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TECHNICAL NOTE 2862

INFLUENCE OF NONMARTENSITIC TRANSFORMATION PRODUCTS ON MECHANICAL PROPERTIES OF TEMPERED MARTENSITE

By J. M. Hodge and W. T. Lankford

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SUMMARY

The influence of nonmartensitic transformation products on the mechanical properties of tempered martensite is presented for samples of an SAE 4340 steel, partially isothermally transformed to specific high-temperature transformation products and quenched and tempered to hardness values of from 25 to 40 Rockwell C. The effects of upper bainite in amounts of 1, 5, 10, 20, and 50 percent, of 5 percent ferrite, and of 5 percent pearlite on the tensile, impact, and fatigue properties are evaluated.

INTRODUCTION

This study was undertaken to evaluate the influence of the presence of definite percentages of specific high-temperature transformation products on the mechanical properties of tempered martensite. Such information is obviously desirable in order to apply intelligently the results of hardenability measurements to the selection of steels for specific purposes. Although the results obtained are in terms of transformation products formed isothermally, it is believed that they can be applied to the mixed microstructures ordinarily obtained on continuous cooling, since the general nature of the nonmartensitic products obtained in such cases will usually be known.

This investigation was sponsored by the Chrysler Steel Standardization Committee which consists of the following men: M. F. Garwood, Chairman, Chrysler Corp.; M. W. Dalrymple, Bethlehem Steel Corp.; M. J. Day, United States Steel Corp.; M. Grossmann, United States Steel Corp.; R. B. Hooper, Carnegie-Illinois Steel Corp.; E. Larned, Youngstown Sheet & Tube Co.; D. H. Ruhnke, Republic Steel Corp.; E. T. Walton, Crucible Steel Co. of America; R. L. Wilson, The Timken Roller Bearing Co.; and J. R. Zanetti, Great Lakes Steel Corp. The report has been made available to the National Advisory Committee for Aeronautics for publication because of its general interest.

MATERIALS AND EXPERIMENTAL WORK

An SAE 4340 steel of the following composition was used in this investigation:

C	Mn	P	S	Si	Ni	Cr	Mo
0.40	0.70	0.009	0.011	0.29	1.82	0.82	0.24

Material in the form of 7/8-inch-diameter rolled bars was furnished to the various participating laboratories by the Carnegie-Illinois Steel Corp. These bars were reforged to 1/2-inch squares for impact testing and to 5/8- to 3/4-inch rounds for tension and fatigue tests. Samples for impact testing were heat-treated in the form of 0.420-inch-square bars and then machined to standard V-notch Charpy specimens. Tension and fatigue specimens having a diameter of 0.25 inch were used; these were machined 0.020 inch oversize for heat treatment and finished to final size after heat treatment. All material was normalized from 1650° F and tempered for 1 hour at 1200° F before machining.

The tempered martensite samples were austenitized at 1600° F for 1 hour, oil-quenched, and tempered at 800°, 1000°, and 1200° F for impact testing and at 800°, 900°, 1000°, 1100°, and 1200° F for tension and fatigue testing. The samples containing nonmartensitic products were austenitized at 1600° F for 1 hour, transferred to a salt or metal bath, and held in accordance with the schedule outlined below. They were then oil-quenched and tempered 1 hour at 800°, 900°, 1000°, 1100°, and 1200° F. The hardness values for the samples ranged from 25 to 40 Rockwell C.

ISOTHERMAL TREATMENTS

Microstructure	Temperature	Time
1 percent upper bainite	850° F	15 seconds
5 percent upper bainite	850° F	55 seconds
10 percent upper bainite	850° F	90 seconds
20 percent upper bainite	850° F	115 seconds
50 percent upper bainite	850° F	25 minutes
5 percent ferrite	1175° F	10 minutes
5 percent pearlite	1175° F	20 minutes

The 5-percent-pearlite structure contained approximately 8 percent free ferrite. Wherever the term "5 percent pearlite" is used, it will be understood that reference is made to a structure containing 5 percent pearlite and 8 percent ferrite.

The impact studies on all structures were carried out at the Duquesne Works of the Carnegie-Illinois Steel Corp. The as-quenched microstructures of the tension and fatigue test specimens, as heat-treated at each of the cooperating laboratories, were checked and rated metallographically by Mr. M. A. Orehoski at Duquesne. The tension and fatigue tests were carried out in the cooperating laboratories as follows:

Microstructure	Laboratory
Tempered martensite	Crucible Steel Co. of America
1 percent bainite	Chrysler Corp.
5 percent bainite	Republic Steel Corp.
10 percent bainite	Bethlehem Steel Corp.
20 percent bainite	American Steel & Wire Co.
50 percent bainite	The Timken Roller Bearing Co.
5 percent ferrite	Great Lakes Steel Corp.
5 percent pearlite	Carnegie-Illinois Steel Corp., South Works

RESULTS AND DISCUSSION

The experimental results are tabulated and presented graphically as follows: Impact properties, table I and figures 1 and 2; tensile properties, table II and figure 3; fatigue properties, table III and figure 4; and ratings of mechanical properties, table IV.

The effects of upper bainite are summarized graphically in figure 5 in the form of a plot of the mechanical properties as a function of the percentage of upper bainite at a constant hardness of 34 Rockwell C. It will be noted from this summary that upper bainite exerts its major effects on the impact properties and yield strength or yield-tensile ratio. The effect on impact properties was, as might be expected, more pronounced in tests conducted at -40° F than at room temperature. The impact strengths are, in general, only slightly decreased by upper bainite in amounts up to 5 percent or by 5 percent ferrite, but are significantly decreased by 10 to 20 percent upper bainite and very markedly lowered by 50 percent upper bainite or 5 percent pearlite.

The tensile properties are, in general, much less sensitive to the presence of nonmartensitic products than are the impact properties. The yield-tensile ratio, however, is quite markedly lowered by the presence of 50 percent upper bainite and seems to be somewhat affected by upper bainite in amounts ranging from 5 to 20 percent or by 5 percent of pearlite. These results also indicate somewhat lower values in reduction of area for material containing 50 percent upper bainite, but no significant effect of smaller percentages. The tensile strength and elongation values for a given hardness seem not to be significantly affected by microstructural changes over the range studied.

The fatigue properties also seem generally insensitive to the presence of upper bainite in amounts below 50 percent, but are significantly lowered by the presence of 50 percent upper bainite or 5 percent pearlite.

The relatively large effect of 5 percent pearlite on toughness, as reflected by the impact strengths at a given hardness, is noteworthy, as the nonmartensitic products in plain carbon steels and some low-alloy steels are predominantly pearlitic, and such steels might, therefore, be expected to have poorer toughness when slack-quenched than alloy steels in which the nonmartensitic products would be predominantly bainitic.

SUMMARY OF RESULTS

The influence of nonmartensitic transformation products on the mechanical properties of tempered martensite was evaluated on samples of an SAE 4340 steel, partially isothermally transformed to specific high-temperature transformation products and quenched and tempered to hardness values of from 25 to 40 Rockwell C. The results may be summarized as follows:

1. For a given hardness value, the impact properties were significantly lowered by the presence of upper bainite in amounts of 10 percent or above or by 5 percent of pearlite, but were not significantly affected by 1 to 5 percent of upper bainite or by 5 percent of ferrite.

2. The tensile ductility remained relatively unaffected by the high-temperature transformation products, but the yield-tensile ratio was markedly lowered by the presence of 50 percent upper bainite or 5 percent pearlite.

3. The fatigue properties were likewise lowered somewhat by the presence of 50 percent upper bainite or 5 percent pearlite, but were not significantly affected by the smaller percentages of upper transformation products.

United States Steel Co.
Pittsburgh 30, Pa., July 16, 1952

TABLE I.- IMPACT PROPERTIES

Microstructure	Tempering temperature (°F)	Rockwell C hardness	Energy absorption (ft-lb)			
			Room temperature	Average	-40° F	Average
100 percent martensite	800	43.5	18-18	18	15-15	15
	1000	37	38-40	39	33-34	33.5
	1200	27	71-75	73	60-65	62.5
1 percent bainite	800	43	17-18	17.5	12-13	12.5
	1000	35.5	43-45	44	42-46	44
	1200	26	68-70	69	65-66	65.5
5 percent bainite	800	43	16-18	17	12-13	12.5
	1000	35	40-42	41	40-41	40.5
	1200	25	69-69	69	68-69	68.5
10 percent bainite	800	41	15-15	15	11-12	11.5
	1000	35	37-38	37.5	28-31	29.5
	1200	23	71-72	71.5	65-68	66.5
20 percent bainite	800	39	15-17	16	11-11	11
	1000	34.5	38-38	38	20-25	22.5
	1200	22.0	74-75	74.5	69-69	69
50 percent bainite	800	35	15-15	15	10-11	10.5
	1000	30.5	40-40	40	15-16	15.5
	1200	20.5	68-72	70	33-35	34
5 percent ferrite	800	43	18-20	19	12-14	13
	1000	37	38-39	38.5	33-36	34.5
	1200	24	73-76	74.5	66-68	67
5 percent pearlite (plus 8 percent ferrite)	800	37	14-14	14	10-11	10.5
	1000	34.5	31-32	31.5	23-23	23
	1200	21.5	67-68	67.5	51-53	52

TABLE II.- TENSILE PROPERTIES

Microstructure	Tempering temperature (°F)	Rockwell C hardness	Strength (psi)		Yield-tensile ratio	Elongation (percent in 1 in.)	Reduction of area (percent)
			Yield	Tensile			
100 percent martensite	800	42.5	193,000	203,000	0.95	13.0	48.0
	900	39	174,000	186.500	.93	14.5	47.0
	1000	35.5	156,500	168,000	.93	16.5	53.0
	1100	32	134,000	149,000	.90	18.0	58.0
	1200	28	120,000	134,000	.90	21.5	61.5
100 percent martensite[1]	800	45	195,500	208,000	.94	15.0	50.5
	900	42	180,500	190,500	.95	16.0	52.5
	1000	39	166,000	172,500	.96	16.0	51.5
	1100	34	147,500	158,000	.93	17.0	59.0
	1200	31	126,500	138,500	.92	20.0	64.0
1 percent bainite	800	44	199,500	212,000	.95	12.5	51.5
	900	40.5	183,500	191,500	.96	15.5	49.5
	1000	37	167,000	174,000	.96	17.0	55.0
	1100	33	146,500	155,000	.95	20.0	59.0
	1200	29.5	131,000	136,500	.96	23.0	61.5
5 percent bainite	800	43	186,000	203,500	.92	12.5	51.0
	900	39	169,000	185,000	.92	13.0	52.0
	1000	36	154,500	170,500	.91	14.0	55.5
	1100	33	136,000	154,000	.89	19.0	58.0
	1200	29	118,500	136,000	.87	22.0	62.0
10 percent bainite	800	42	177,000	197,500	.90	11.5	43.0
	900	39	163,500	180,000	.91	15.0	48.5
	1000	36	150,000	166,000	.90	16.5	52.5
	1100	32	130,500	146,500	.89	20.0	57.0
	1200	28	114,500	130,500	.88	23.5	59.5
20 percent bainite	800	41.5	181,000	194,500	.93	14.5	52.0
	900	37	168,500	179,500	.94	16.5	54.5
	1000	35.5	151,000	166,000	.91	17.5	54.5
	1100	32	131,000	148,500	.88	20.0	58.0
	1200	27	113,000	133,500	.85	23.0	60.5
50 percent bainite	800	37	134,500	166,000	.81	17.0	47.0
	900	34.5	126,500	156,500	.81	18.5	50.0
	1000	32	117,500	144,500	.81	19.5	50.5
	1100	28	107,500	130,000	.83	23.0	56.0
	1200	26	97,500	124,500	.78	23.0	57.0
5 percent ferrite	800	40.5	205,000	217,000	.94	13.0	48.0
	900	37	186,500	194,000	.96	14.5	50.0
	1000	34	168,000	178,000	.94	18.0	52.5
	1100	29.5	148,500	160,000	.93	19.5	57.0
	1200	24	122,000	137,500	.89	23.5	62.0
5 percent pearlite (plus 8 percent ferrite)	800	41	169,500	195,000	.87	10.5	40.0
	900	38.5	159,500	176,500	.90	13.5	45.5
	1000	36	148,000	165,500	.89	16.5	48.5
	1100	31.5	131,500	149,000	.88	18.5	54.5
	1200	29	119,500	134,500	.89	22.0	58.0

[1]These tests were carried out by the Bethlehem Steel Corp.; all other tensile tests were carried out by the laboratories specified in the text.

TABLE III.- FATIGUE PROPERTIES

Microstructure	Tempering temperature (°F)	Rockwell C hardness	Endurance limit (psi)	Endurance-limit and tensile-strength ratio	Endurance-limit and yield-point ratio
100 percent martensite	800	42.5	79,000	0.39	0.41
	900	39	77,500	.42	.45
	1000	35.5	76,000	.45	.49
	1100	32	70,500	.47	.53
	1200	28	65,000	.49	.54
1 percent bainite	800	43	79,000	.37	.40
	900	40	73,000	.39	.40
	1000	37.5	72,000	.41	.43
	1100	34	67,000	.43	.46
	1200	28.5	65,000	.48	.50
5 percent bainite	800	43.5	82,000	.40	.44
	900	39	77,000	.42	.46
	1000	37	75,000	.44	.49
	1100	32.5	72,000	.47	.53
	1200	28	64,000	.47	.54
10 percent bainite	800	42	81,000	.41	.46
	900	39	79,000	.44	.48
	1000	36	74,000	.45	.49
	1100	31	69,000	.47	.53
	1200	27	68,000	.52	.59
20 percent bainite	800	41	83,000	.43	.46
	900	36.5	75,000	.42	.44
	1000	34.5	68,000	.41	.45
	1100	31.0	66,000	.44	.50
	1200	26.0	62,000	.47	.55
50 percent bainite	[a]800	39.5	72,000	----	----
	800	33.5	56,000	.33	.44
	[b]800	34	47,000	.28	.35
	900	32.5	59,000	.38	.47
	1000	29.5	57,000	.39	.49
	1100	25.5	54,000	.42	.50
	1200	24	49,000	.39	.50
5 percent ferrite	800	40.5	87,000	.40	.42
	900	37.0	85,000	.44	.46
	1000	34.0	84,000	.47	.50
	1100	29.5	70,000	.44	.47
	1200	24.0	61,000	.46	.50
5 percent pearlite (plus 8 percent ferrite)	800	43	67,000	.34	.40
	900	39.5	66,000	.37	.41
	1000	37.5	68,000	.41	.46
	1100	32.5	62,000	.42	.47
	1200	29.5	57,000	.42	.48

[a]Double tempered.
[b]Recheck.

TABLE IV.- RATINGS[1] OF MECHANICAL PROPERTIES

Microstructure	Impact strength at room temperature	Impact strength at -40° F	Yield strength	Elongation	Reduction of area	Endurance limit
T. M. + 1 percent bainite	100	100	100	100	100	100
T. M. + 5 percent bainite	92	99	97	100	100	100
T. M. + 10 percent bainite	82	87	97	100	100	100
T. M. + 20 percent bainite	80	62	97	100	100	100
T. M. + 50 percent bainite	30	50	84	100	95	87
T. M. + 5 percent ferrite	100	100	100	100	100	100
T. M. + 5 percent pearlite	67	57	93	100	95	90

[1]Expressed as percentage of tempered-martensite (T. M.) value at constant hardness of 34 Rockwell C.

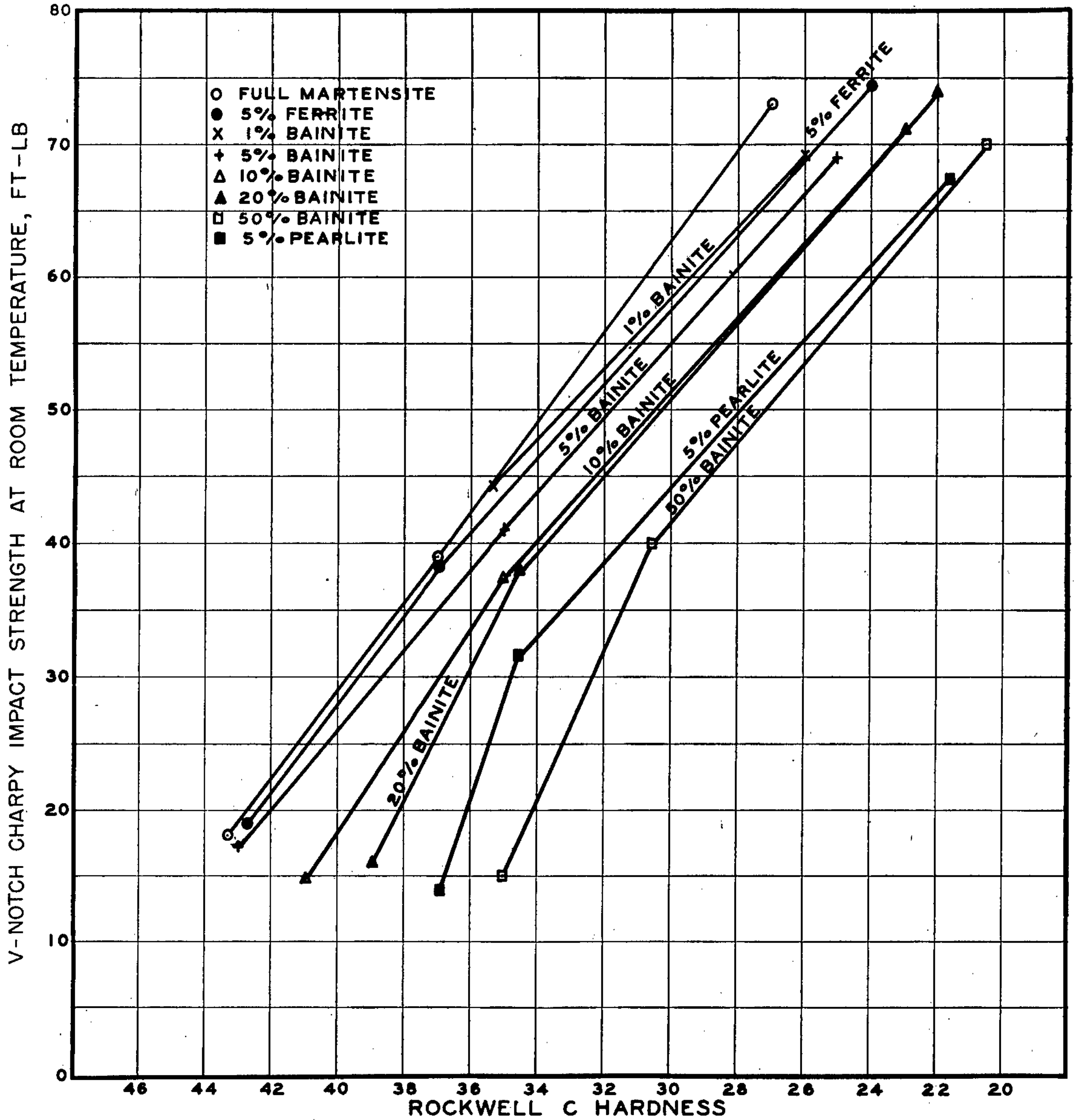

Figure 1.- Effect of nonmartensitic products on impact strength at room temperature.

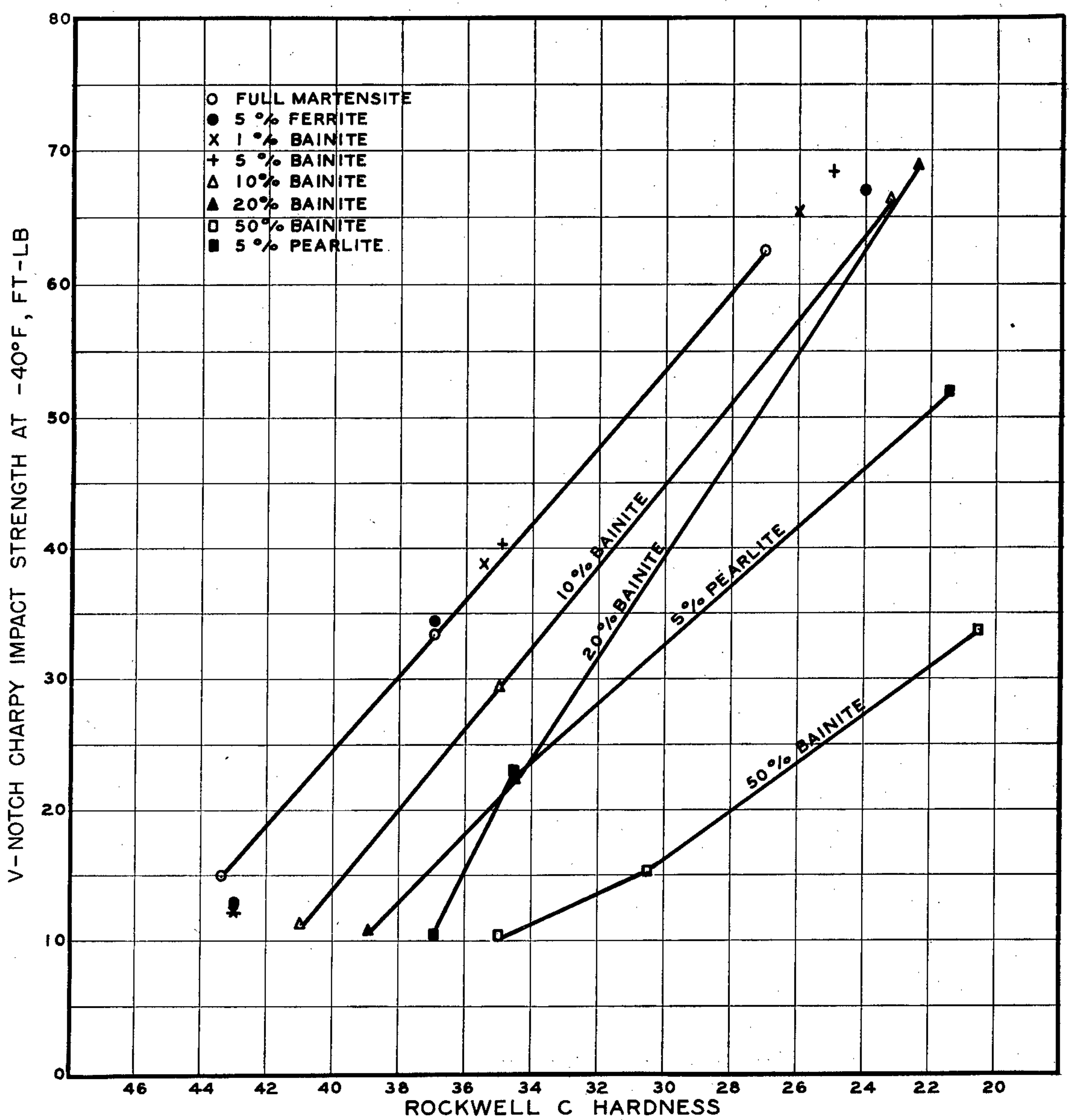

Figure 2.- Effect of nonmartensitic products on impact strength at -40° F.

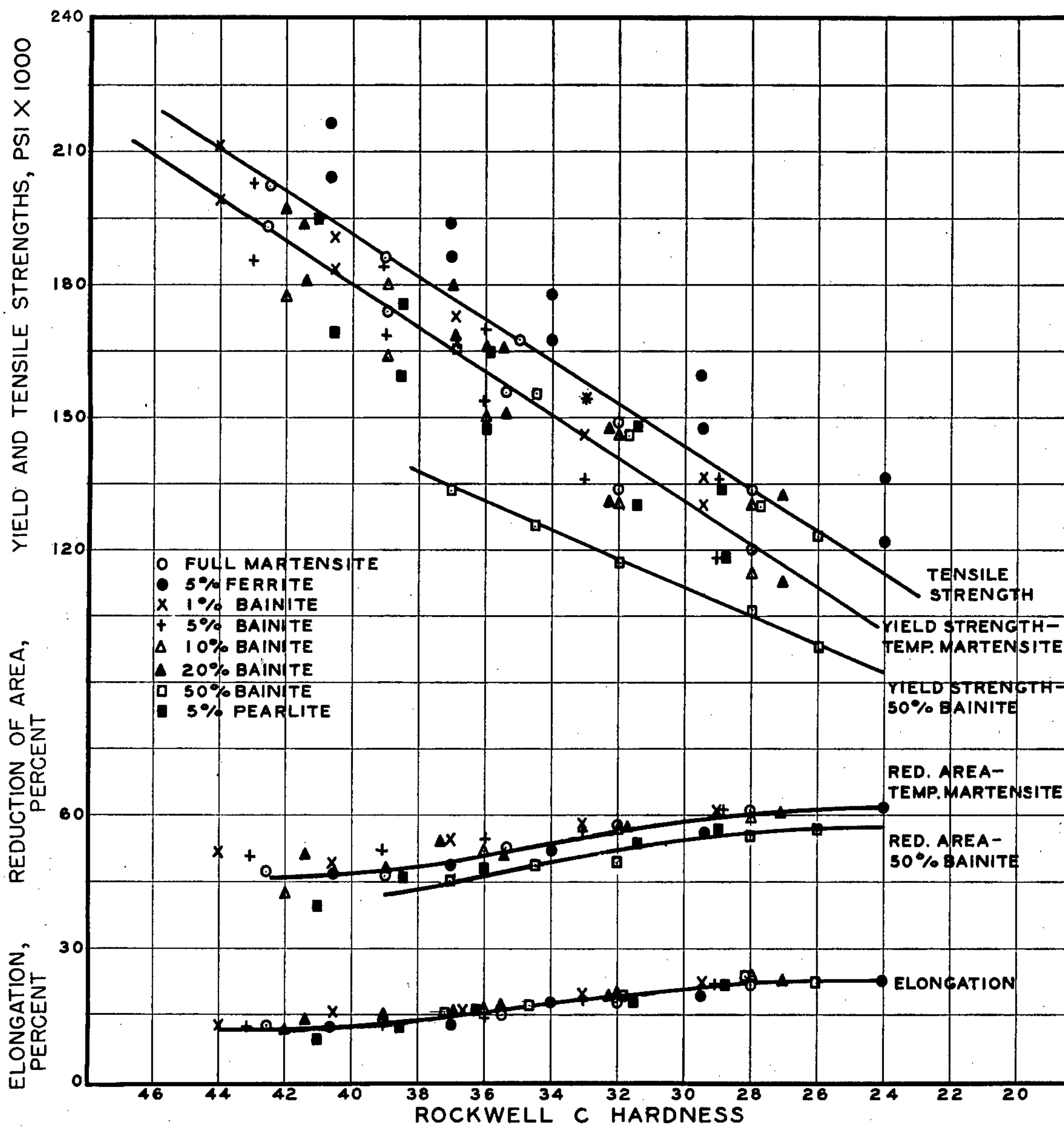

Figure 3.- Effect of nonmartensitic products on tensile properties.

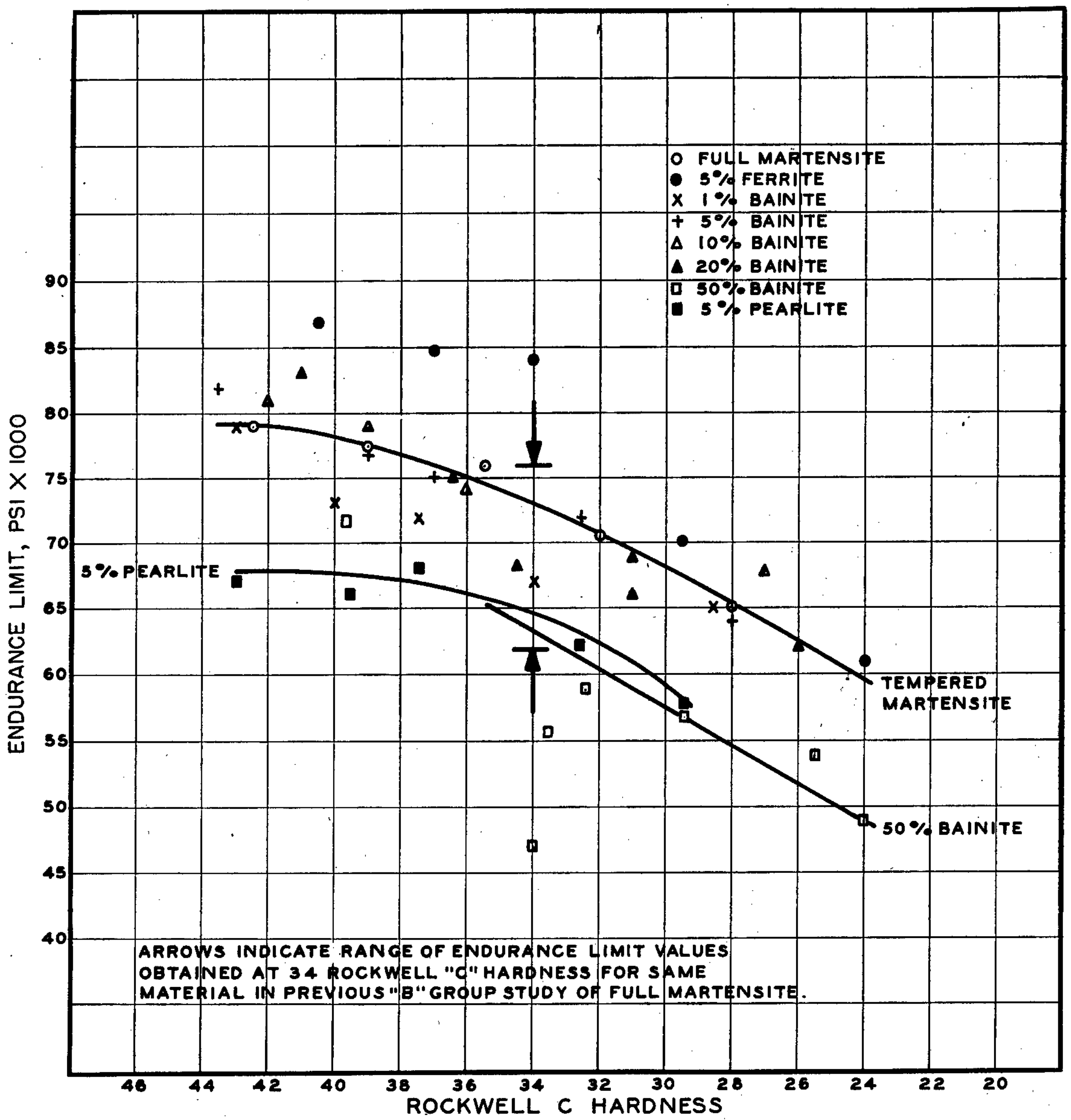

Figure 4.- Effect of nonmartensitic products on endurance limit.

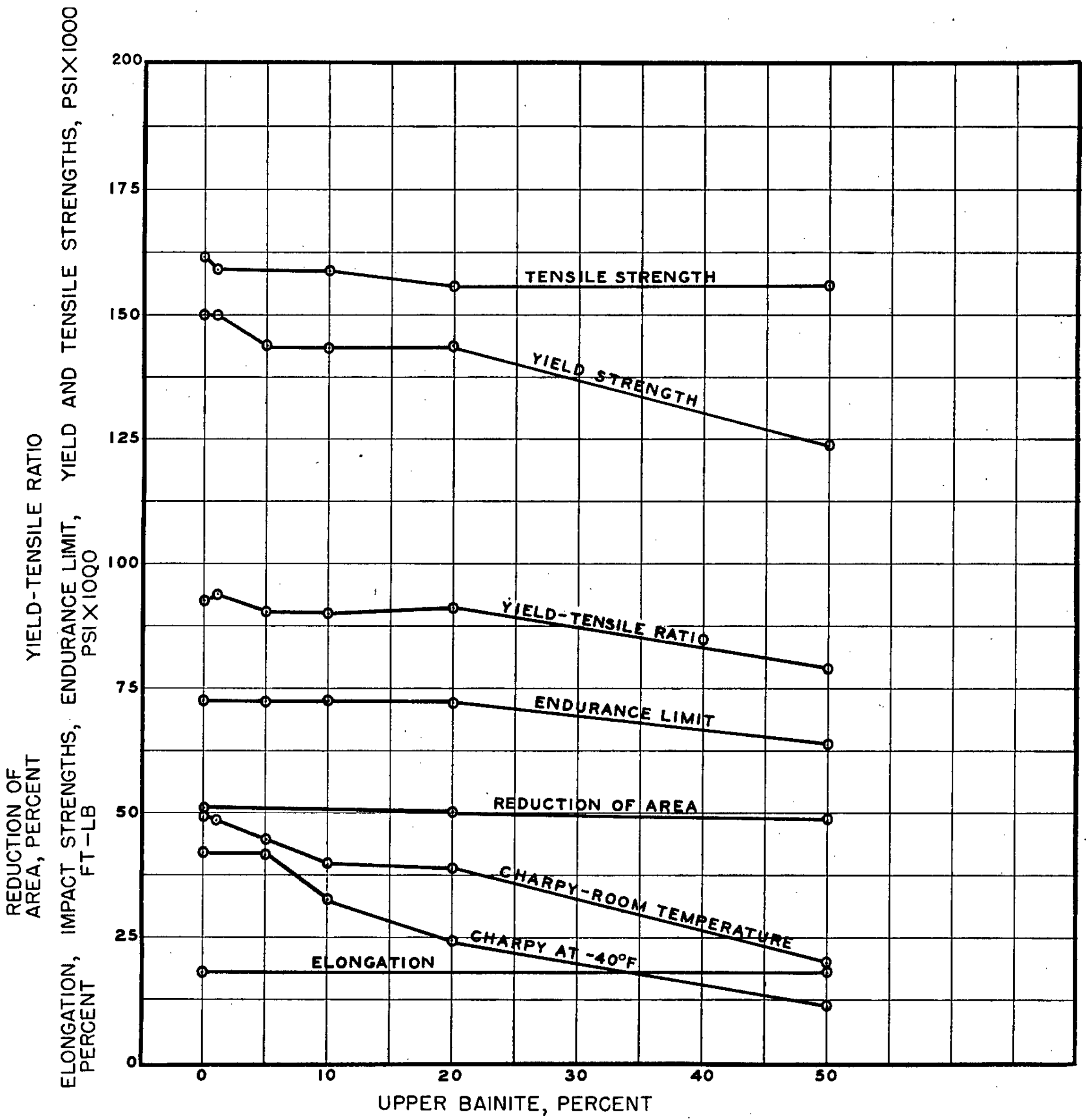

Figure 5.- Effect of upper bainite on mechanical properties at 34 Rockwell C.

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Copies obtainable from NACA, Washington

1. Steels (5.1.3)
2. Materials, Properties - Tensile (5.2.1)
3. Materials, Properties - Fatigue (5.2.5)

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