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LITERATURE REVIEW: IMPACT TOUGHNESS OF
BAINITE VS. MARTENSITE

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ACKNOWLEDGEMENT

The majority of the references of this paper were compiled from an unpublished literature survey by Thomas Hey.

INTRODUCTION

In 1934, the discovery by Davenport, Roff, and Bain¹ of a new phase in steel, which was later to become known as "bainite", sparked off a series of investigations which have continued with somewhat diminishing fervor until today. The "improved technique" of Davenport et al, yielded a twelvefold increase in impact toughness over conventional martensite while maintaining comparable strength, but unfortunately, such dramatic improvements were not at all universal for steels, and further research into the mechanical properties of bainite produced a wealth of confusing, often conflicting, data as to the suitability of bainite for commercial applications. The purpose of this paper is to briefly review the significant results of the research in the hope of determining the suitability of bainitic steel for moderately high strength, high toughness applications - specifically, as a gun tube material.

DESCRIPTION OF BAINITE AND MARTENSITE

Before delving into the literature on bainite, it would be well to quickly review the nature of bainite and martensite². If a steel at an austenitizing temperature is cooled rapidly to a temperature of the order of 350°C (662°F), then we no longer have the equilibrium cooling conditions which produce the platelike structure of pearlite, where ferrite and cementite lie side by side. Because the diffusion rates are so low at this lower temperature, the carbon atoms do not have time to diffuse over the distances required to form the cementite plate. Therefore,

they congregate over only short distances as fine particles, and when combined with the fine ferrite grain size produced under these conditions, the result is a microstructure of high strength bainite.

Actually the precise mechanism for the bainite transformation is not yet established, and the subject becomes even more complicated when one recognizes that there are at least two forms of bainite, "upper" and "lower" bainite (upper and lower referring to the relative temperatures at which the bainite is formed). The morphological difference is that in upper bainite one often finds elongated particles of carbide between the ferrite grains, while in lower bainite, the carbides generally precipitate at an angle to the major growth direction of the ferrite grain. For one plausible mechanism of the bainitic transformation, the reader is referred to F. B. Pickering's excellent article³ on bainite in steels.

The martensitic transformation is more easily described. At even lower quenching temperatures, the diffusion rates are so low that cementite cannot precipitate from the austenite lattice in any form, but the large driving force of the FCC austenite to transform to BCC ferrite is so overwhelming that a diffusionless phase transformation occurs by a shearing of the austenite lattice. The resulting structure is body centered tetragonal supersaturated with excess carbon.

SURVEY OF THE LITERATURE

The debate over the relative merits of bainite vs. martensite is simplified if one considers separately two realms of steels: those of

low to moderate carbon content (up to approximately .5 - .6%C) and those with higher carbon contents. The initial success of bainite was with higher carbon steels, and we shall discuss these first. The "improved technique" that Davenport, Roff and Bain¹ reported in 1934, and which became known as "Austempering" (isothermally holding unstable austenite at a temperature in the bainitic region until the desired amount of bainite is attained and then quenching to transform the remaining austenite to martensite) yielded amazing results for a .74%C steel. Table 1 shows that with equivalent hardness and slightly superior strengths, the impact value* of the bainite was 35.3 ft-lb (47.9J) compared to 2.9 ft-lb. (3.9J) for the martensite. Unfortunately, these values are presumedly at room temperature, and no transition temperature was reported.

James⁴ obtained results similar to Davenport's for a .78%C steel, as the Austempering process gave 36.6 ft-lb. (49.6J) impact* compared to 14.0 ft-lb. (19.0J) for a quenched and tempered martensite with similar strength (Table 2). Legge⁵ tested a range of higher carbon steels and found the impact property of the Austempered steel to be superior to the martensite steel with comparable strengths in every case. A closer examination of the data (Table 3) shows that as the carbon content of the steels increased, so did the relative impact toughness* superiority of the bainitic steel over the martensite: a 10-23% increase for 0.62%C, 45% for 0.74%C, and 97% for 0.85%C. Again, all values are presumedly at room temperature.

If we now turn our attention to the lower carbon steels, we soon

*These early impact values were taken with .180 inch unnotched round specimens, not the present standard V-notch.

see that the mechanical properties of bainite no longer dominate over those of martensite. The results of Rosenthal and Manning⁶ given in Table 4, show that although certain percentages of bainite can give Charpy values approaching those of martensite, in no case do they meet or exceed the martensite values for steels of .27%C and .28%C. Holloman et al⁷, even more convincingly demonstrated the inferiority of bainite in .34%C and .35%C steels, particularly in terms of impact values, in which Bainite-Martensite and Bainite-Pearlite microstructures yielded only 20 ft-lb at -40°F (-40°C) compared to 100 ft-lb for tempered martensite. Their conclusion was that only tempered martensite was suitable for guns and armor. The tests of Hodge and Lankford⁸ on .40%C steel showed that while several mechanical properties were unaffected by the presence of upper bainite in martensite, Charpy impact and yield strength were both adversely affected (see Figure 1).

Bailey⁹ showed that AISI 1340, 2340, and 5410 steels with 10% bainite and 30% bainite were, with only one exception, slightly poorer in impact property tests than their fully martensitic counterparts. In every case, the lower bainite performed the best of the bainites. Similar results were obtained by Hehemann, Luhan, and Troiano¹⁰ for 4340 steel. With only two exceptions, the steel which contained any percentage of bainite, under any tempering treatment, was inferior to the 100% martensite in impact values (and a variety of other mechanical properties).

Significantly, the exceptions mentioned above occurred under similar conditions. Bailey found that a 30% bainite transformed at 700°F (371°C - the lowest transformation temperature studied) yielded a slightly

higher maximum shelf energy than the martensite. Hehemann, Luhan, and Troiano also found that the lowest bainites could have superior properties. They found that a bainite (either 100% bainite or any percentage of bainite) which was transformed at 600°F (316°C) was superior to the martensite, and in another case a transformation temperature of 675°F (358°C) was best of all. Figure 2 shows the increase in maximum shelf energy with bainitic transition temperature of 600°F (tempered at 800°F - 427°C) or 675°F (400°F - 205°C - temper). The 99% bainite composition is especially attractive, for at 205,000 psi (1410 MPa) strength, it yields approximately 22 ft-lb (30J) impact energy ("Charpy V") at -40°F (-40°C).

In a Cr-Mo-V steel investigated by Malerich and Cash¹¹, tempered martensite was found to have much better impact energy values than bainite although "fine" (lower) bainite had slightly superior yield strength and ductility, particularly at high testing temperatures. In testing .34%C steel, Edwards¹² confirmed that for this steel, tempered martensite is tougher than lower bainite which in turn, is tougher than upper bainite, at comparable strengths. The same conclusion was reached by DeFries, Nolan, and Brassard¹³, after they tested two versions of .32%C gun steel.

Two graphs (Figures 3 and 4) from the article by F.B. Pickering³, help lend order to the discussion of the forms and merits of bainites. Figure 3 displays the effect of carbon on the temperature of change from upper to lower bainite, although it must be remembered that the actual

transformation is over a range of temperatures and that other alloying elements quite probably affect the curve as well. Figure 4 demonstrates why lower bainites are generally preferred over upper bainites, although even with lower bainites, the graph indicates an unacceptable impact transition temperature (with the required tensile strength) for gun tube applications.

It is clear from the results given above that while bainite may well possess superior mechanical properties with higher carbon content steels, it is definitely inferior with those of lower carbon content. A (perhaps simplistic) explanation of these results comes to mind if we remember that the specific volume of the BCT martensite is greater than that of transforming FCC austenite, and the difference increases with increasing carbon content. Thus, large residual strains are introduced into martensite and it may be that while for low enough carbon content these strains are largely tempered out to yield a product of equal or better toughness than bainite, as the carbon content increases this becomes more difficult until above .5 - .6%C, the bainite possesses superior toughness. However, the higher carbon bainites still do not appear to have sufficient impact toughness at -40°F to meet gun tube specifications.

A third alternative to the utilization of martensite or bainite is to develop a composite structure by quenching below M_s but above M_f and then tempering at a temperature in the bainitic region. The tempering not only tempers the martensite but also transforms the retained austenite

to bainite. Although he did not explicitly test for fracture toughness, Elemendorf¹⁴ reported that such a process gave tensile properties similar to those of tempered steel with the ductility comparable to an Austempered steel for .64%C - .91%C. In his paper cited earlier, Edwards indicated that this process gave a structure whose fracture resistance was superior to either martensite or bainite alone. Ohmori, Ohtani, and Kunitake^{15,16} formed the same composite structure, which they term a "duplex" structure, in .12%C steel. They stated that "the optimum combination of toughness and strength can be achieved by producing the tempered bainite/martensite duplex structure at all strength levels". With the .12%C martensitic steel and a 250°C (482°F) temper they achieved a 138,000 psi (952 MPa) yield strength, a Charpy V-notch impact value of 135 ft-lb (183J) at 0°C (32°F) and a transition temperature of -75°C (-103°F) whereas the duplex structure (with 138,000 psi yield strength) gave an impact value of 145 ft-lb (197J) and a transition temperature of -130°C (-202°F). Very recently, however, Nakajima and Araki¹⁷ found that duplex structures in .34%C and .54%C AISI 4300 type steel gave somewhat higher transition temperatures than pure martensite with comparable hardnesses (Figure 5).

SUMMARY

From the evidence cited above we find that:

1. Lower bainite has generally higher impact toughness for comparable yield strength than upper bainite.
2. The maximum shelf energies are often higher in bainites than martensites.

3. Except as noted in (5) below, at lower carbon contents (less than .5%C) tempered martensite has superior impact properties than bainite at comparable strengths.

4. At higher carbon contents (greater than .6%C) tempered martensite has inferior impact properties than bainite at comparable strength, and this inferiority of martensite appears to increase with carbon content.

5. A bainitic transition temperature of 600°F (316°C) or 675°F (358°C) produced a superior bainitic structure of exceptionally good tensile and impact properties in 4340 steel.

6. In several tests, a bainitic/martensitic duplex structure gave optimal tensile and impact properties for steels of both high and low carbon content, although the duplex process has not been universally successful.

CONCLUSIONS

Although the brief review of the literature given above indicates that tempered martensite is generally superior over bainite in obtaining high strength with low temperature impact toughness, two avenues of research involving bainite hold promise for improved mechanical properties. The astounding success of Hehemann et al with 4340 steel, viz., 22 ft-lb at a yield strength of 205,000 psi, merits an attempt to duplicate his results with 4340 bainite transformed at 600°F, tempered at 800°F, and bainite transformed at 675°F, tempered at 400°F. Secondly, the possible advantages of the duplex structure should be explored further.

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TABLE 1. MECHANICAL PROPERTIES OF AUSTEMPERED BAINITE VS. MARTENSITE

COMPOSITION	C	Mn	Si	S	P
	0.74	0.37	0.145	0.039	0.044

BAINITE
Mechanical Properties
(Average of 6 Tests)

Rockwell C Hardness	50.4
Ultimate Strength (psi)	282,700
Yield Point (psi)	151,300
Elongation (percent in 6 in)	1.9
Reduction in Area (percent)	34.5
Impact* (Ft-lb)	35.3

MARTENSITE
Mechanical Properties
(Average of 6 Tests)

Rockwell C Hardness	50.2
Ultimate Strength (psi)	246,700
Yield Point (psi)	121,700
Elongation (percent in 6 in)	0.3
Reduction in Area (percent)	0.7
Impact* (Ft-lb)	2.9

*Ft-lb absorbed in breaking 0.180 inch round, unnotched specimens.

TABLE 2. PROPERTY TESTS OF 0.180 IN. DIAMETER RODS (JAMES)

COMPOSITION:	C	Mn	Si	S	P
	0.78	0.58	0.146	0.040	0.042
<u>Properties</u>	<u>Austempering</u>		<u>Quench and Temper</u>		
Rockwell C	50.1		49.8		
Brinell	489		486		
Tensile strength, psi	259,300		259,000		
Rupture stress, psi	355,500		312,150		
Elongation, percent in 2 in	5.0		3.75		
Reduction area, percent	46.4		26.1		
Impact, ft-lb	36.6		14.0		
Bending (free bend in 3/4 in length)	Greater than 150 deg. without rupture		Ruptured at 45 deg.		

TABLE 3. MECHANICAL PROPERTY TESTS OF 0.180 IN. DIAMETER RODS (LEGGE)

Property Measured	Quench and Temper Method	Aus-tempering	Composition		
			C	Mn	Si
Hardness (Rockwell C, flat surface)	50	50	0.85	0.42	0.180
Yield Str., psi 0.1% set	224,750	210,950			
Tensile Str., psi	261,100	256,700			
Elong. in 2 in, percent	4.7	6.2			
Red. Area, percent	28.3	44.8			
Impact (ft-lb)	20.4	40.2			
Hardness (Rockwell C, flat surface)	45	45	0.74	0.37	0.145
Tensile Str., psi	250,000	254,300			
Elong. in 2 in, percent	6.0	6.3			
Red. Area, percent	42.5	49.0			
Impact (ft-lb)	41.1	No fracture			
Hardness (Rockwell C, flat surface)	41	41	0.74	0.37	0.145
Tensile Str., psi	226,300	224,700			
Elong. in 2 in, percent	8.8	9.0			
Red. Area, percent	42.7	54.2			
Impact (ft-lb)	34.5	50.1			

TABLE 3. MECHANICAL PROPERTY TESTS OF 0.180 IN. DIAMETER RODS (LEGGE)(cont)

Property Measured	Quench and Temper Method	Aus-tempering	Composition		
			C	Mn	Si
Hardness (Rockwell C, flat surface)	46	46	0.62	0.80	0.171
Tensile Str. psi	253,700	248,000			
Elong. in 2 in, percent	7.0	7.3			
Red. Area, percent	46.2	50.4			
Impact (ft-lb)	35.9	39.6			
Hardness (Rockwell C, flat surface)	41	41	0.62	0.80	0.171
Tensile Str. psi	223,700	225,000			
Elong. in 2 in, percent	8.0	7.5			
Red. Area, percent	50.3	56.4			
Impact (ft-lb)	37.4	45.9			

TABLE 4. EFFECT OF BAINITE ON V-NOTCH CHARPY VALUES

<u>Treatment</u> ¹	<u>Micro-Structure Before Tempering</u>	<u>V-Notch Charpy Values (-40° F)</u>
Water Quenched ¹	100% Martensite	60.5
10,000 s at 800° F1	40% Bainite	56.5
1,000 s at 750° F1	65% Bainite	40
1,000 s at 650° F1	80% Bainite	56
Water Quenched ²	100% Martensite	59
10,000 s at 800° F2	50% Bainite	38
1,000 s at 750° F2	65% Bainite	29
1,000 s at 650° F2	90% Bainite	54

1. Composition was .27% C, 1.50% Mn, .75% Cr, 2.09% Ni, .49% Mo.

2. Composition was .28% C, 2.14% Mn, .65% Cr, .49% Mo.

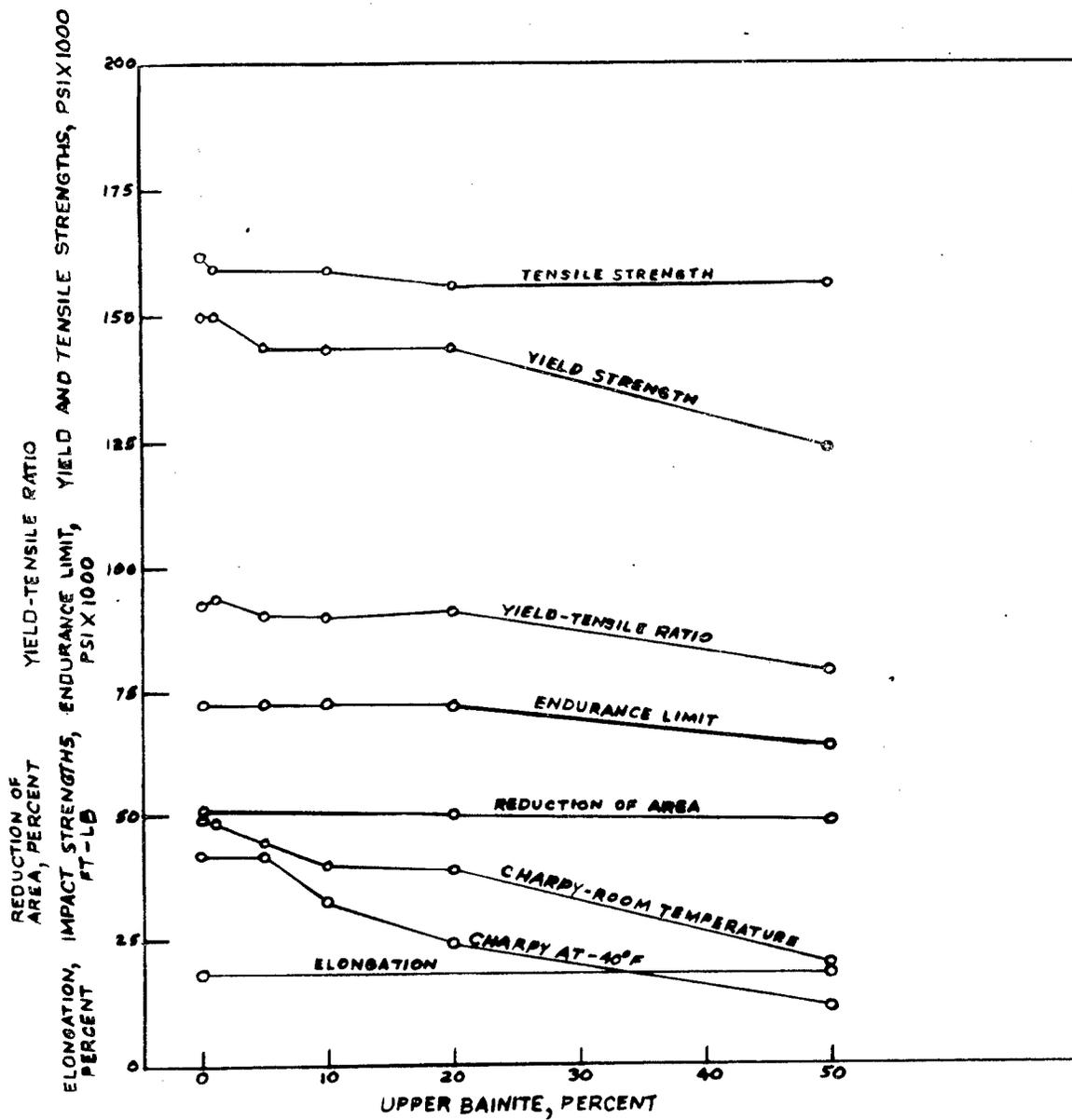


Figure 1. Effect of Upper Bainite on Mechanical Properties of .40% C Steel at 34 Rockwell "C".
(From Hodge and Lankford).

- OIL-QUENCHED - TEMPER 800° F
- △ 35% BAINITE 900° F - TEMPER 600° F
- 100% BAINITE 600° F - TEMPER 800° F
- 99% BAINITE 675° F - TEMPER 400° F

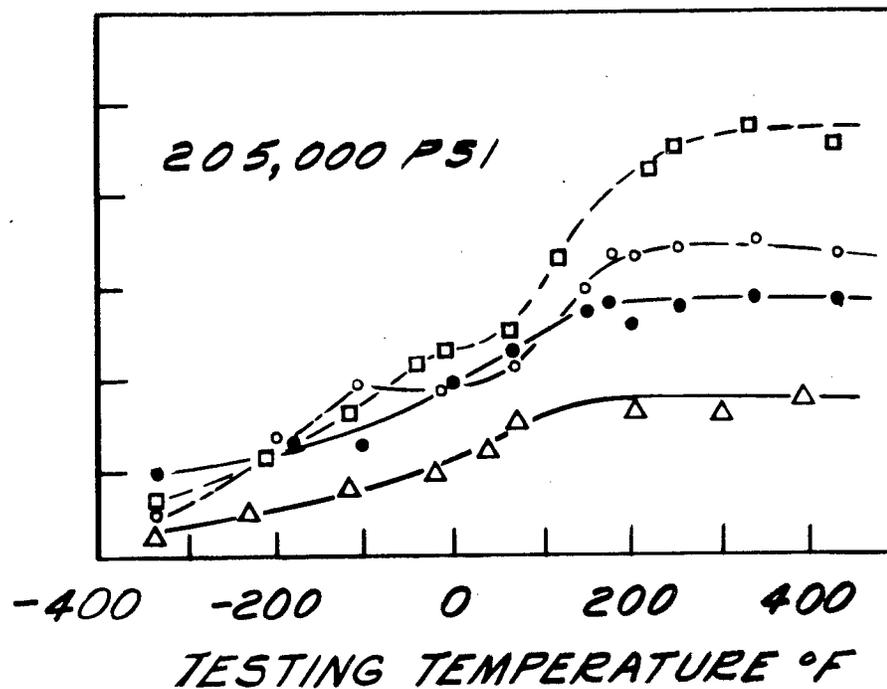


Figure 2. Transition Curves for Various Microstructural Constituents of 4340 Steel.
(From Hehemann, Luhan, and Troiano)

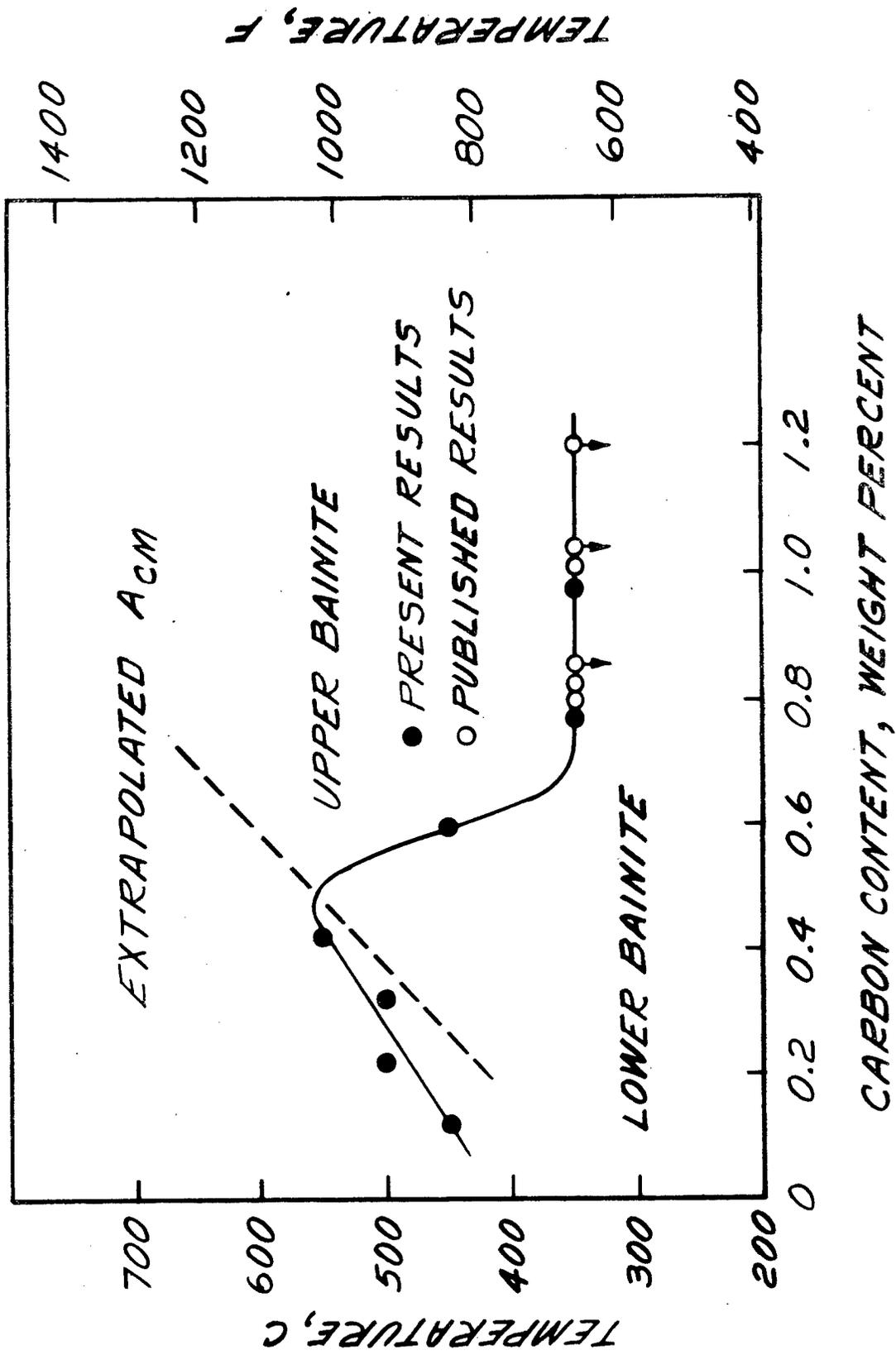


Figure 3. Effect of Carbon on the Temperature of Change from Upper to Lower Bainite. (From Pickering).

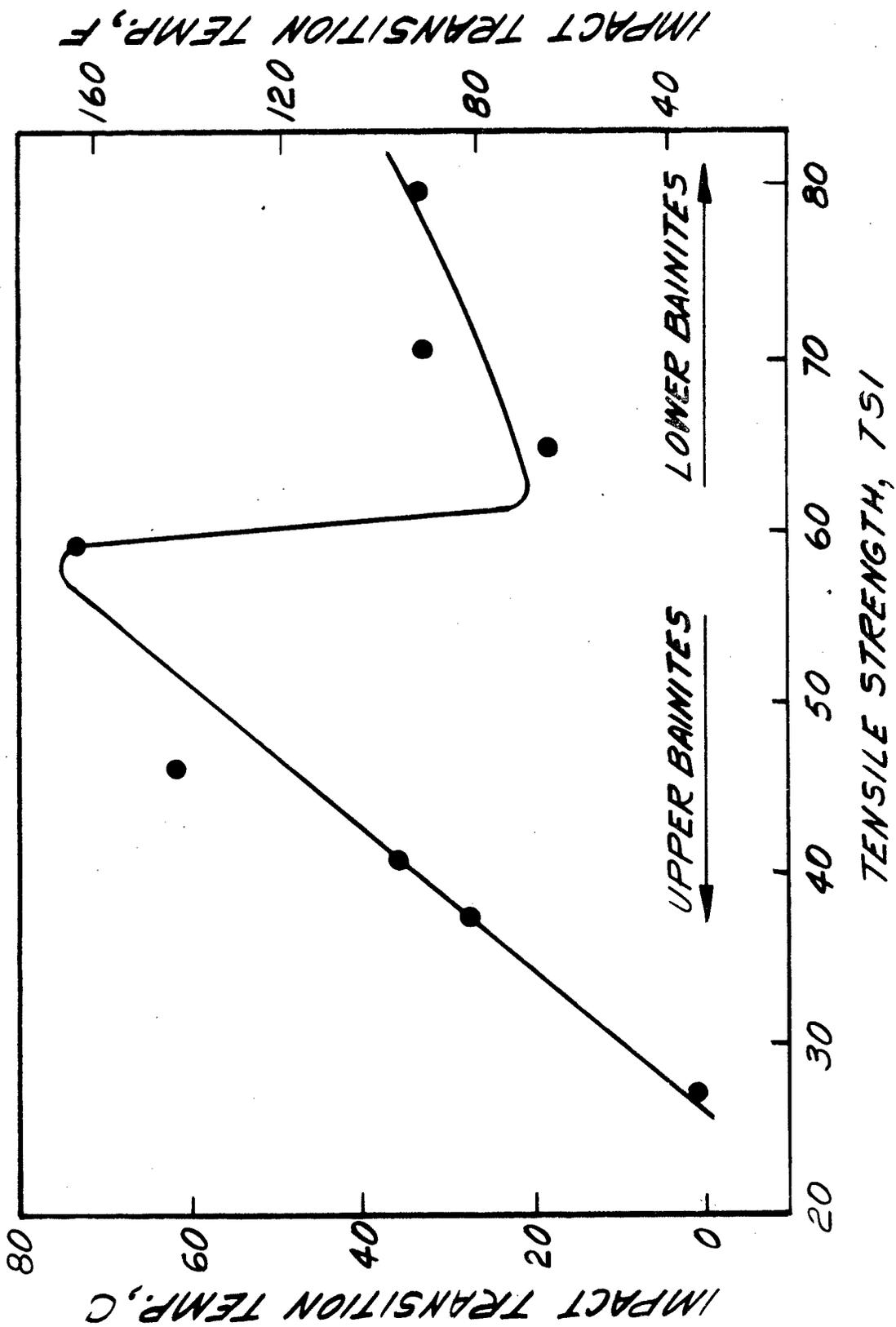


Figure 4. Effect of Tensile Strength on Impact Transition Temperature in Bainite Steels. (From Pickering)

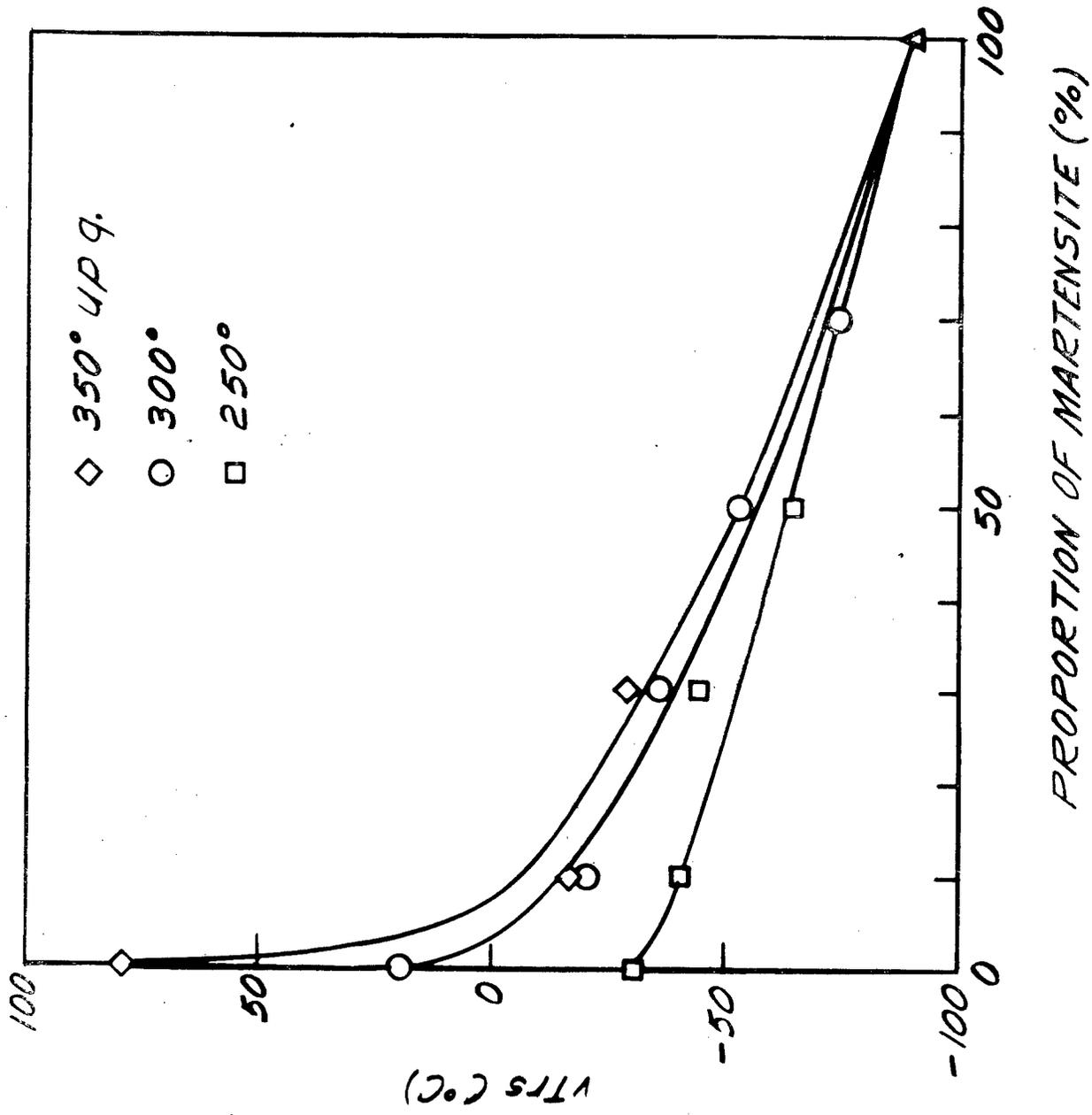


Figure 5. Transition Temperature vs. Proportion of Martensite. (From Nakajima and Araki)

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