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TECHNICAL REPORT ARCCB-TR-90032

**UNUSUALLY HIGH FRACTURE TOUGHNESS  
OF ASTM A723 STEEL FROM A MIXED  
MARTENSITE/BAINITE MICROSTRUCTURE**

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4. TITLE (and Subtitle) UNUSUALLY HIGH FRACTURE TOUGHNESS OF ASTM A723 STEEL FROM A MIXED MARTENSITE/BAINITE MICROSTRUCTURE		5. TYPE OF REPORT & PERIOD COVERED Final
		6. PERFORMING ORG. REPORT NUMBER
7. AUTHOR(s) J.A. Kapp, J. Barranco, L. Meisel, P.J. Cote, and R.N. Wright (See reverse)		8. CONTRACT OR GRANT NUMBER(s)
9. PERFORMING ORGANIZATION NAME AND ADDRESS U.S. Army ARDEC Benet Laboratories, SMCAR-CCB-TL Watervliet, NY 12189-4050		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS AMCMS No. 6111.02.H610.011 PRON No. 1A05Z0CANMSC
11. CONTROLLING OFFICE NAME AND ADDRESS U.S. Army ARDEC Close Combat Armaments Center Picrtinny Arsenal, NJ 07806-5000		12. REPORT DATE November 1990
		13. NUMBER OF PAGES 10
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report)  Approved for public release; distribution unlimited.		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Fracture Behavior, High Strength-High Toughness Steels, Martensite, Bainite, Toughening Mechanisms		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A mixed martensite/bainite microstructure in the high strength-low alloy steel (ASTM A723 pressure vessel steel) can be obtained by quenching from the austenitizing temperature to below $M_s$ , but above $M_f$ , and isothermally holding. As the supercooled austenite cools below $M_s$ , some martensite is formed and the isothermal hold results in the remainder of the untransformed austenite transforming to bainite. The resulting microstructure may be very fine depending on the prior austenite grain size. Since the martensite is formed first, the (CONT'D ON REVERSE)		

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supercooled austenite between the martensite needles transforms to bainite during the isothermal hold. The resultant lamellar structure can result in remarkable fracture toughness with quite high strength ( $K_{Ic}$  of 255 MPa $\sqrt{m}$  and ultimate tensile strength of 1200 MPa). In this report, the results of varying prior austenite grain size on strength and toughness and the strength-toughness relationship for the martensite/bainite mixture that may produce the highest toughness are presented.

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## INTRODUCTION

It has generally been assumed that the optimum strength-toughness properties for ASTM A723 pressure vessel steel (gun steel) were obtained with a tempered martensite microstructure. To the authors' knowledge, no heat treating experiments below  $M_s$  have been performed on this material. This report outlines the results of some experimental work.

The heat treatment is shown in Figure 1. The steel is raised to its austenitizing temperature and quenched to a temperature below its  $M_s$  temperature but above its  $M_f$  temperature. This results in an incomplete martensite transformation of the supercooled austenite. The remainder of the austenite then transforms to lower bainite upon the ensuing isothermal hold treatment. Since the martensite is formed first, the bainite forms between the martensite needles resulting in a very fine alternating microstructure of martensite needles with lower bainite in between. This is essentially a composite microstructure. The resulting toughness properties from this heat treatment are shown in Figure 2. It is clear from this figure that some unusual toughness properties can be obtained. These data were obtained in the FY87 program. The effects of tempering on the mixed microstructure, as well as the establishment of strength-toughness relationships, were studied in the FY88 program.

## EXPERIMENTAL PROCEDURE

We wish to determine the strength-toughness relationship for a mixed microstructure of martensite and bainite with the martensite produced first. This can be accomplished by producing the microstructure with the isothermal hold heat treatment below  $M_s$ , shown in Figure 1, and tempering at various temperatures to change strength. The specific treatment chosen was austenitizing

at 830°C and isothermal holding at 250°C. This resulted in a microstructure of 33 percent martensite and 67 percent bainite that previously resulted in the highest fracture toughness (Figure 2). The tempering temperatures studied were 25°C (no temper), 260°C, 370°C, 480°C, 590°C, and 700°C. In addition, the effects of tempering on an all-bainite microstructure produced with austenitizing at 830°C and isothermal holding at 300°C (austempering in Figure 1) were studied to determine if a relationship existed between the properties of the bainite constituent and the properties of the mixed microstructure.

## RESULTS AND DISCUSSION

The strength-toughness properties of all the mixed microstructures produced are shown in Figure 3. Also plotted in Figure 3 is the range of the previously measured strength-toughness relationship for an all-martensite microstructure for ASTM A723 steel. As shown in the figure, the properties obtained with an all-martensite microstructure (the filled squares and the Xs) overlap the band of the previously observed results. Furthermore, it is apparent that the mixed microstructure (open diamonds) will produce equal or superior properties. Thus, we have somewhat expanded the envelope of attainable properties with the mixed martensite/bainite microstructure.

The effects of tempering on the mixed martensite/bainite microstructure are shown in the strength-toughness plot in Figure 4. The range of properties observed with an all-martensite microstructure is plotted again for reference. The data that are outside the box at 170 Ksi ultimate tensile strength are the measurements obtained in FY87 and repeated in FY88. Unfortunately, it is clear that the effect of tempering at different temperatures to produce a higher strength material is to decrease toughness to the point that the resultant

strength-toughness relationship is no better than, or even worse than, the all-martensite microstructure.

These results are also presented as the overlay plot of strength or toughness versus tempering temperature shown in Figure 5. In this plot, the basic trend from tempering is as expected. Referring to ultimate tensile strength (the filled diamonds), increasing the tempering temperature gradually decreases the strength to about 590°C tempering temperature. At 700°C, there must be some secondary hardening phenomenon taking place. However, that discussion is beyond the scope of this report. The proper trend is also observed with the fracture toughness results (the open diamonds). As tempering temperature is increased, the toughness gradually increases, but at 590°C the toughness increases dramatically. Also shown in Figure 5 are the effects of tempering on an all-bainite microstructure. At low temperature tempers, the toughness of all-bainite is essentially the same as the toughness of the mixture. At 480°C, the mixed microstructure is somewhat above the all-bainite properties, and at 590°C the mixed microstructure gives properties significantly above the all-bainite microstructure. This suggests that with low temperature tempering, the toughness properties of the mixed microstructure are controlled by the properties of the bainite. At higher tempering temperatures, some other property must control the properties of the mixture.

Figure 6 demonstrates which property may control the toughness properties by showing the effects of tempering on the hardness of an all-martensite and an all-bainite microstructure. This figure also compares the effects of tempering on the hardness of the mixed microstructure. At tempering temperatures below about 700°F (370°C), bainite does not temper; the hardness remains constant. In the same tempering temperature range, martensite and the mixed microstructure



will gradually soften. However, the hardness of the mixed microstructure cannot be determined from a knowledge of the properties of the two constituents. This suggests that under these conditions, there must be a different mechanism controlling the hardness of the mixed microstructure and the hardness of the two constituents. Weak bonding of the martensite/bainite interfaces may be the culprit. Tempering above 700°F (370°C) does indeed temper the bainite, and the change in the hardness of the bainite between 700°F (370°C) and 900°F (480°C) is significant. There is also a much larger relative change in hardness in an all-martensite microstructure between these two tempering temperatures. At the same tempering temperature range (above 900°F (480°C)), the hardness of the mixed microstructure falls between the hardness of the two constituents, suggesting that the same mechanism is controlling the hardness in all three cases. It is also interesting to note from Figure 5 that tempering at 480°C results in the mixture having a greater toughness than the all-bainite microstructure. This suggests that for increased toughness (as compared with an all-bainite microstructure), the bainite must be tempered.

## CONCLUSIONS

The results of the FY88 program have clearly demonstrated that it is possible to produce a mixed microstructure in ASTM A723 steel with superior strength and toughness relative to an all-martensite microstructure. The effect of tempering this microstructure is that the strength and toughness will be comparable to the properties of an all-martensite microstructure. To obtain superior properties, the microstructure must be tempered near 600°C.

TEMPERATURE

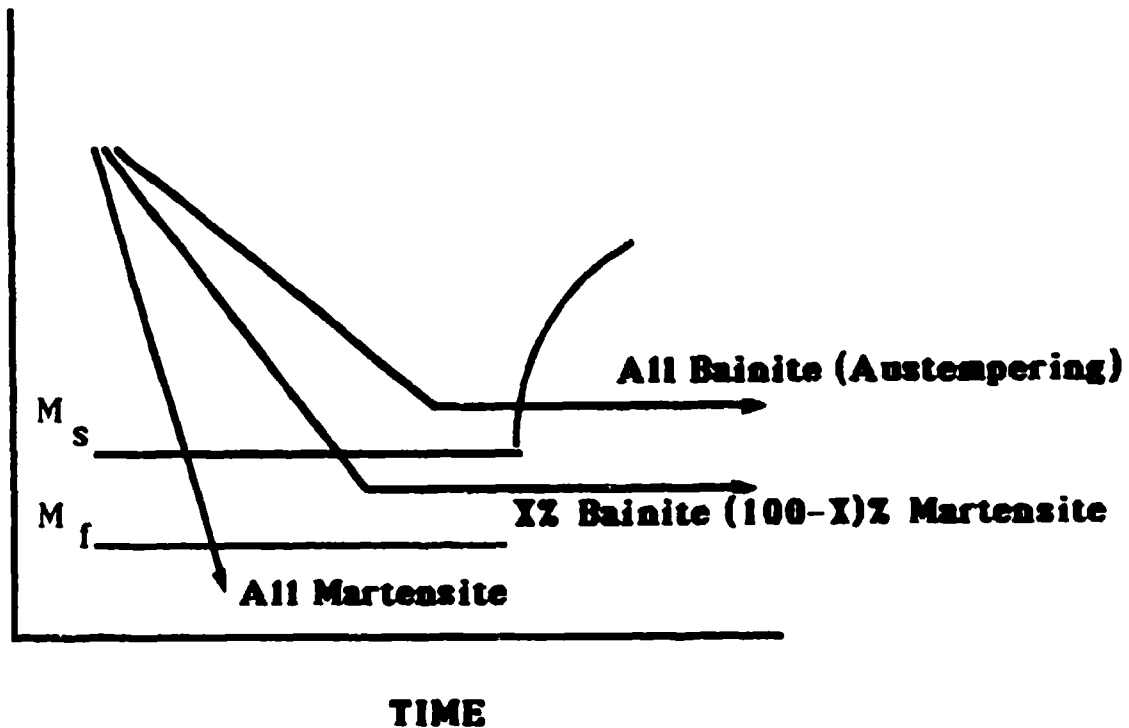


Figure 1. Various heat treatments possible with ASTM A723 pressure vessel steel.

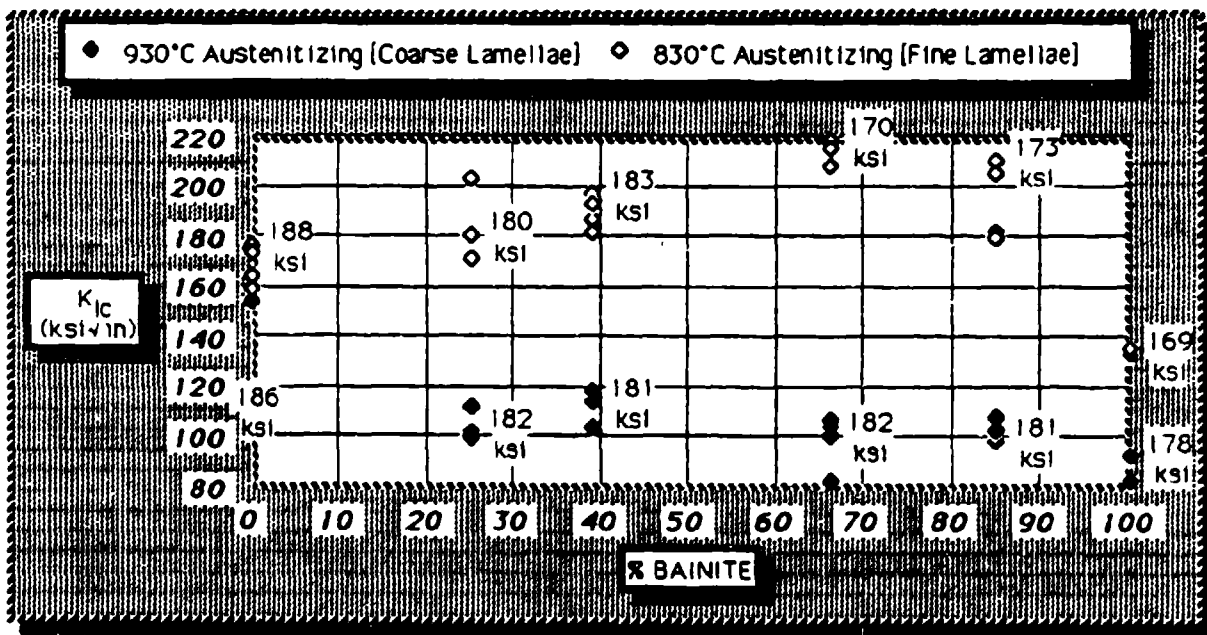
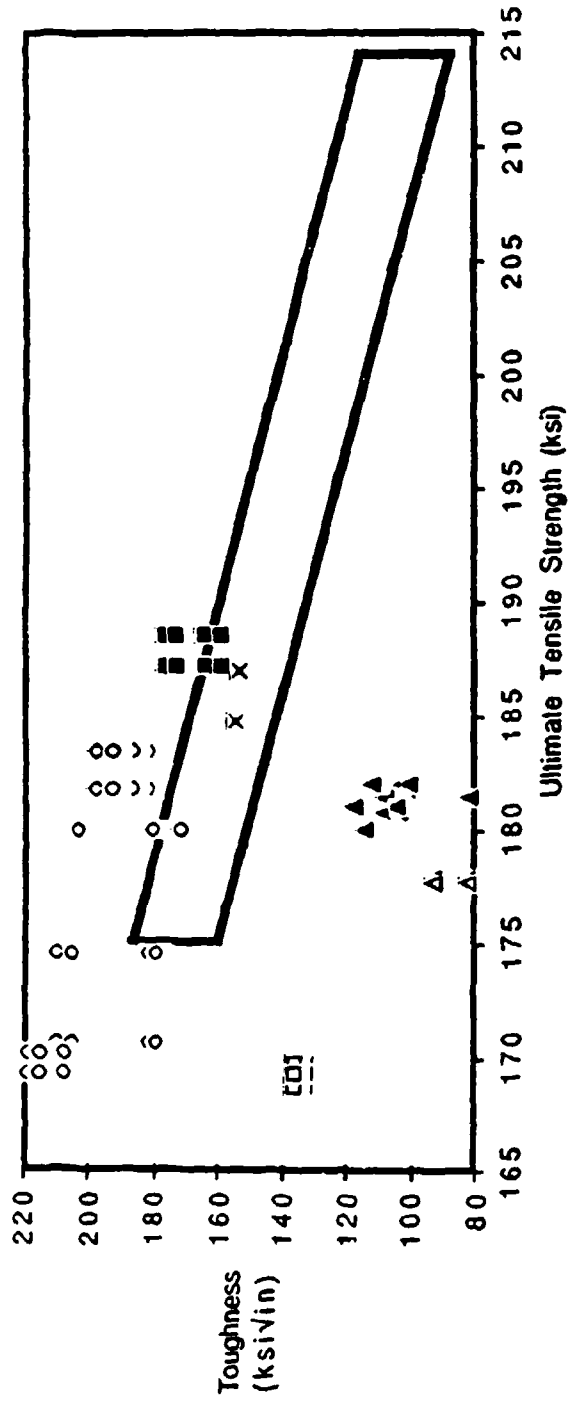


Figure 2. Toughness as a function of bainite amount.



- Range for All Martensite Microstructure
- Mixed Microstructure (830°C- Various Hold- 590°C Temper)
- All Martensite (830°C- Quench- 590° Temper)
- ◊ All Bainite (830°C- 300°C Hold- 590°C Temper)
- ▲ Mixed Microstructure (930°C- Various Hold- 590°C Temper)
- ▼ All Bainite (930°C- 300°C Hold- 590°C Temper)
- ⊗ All Martensite (930°C- Quench- 590° Temper)

Figure 3. Strength-toughness comparisons.

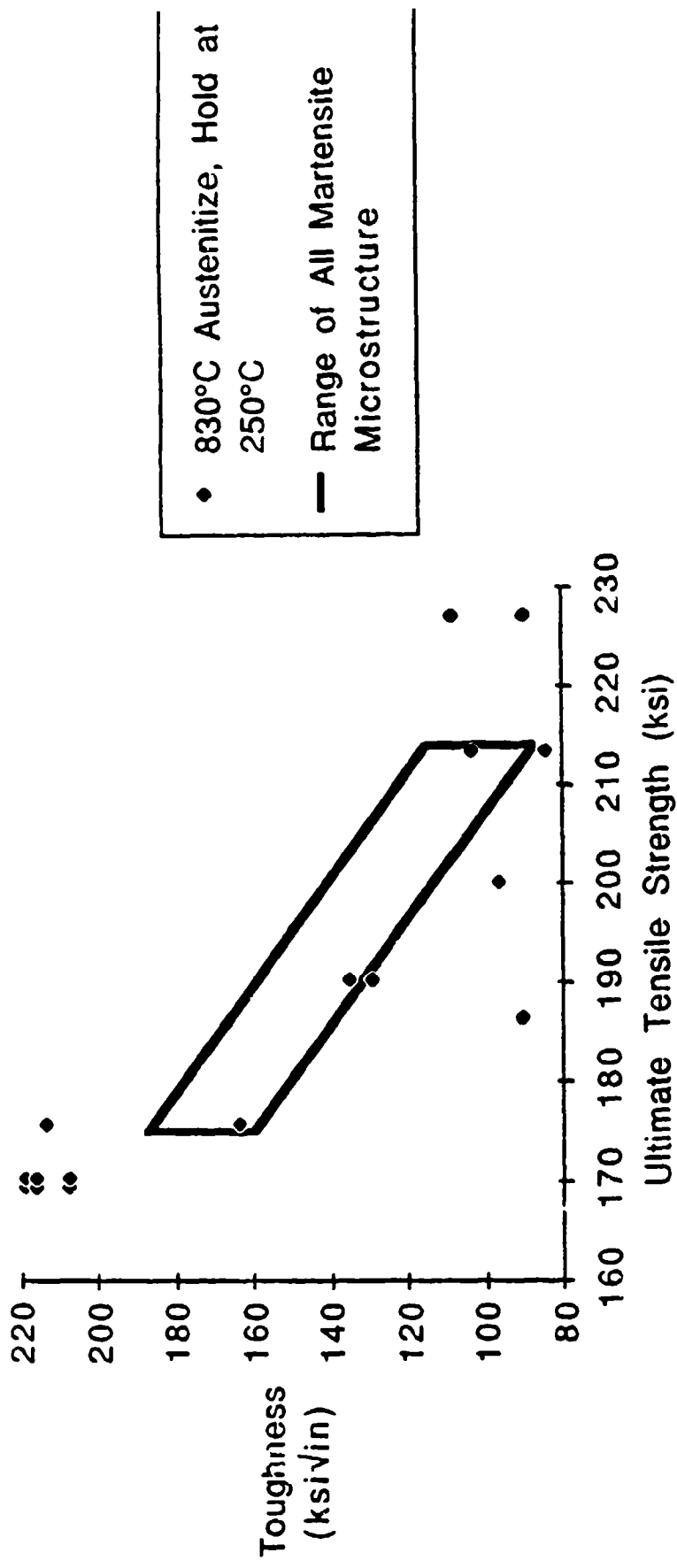


Figure 4. Effects of tempering on toughness.

830°C Austenitize, Hold at 250°C

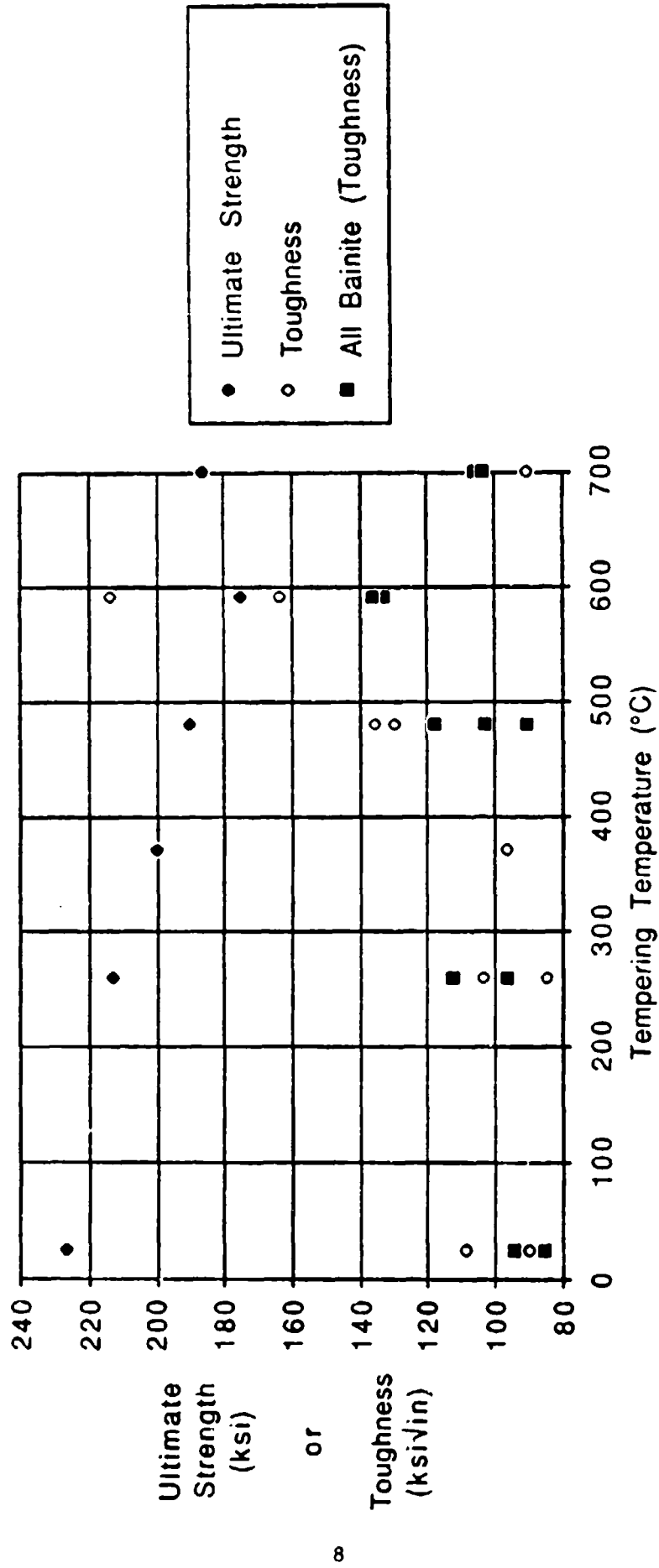


Figure 5. Effects of tempering on properties.

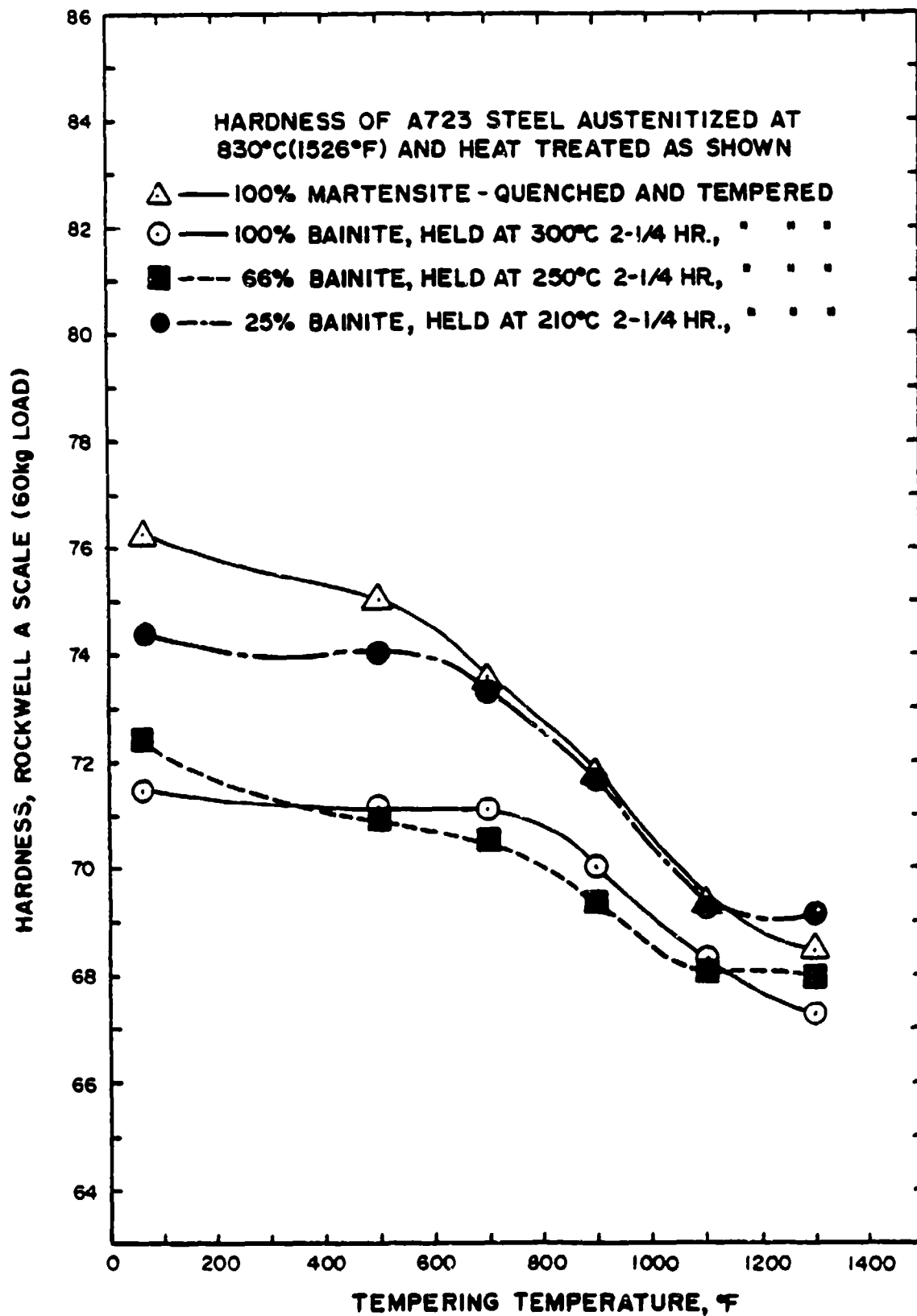


Figure 6. Hardness of A723 steel austenitized at 830°C (1526°F) and heat treated.

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