. which is more than one year's U. S. consumption and about one-third of the free world's supply. Probably because of the location of the major Cobalt producing areas overseas, it is estimated that the stock pile presently contains more than five years U. S. supply at the present rate or about two years supply for the free world. Just to sum it up, if the Katanga production were not available there is enough capacity in the U. S. and Canada to take care of U. S. consumption or one-third of the free world's consumption plus the stockpile back-up.

With molybdenum, I'm going to get even briefer. About all I can say is that the present free world consumption is approximately 77 million lbs. Production is pretty well balanced with consumption. There is a reserve and it should stay in balance. The U. S. produces 85% of the free world supply so in case of trouble the U. S. actually has 85% of the free world supply. There is also a stockpile of approximately one year's supply.

APPENDIX

MACHINING OPERATIONS

Cutting Lubricants

A copious, smooth flowing stream of cutting lubricant should be supplied to all machining operations making every effort to get the lubricant to the tool work cutting zone. Suggested cutting lubricants are noted below.

Operation	Cutting Lubricant*	
	High Speed Steel Tools	Cemented Carbide Tools
Rough Turning	1, 2, 3	3, 2, 1
Finish Turning	1, 2, 3	1, 2, 3
Rough Planing	2, 1	4
Finish Planing	1	4
Parting & Grooving	1, 2	4
Circular Sawing	1, 2	4
Power Hacksawing	2, 3	4
Drilling	1, 2, 3	4
Reaming	1	
Tapping	1	4
Milling	1, 2, 3	2, 3, 1

*1 - Chlorinated, sulfurized, fatty mineral and/or sperm oil.

2 - Rich solution of soluble oil and water, (15 parts water 1 part soluble oil).

3 - Chemical active water soluble oil.

4 - The type tools are not recommended for the indicated operation.

TURNING

Operating Speeds

Alloy Condition	Dimensions of Cut		Cutting Speed sfpm — Tool Material			
				Type Cemented Carbide		
	Depth inch	Feed ipr	HSS	883	370	350
Hot Worked or Annealed	.1	.01	80-95		350-400	
	.2	.01	70-85		300-370	
	.2	.018	55-65		260-325	
	.4	.01	60-75		265-320	
	.4	.018	50-60		220-260	
Maraged(1)	.1	.01	30-35	90-100		90-115

(1) Greater depth cut and feed are not generally recommended. However, where a chip of .002 inch cross-sectional area (feed X depth) is removed, reduce the cutting speed (sfpm) about 25%.

Cutting Tools

(a) HSS Types T-15, M-3 type 2, M-15 and M-34.

Tool Geometry

Hot Worked or Annealed Material:
0 to 5° BR, 10 to 15° SR, 15 to 20° SCEA, 5 to 7° ECEA, 5 to 7° Relief, 1/32" NR. Use a chip breaker.

Maraged Material:
Same as above except the back and side rake is on the order of 0 to 3°.

(b) Cemented Carbide

Type carbide as noted in Table of Operating Speeds. Use precision ground throw-away inserts of (-5°) back and side rakes; for light finish cuts on hot worked or annealed material positive rake inserts of (+5°) back and side rakes are satisfactory. Square or rectangular inserts are preferred. A chip breaker is essential; mechanical attached breakers are preferred.

Cutting Horsepower

The average unit horsepower for machining hot worked or annealed material is .8 hp/cu.in/min and for maraged material 1.3 hp/cu.in/min.

PLANING

Operating Speeds

Hot Worked or Annealed Material	-	Speed 40 to 50 fpm Feed - roughing .015", finishing to 3/16", parting to .008"
Maraged Material	-	Speed 25 fpm Feed - roughing .015", finishing to 3/16", parting to .004"

Cutting Tools

HSS Types T-15, M-2, M-35

Goose-neck type tools are suggested. Clapper boxes with return stroke lifting devices are recommended.

Tool Geometry

Hot Worked or Annealed Material:

Roughing: 8°BR, lip grind face of cutting edge to 30° hook, 35° lead angle, 3° side relief, 5° end relief, 1/16" NR.

OR

8° BR, 20° SR, 35° lead angle, 4° side relief, 7° end relief, 3/32" NR.

Finishing: 8° BR, cutting edge is inclined at an angle of 12 to 15° with line of travel of the work, 5° end relief.

Parting: Grind face to 25° hook angle, 6° axial side clearance, 4° side relief, 12° end relief, break corners.

Maraged Material:

Roughing: (-3°) BR, 6° SR, 35° lead angle, 2 to 4° side relief, 5° end relief, 1/16" NR.

Finishing: 3 to 5° BR, other angles are the same as for hot worked or annealed materials.

Parting: 3 to 5° BR, 4° axial side clearance, 3° side relief, 6° end relief, break corners.

DRILLING

Drilling Feeds and Speeds

Material Condition	DRILL SPEED[1]					
	fpm	Feed (ipr) for Drill Size				
		1/8"	1/4"	1/2"	3/4"	1"
Hot worked	60 to 70	.0015	.0025	.006	.011	.012
Annealed	65 to 85	.0015	.0025	.006	.011	.012
Maraged	20 to 25	.001	.002	.005	.005	.009

(1) Operate drills below ¼ inch diameter at or 20% below the cited minimum speeds.

Suggested Decrease in Speed[1] And Feed for Depth of Drilled Hole to Drill Diameter

Depth Hole	PER CENT REDUCTION IN SPEED	
	fpm	feed (ipr)
3 times drill diameter	10	10
4 times drill diameter	20	10
5 times drill diameter	30	20
6 to 8 times drill diameter	40	20

(1) When drilling holes to a depth of 3 or more drill diameters retract the drill from the hole after its initial penetration of 2 drill diameters and one drill diameter penetration thereafter.

Type of Drills

Standard helical drills of T-15, M-2 or M-33 H.S.S. The preferred drills are those having surface treatment to improve their resistance to wear and abrasion.

Drill Grinds

118-120° included point angle for material in all conditions. Thin the web of the drill at the chisel point 40 to 50% of its original thickness, 120-135° chisel edge angle, 9-12° lip clearance.

A notch or crankshaft grind of 135° included point angle, 115 to 125° chisel edge angle, 9° lip clearance can be used with maraged material.

DRILLING HORSEPOWER

Condition of Material	Drill Diam. inch	Cutting Speed (sfpm.)	Feed ipr	Hp/cu.in./min
Hot Worked	3/8	68	.005	3.4
" "	3/8	86	.005	3.0
Annealed	3/8	86	.005	2.7
Maraged	3/8	27	.005	3.8
Hot Worked	3/4	67	.011	1.4
Annealed	3/4	67	.011	1.4
Maraged	3/4	23	.005	3.8

REAMING

Reaming Speed

Hot Worked or Annealed Material	- HSS Reamers: Speed 40 to 55 sfpm. Feed is 1-½ to 2 times that of the size drill corresponding to the size reamer. Carbide Reamers: Speed 70 to 100 sfpm. Feed is same as for HSS reamers.
Maraged Material	- HSS Reamers: Speed 15 to 25 sfpm. Feed is 1 to 1½ times that of the size drill corresponding to the size reamer. Carbide Reamers: Speed 25 to 50 sfpm. Feed is same as for HSS reamers.

Cutting Tools

HSS	- Tungsten or Molybdenum high speed steels having a surface treatment to improve their resistance to wear and abrasion are preferred.
Cemented Carbide	- Type 370 carbide is used with hot worked or annealed materials. Type 883 or 350 carbide is used with maraged material.

Reamer Geometry

End cutting, straight fluted reamers are preferred for reaming straight, non-interrupted holes.

End cutting, spiral fluted reamers with the hand of spiral opposite to the hand of cut are satisfactory for reaming interrupted cuts.

Spiral fluted reamers with the hand of spiral opposite to the hand of cut are suggested for reaming tapered holes.

Suggested Geometry For HSS And Carbide
End-Cutting Straight And Spiral Fluted Reamers*

Radial+ Rake Angle deg.	Chamfer		Circular Margin		Land	
	Angle, deg.	Relief,++ deg.	Reamer Dia, in.	Width in.	Reamer Dia, in.	Relief, deg.
0 to 5°	45	20 to 10 10 to 8 8 to 6	to 1/2 $\frac{1}{2}$ to 1 $1\frac{1}{2}$ to 2	.004 to .010 .010 to .015 .015 to .020	to 1/2 $\frac{1}{2}$ to 1 $1\frac{1}{2}$ to 2	20 to 10 10 to 8 8 to 6

*Manufacturers' standard back taper.
+Use 0° with cemented carbide and spiral fluted reamers.
++Secondary relief equals primary relief plus 15 to 6°.

TAPPING

Percentage of Thread Tapped

Threads may be tapped in hot worked or annealed materials to 70-75% of full depth.

Difficulties are encountered when endeavoring to tap threads in maraged material to more than 50-55% of full depth.

Tapping Speed

Hot Worked or Annealed Material	-	Speed 15 sfpm.
Maraged Material	-	Speed 7 sfpm.

Type of Taps

High speed steel straight fluted, ground thread taps having a surface treatment to improve their resistance to wear and abrasion are generally preferred.

Helical fluted taps are advantageous for tapping deep blind holes. The spiral or helix of such taps should be opposite to the hand of the tap.

Hot Worked or Annealed Material:
Machine or Hand Tapping
Spiral pointed taps are preferred for machine tapping through holes.
Conventional chamfered plug taps are satisfactory for tapping bottoming holes.
Serial hand taps are likewise satisfactory.
Interrupted thread taps are satisfactory.

Maraged Material:
Machine or Hand Tapping
Conventional chamfered plug taps are preferred for machine tapping.
Interrupted thread taps are satisfactory.
Serial hand taps are satisfactory.
Conventional taper, plug and bottoming taps are likewise suitable.

Suggested Tap Geometries[1]

Condition of Material	Rake Angle, deg.	Chamfer[2] Angle, deg	Chamfer Relief Angle, deg	Land Relief	Spiral Point Angle, deg
Hot Worked or Annealed	6 to 8	10 to 12	4 to 6	Concentric[3]	12 to 20
Maraged	2 to 4	4 to 6	3 to 5	Eccentric[4]	—

(1) Manufacturers' standard back taper.
(2) Proportion chamfer angle and number of flutes so the chip load per tooth is not more than .004 inch on hot worked and annealed materials and .0015 to .002 inch on maraged material.
(3) Concentric taps are suitable to 3/8 inch diameter.
(4) Grind may be full eccentric at pitch diameter and concentric on major diameter with somewhat increased back taper.

MILLING

Operating Speeds

Alloy Condition	Operating Speed	TYPE OF MILLING				
		Plain	Face		Slotting and End(1)	
		HSS	HSS	C-C	HSS	C-C
Hot Worked or Annealed	Cutter, sfpm. Feed per cutter tooth, inch	60-70 .002-.004	60-80 .003-.004	275-325 .005-.008	50-80 .001-.003	175-250 .001-.004
Maraged	Cutter, sfpm. Feed per cutter tooth, inch	Not recommended	15-25 .003	60-80 .005	15-25 .0005-.002	50-70 .0007-.002

(1) The minimum speeds and feeds are intended for narrow slotting cutters and end mills.

Cutting Tools

HSS types T-15 and M-3 type 2 are suggested for all type milling operations.

Cemented carbides designated 370 are suggested for face milling and those designated 883 for slotting and end milling the alloy in all conditions.

Tool Geometries

Plain Milling

Hot worked or annealed material.
HSS heavy duty plain milling cutters.
Radial rake 8 to 12°
Clearance angle; 4° sufficient on cutters above 3 inch diameter; somewhat larger clearance is necessary on smaller diameter cutters.
Helix angle, 25 to 40°.

FACE MILLING CUTTERS

Designation of Cutting Angle	CUTTING ANGLE IN DEG.			
	Hot Worked or Annealed Material		Maraged Material	
	HSS Tool	C-C Tool	HSS Tool	C-C Tool
Axial rake	5 to 8	0 to -7	0	-5 to -7
Radial rake	5 to 8	-10	0	-10 to -15
Chamfer angle	45	45	45	45
Face cutting edge angle	4 max.	4 max.	3 max.	3 max.
Face relief	4 to 6	4 to 6	4	4
Peripherial relief	4 to 6	4 to 6	4	4

SLOTTING CUTTERS(1)

Designation of Cutting Angle	CUTTING ANGLE IN DEG.			
	Hot Worked or Annealed Material		Maraged Material	
	HSS Tool	C-C Tool	HSS Tool	C-C Tool
Radial rake	5	0	0	0 to -5
Side reliefs	3 to 5	3 to 5	3	3
Peripherial clearance(2)	4 to 5	3 to 4	3 to 4	3 to 4

(1) Staggered tooth cutters with alternate teeth of opposite helix are quite satisfactory.

(2) Clearances noted are for cutters above 1 inch diameter. Larger clearances are required for smaller diameter cutters.

END MILLS

When profiling with the periphery of the cutter use a cutter of right hand cut and right hand helix or left hand cut and left hand helix.

When milling slots where the end of the cutter is in contact with the work use a cutter with hand of cut the same as the hand of helix such as right hand cut and right hand helix.

END MILLING CUTTERS

Designation of Cutting Angle	CUTTING ANGLE IN DEG.			
	Hot Worked or Annealed Material		Maraged Material	
	HSS Tool	C-C Tool	HSS Tool	C-C Tool
Helix angle	25 to 35	25 to 35	25 to 35	25 to 35
Radial rake	8 to 10	0	0 to 3	0
Face cutting edge angle	3 to 4	3	3	3
Flute corner angle	45	45	45	45
Face relief	5	4	3 to 4	3 to 4
Peripherial relief (1)	4 to 5	4 to 5	4 to 5	4 to 5

(1) Clearances noted are for cutters above 1 inch diameter. Larger clearances are required for smaller diameter cutters.

SAWING

Circular Sawing

Operating Speed

Hot Worked or Annealed Material	-	Saw Speed 60 to 70 sfpm; Feed .001 to .002 in. per saw tooth

Cutting Tool

HSS is recommended.

Type Saw

High and low set insert teeth.

Tooth Grind

20° face hook, 3° axial side clearance, 3° side relief, 9° peripherial clearance on large diameter saws. Larger clearance on saws below 6 inch diameter, break corners on the teeth of low set teeth, 30° chamfer on sides of high set teeth.

Maraged Material	-	Not recommended for sawing.

Power Hacksawing

Operating Speed

Hot Worked or Annealed Material	-	Speed - 90 strokes per minute. Feed - positive medium pressure

Cutting Tool

Saw Blade - HSS of heavy construction, milled raker set teeth, 4 to 6 teeth per inch for heavy work, 10 to 14 teeth per inch for sawing medium to light sections.

Maraged Material	-	Not recommended for sawing.

GRINDING

Grinding determinations made by Norton Company, Worcester, Massachusetts reveal that the 18 per cent nickel maraging steel grinds essentially the same as ordinary constructional steels when using a heavy duty water soluble grinding fluid as employed with the stainless steels. It is essential to use the heavy duty grinding fluid as wheel wear is about ten times greater with an ordinary water soluble oil.

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