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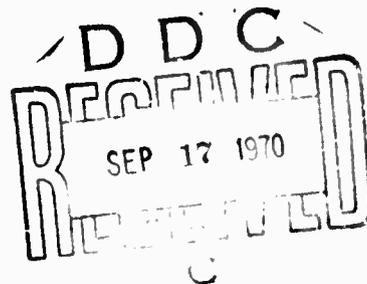
OPTIMIZATION OF PROPERTIES
IN
TWO HIGH STRENGTH STAINLESS STEELS

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OPTIMIZATION OF PROPERTIES IN TWO HIGH-STRENGTH STAINLESS STEELS

by D. Webster

ABSTRACT

It has been found possible to increase the strength and toughness of two high-strength stainless steels, AFC 77 and AFC 260, by austenitizing at temperatures that are in the range where both austenite and delta ferrite are stable. The delta ferrite is then removed by isothermal transformation in the range 1800° to 2000°F. This technique results in a greater solution of carbides and intermetallic particles and consequently in a greater amount of retained austenite than is possible at austenitizing temperatures below the delta-ferrite range. In addition, the technique permits optimum mechanical properties to be obtained over a wider compositional range.

INTRODUCTION

Previous work (1) has demonstrated the increased toughness and stress-corrosion resistance that may be produced in AFC 77 by controlled amounts of retained austenite. The high austenitizing temperatures used to insure the presence of austenite in the final structure also increase the alloy content of the matrix through greater solution of carbides and intermetallic particles. A limit on the maximum austenitizing temperature that can be used is set by the formation of delta ferrite, which is known to lower ductility and toughness in stainless steels. However, in AFC 77 and AFC 260 it has been found possible to remove the ferrite isothermally at temperatures in the range 1800° to 2000°F. This allows use of

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austenitizing temperatures that are higher than normal, greater retention of austenite and, in general, improves mechanical properties. The object of the present work is to document the changes in microstructure and mechanical properties produced by this technique.

MATERIAL

Two steels--AFC 77 and AFC 260--were studied in this investigation. Both steels were developed by Crucible Steel Company under Air Force contracts. The AFC 260 was obtained as 9/16-in.-thick plate and the AFC 77 both as 3-in.-dia. bar and 0.090-in.-thick sheet. Analysis showed the AFC 77 sheet, nominally 0.15% carbon, to be only 0.115% carbon, which is outside the recommended range (0.13% to 0.18%). However, in this study the low carbon content was an advantage in that it provided a more severe test of the delta-ferrite removal technique than would be provided by material within the AFC 77 composition range. The chemical compositions of the materials tested are given in Table 1.

EXPERIMENTAL PROCEDURE

HEAT TREATMENT

Specimens from the AFC 77 bar and the AFC 260 plate were austenitized 1 hr in argon or vacuum at several temperatures between 1800° and 2200°F; however, those from the AFC 77 sheet were austenitized at 1900° and 2200°F only. Delta ferrite was formed at austenitizing temperatures above 2100°F in the AFC 77 specimens and above 1900°F in the AFC 260 specimens. The amount of delta ferrite was reduced in these specimens by isothermal treatments at 1900°F, using isothermal holding times of 1 hr for the AFC 77 bar and AFC 260 plate and 20 hr for the AFC 77 sheet.

Delta-ferrite stringers that had been present in the AFC 77 sheet in the as-received condition and that because of the low carbon content of the material had not been removed by austenitizing 1 hr at 1900°F were removed by this two-stage austenitizing treatment.

After the austenitizing treatments, the AFC 77 bar and sheet specimens were cooled to -100°F for 1 hr and then tempered at temperatures between 700° and 1100°F for 2 + 2 hr. The AFC 260 plate specimens were also cooled to -100°F for 1 hr, but were then cooled to -320°F for 1 hr before tempering at temperatures between 800° and 1100°F for 2 + 2 hr. Some AFC 260 specimens were given an extended subzero treatment of 48 hr at -100°F followed by 1 hr at -320°F.

Isothermal-transformation diagrams for the AFC 77 sheet and AFC 260 plate were determined at temperatures between 2000° and 1600°F for times between 15 min and 100 hr. Specimens were transferred from a furnace at 2200°F to a second furnace at the isothermal holding temperature. After the isothermal treatment, the specimens were water quenched and examined metallographically. The amount of delta ferrite was determined by point counting, using 1,000 points. Because of the time required for the specimens to cool from 2200°F to 1700°F and 1600°F, some ferrite transformation probably occurred during cooling; this has been taken into account in drawing the isothermal-transformation diagrams.

MECHANICAL-PROPERTY TESTS

Mechanical-property tests were performed on specimens of the AFC 77 bar and sheet and the AFC 260 plate after heat treatment. Some mechanical-property tests were also conducted on specimens of AFC 77 sheet from which the ferrite formed during austenitizing at 2200°F had not been removed.

Tension tests on the AFC 77 bar and AFC 260 plate were conducted at room temperature on 0.25-in-dia specimens tested at a strain rate of 0.005 in./in./min through yield and then loaded at a crosshead rate of 0.10 in./min to failure. Tension tests on the AFC 77 sheet were conducted at 0.02 in./in./min to failure.

Fracture-toughness tests on the AFC 77 bar and AFC 260 plate were conducted on fatigue-precracked, single-edge-notched bend (1.5 by 7.5 by 0.48 in.) and Charpy specimens. For K_{Ic} values above $100 \text{ ksi}\sqrt{\text{in.}}$, the Charpy specimens gave values about 10% lower than the notched bend specimens. Some of the notched bend specimens in the toughest heat-treatment conditions were too thin to meet ASTM requirements, so the reported values may be conservative (2).

Fracture-toughness tests on AFC 77 sheet were conducted on precracked, subsize Charpy specimens tested in three-point bending, using maximum load to calculate a K value. Although the specimens were too thin to provide valid K_{Ic} values, it is thought that the results will reliably indicate relative toughness. The results on these subsize specimens show the same trend of increasing fracture toughness with increasing austenitizing temperature and decreasing tempering temperature as the larger specimens from the AFC 77 bar.

Stress-corrosion tests on the AFC 260 plate were carried out on fatigue-precracked Charpy and single-edge-notched bend specimens tested in cantilever bending. Testing was carried out in 3.5% salt solution (sodium chloride) with fresh solution constantly dripping into the upturned notch. The crack was immersed in the salt solution before the load was applied.

RESULTS

MAXIMIZATION OF RETAINED AUSTENITE CONTENT

It has previously been shown (1) that the fracture toughness of AFC 77 is a function of the retained austenite content, which can be increased by raising the austenitizing temperature. The delta ferrite formed at high austenitizing temperatures is unstable at lower temperatures and can be isothermally transformed to austenite (Fig. 1). The rate of this transformation for AFC 77 sheet and AFC 260 plate austenitized at 2200°F is shown in Fig. 2. If allowance is made for the ferrite transformation that probably occurs during cooling to the lower transformation temperatures, a classical C-curve can be

constructed for both materials (Figs. 3 and 4). Only in the range 1800° to 2000°F can the delta ferrite be completely removed. Transformation curves for AFC 77 of normal carbon content would be moved to the left of that shown in Fig. 3.

The large amount of delta ferrite present in a sample of AFC 77 sheet that was austenitized at 2200°F is shown in Fig. 5. After holding 100 hr at 1900°F, the sample is virtually free of delta ferrite (Fig. 6). The delta ferrite effectively pins the austenite grain boundaries at high temperatures, resulting in a fine austenite grain size. As the ferrite is isothermally removed, a marked increase in austenite grain size is observed (compare Figs. 5 and 6).

The morphology of the delta ferrite changes with transformation temperature. At 2000° and 1900°F the delta-ferrite islands shrink uniformly while maintaining approximately the same shape. At lower temperatures the large islands of ferrite break up into numerous smaller particles, and this effect becomes more pronounced as the transformation temperature is lowered. The skeletal remains of a large ferrite block held 4 hr at 1600°F can be seen in Fig. 7.

MECHANICAL PROPERTIES

AFC 77 Bar

A summary of the tensile and toughness values for AFC 77 bar is shown in Fig. 8. In general there is a continuous improvement in the strength-toughness combination as austenitizing temperature is increased, with the most dramatic improvements being obtained in the 1800° to 2000°F range. The ductility of the material does not seem to be markedly dependent on austenitizing temperature (Fig. 9). However, the low ductility obtained by tempering at 900° and 1100°F after austenitizing at 2000° and 2100°F seems to be eliminated by the two-stage (2200° + 1900°F) austenitizing treatment.

AFC 77 Sheet

The strength of AFC 77 sheet (Fig. 10) is similar to that of the bar stock, although it is somewhat lower as a result of the low carbon content. Raising the austenitizing temperature from 1900° to 2200°F produces a marked drop in strength due to the formation of delta ferrite. Removal of the delta ferrite produced at 2200°F by isothermal transformation at 1900°F increases the strength to that obtained by austenitizing directly at 1900°F, while maintaining a much higher toughness level. A comparison of the toughness values of specimens austenitized at 2200°F shows that the removal of delta ferrite increases the toughness at all tempering temperatures. However the embrittling action of delta ferrite is more pronounced after tempering at 900°F and 1100°F than at 700°F and this may be related to precipitation within the ferrite at the higher temperatures. Little difference in toughness and strength was observed between specimens taken in the transverse and in the longitudinal grain directions.

This same 0.090-in.-thick AFC 77 sheet material was extensively investigated by Ault et al. (3), who used a single austenitizing temperature of 1900°F. The strength properties reported by these workers is in general agreement with the results reported here for the same austenitizing temperature.

AFC 260 Plate

The effect of austenitizing temperature on the tensile properties of AFC 260 plate is shown in Fig. 11. Small but significant increases in tensile strength are observed for each increase in austenitizing temperature. However, the yield strength is somewhat lower in specimens austenitized at 1900°F than in those austenitized at 1800°F. An extended subzero treatment of 48 hrs. at -100°F produces a significant increase in yield strength but little change in ultimate strength. The toughness of specimens austenitized at 1800°F is markedly lower than that of specimens austenitized at temperatures from 1900° to 2200°F (Fig. 12).

The stress-corrosion threshold K_{Isc} decreases slightly as the tempering temperature is increased. There was no measurable change in fracture toughness produced by the extended subzero treatment.

DISCUSSION

A significant improvement in mechanical properties can be achieved in AFC 77 and AFC 260 by austenitizing at temperatures high enough to form delta ferrite. Although the delta ferrite thus formed is detrimental to strength, toughness, and ductility, its removal by isothermal transformation results in a final microstructure that possesses a superior combination of strength and toughness.

A further advantage of the two-stage austenitizing treatment is that it allows a wider composition range to be specified for these high-strength stainless steels. This is illustrated in Fig. 12. If the ratio of austenite-forming elements to ferrite-forming elements is high, there will be a region around 2000°F where the austenitizing temperature is high enough to cause a significant amount of austenite to be retained after heat treatment, but low enough to avoid the formation of delta ferrite (Fig. 13a). This is the normal condition for AFC 77 within the specified composition range. However, if the ratio of austenite-forming elements to ferrite-forming elements is low, there may be no range of austenitizing temperature in which optimum properties can be obtained (Fig. 13b). AFC 260, because of its low carbon content and in spite of its higher nickel content, has a greater tendency to form delta ferrite than AFC 77.

CONCLUSIONS

1. Delta ferrite produced by austenitizing AFC 77 and AFC 260 at high temperatures can be isothermally transformed to austenite in the range 1800° to 2000°F.

2. A two-stage austenitizing treatment designed to take advantage of this effect has been shown to produce a better combination of strength and toughness in these steels.
3. Delta ferrite reduces the strength and toughness of AFC 77, especially after tempering temperatures above 700°F are used.

ACKNOWLEDGMENT

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3. R. T. Ault, R. B. Holtman, and J. R. Myers, "Heat Treatment of a Cr-Mo-Co Martensitic Stainless Steel for Optimum Combinations of Strength, Toughness, and Stress-Corrosion Resistance," Trans. ASM Quart., Vol. 61, March 1968, p. 75.

Table 1 Composition (weight percent)

Material	Heat	C	Si	Mn	S	P	Mi	Cr	Mo	V	Co	Cb	N
AFC 77 3-in.-dia bar	64555	0.16	0.13	0.18	0.021	0.015	0.21	14.0	5.02	0.23	13.41	---	0.04
AFC 77 0.090-in.-thick sheet	46073	0.115	0.07	0.10	0.008	0.010	0.080	14.22	4.62	0.30	12.93	---	0.03
AFC 260 9/16-in.-thick plate	063573	0.08	0.30	0.34	0.012	0.015	1.94	15.42	4.30	---	13.03	0.14	0.04

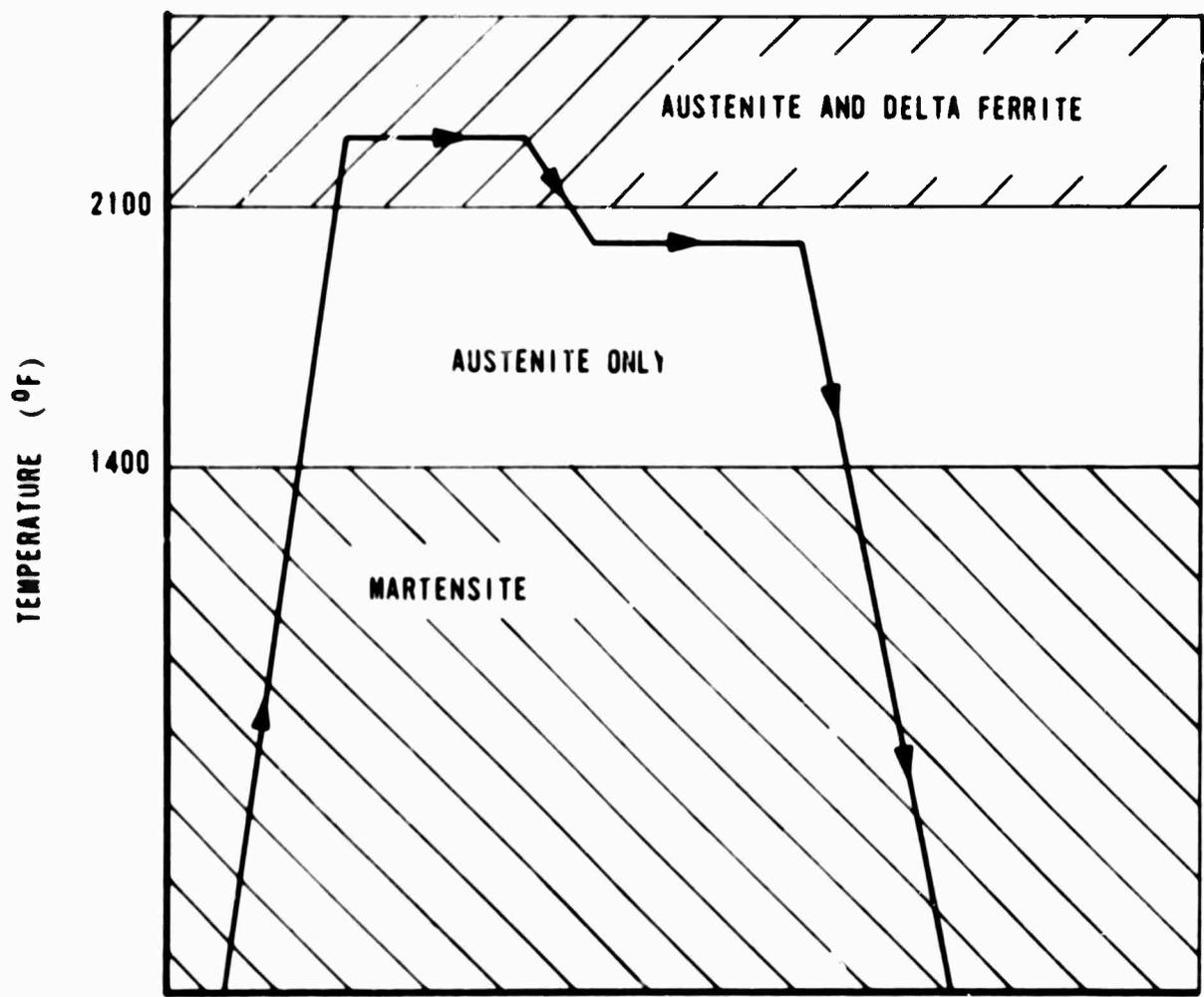


FIGURE 1 - TWO-STAGE AUSTENITIZING TREATMENT FOR REMOVAL OF DELTA FERRITE.

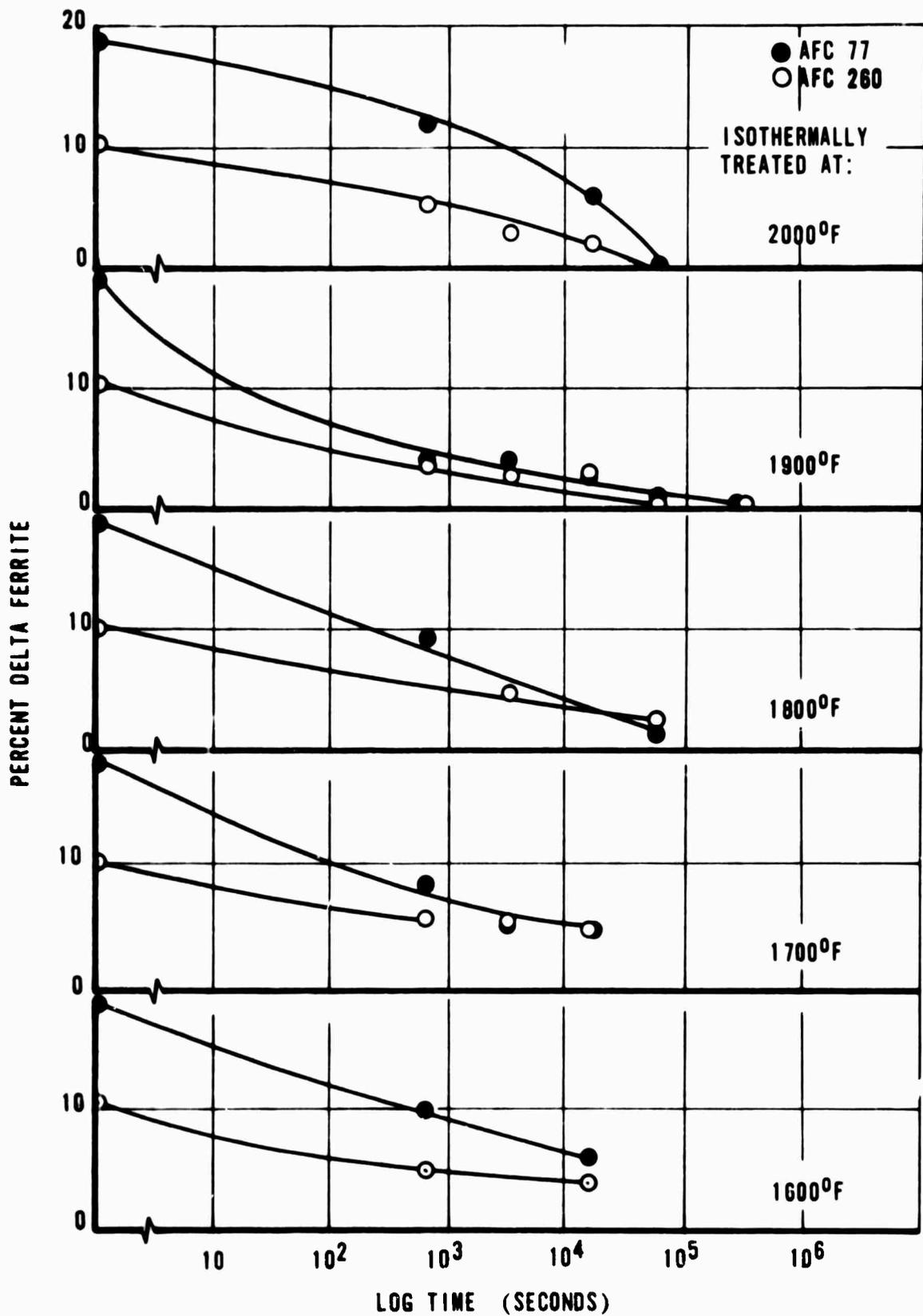


FIGURE 2 - RATE OF DELTA-FERRITE REMOVAL IN AFC 77 SHEET AND AFC 260 PLATE AUSTENITIZED 1 HR AT 2200 F

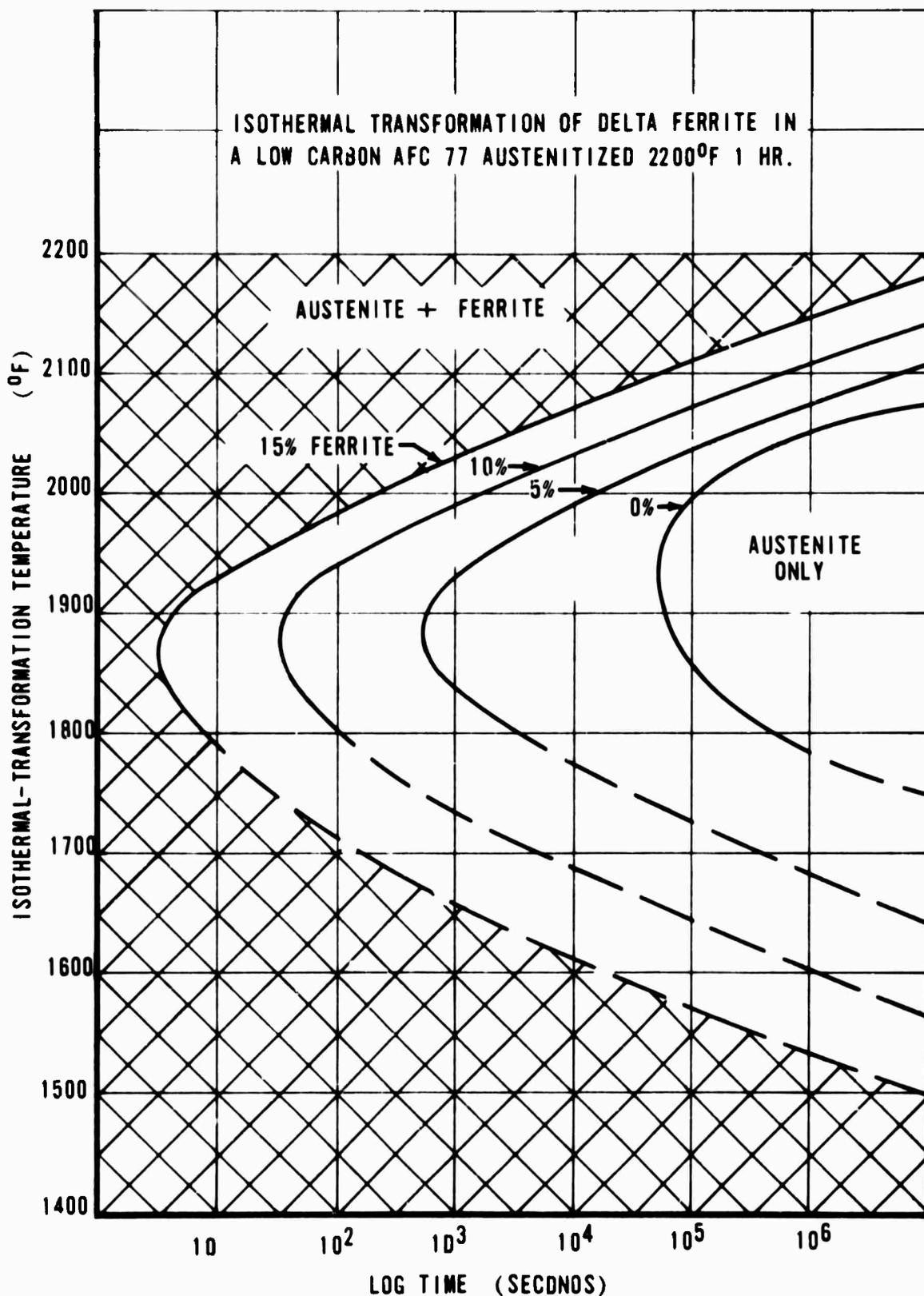
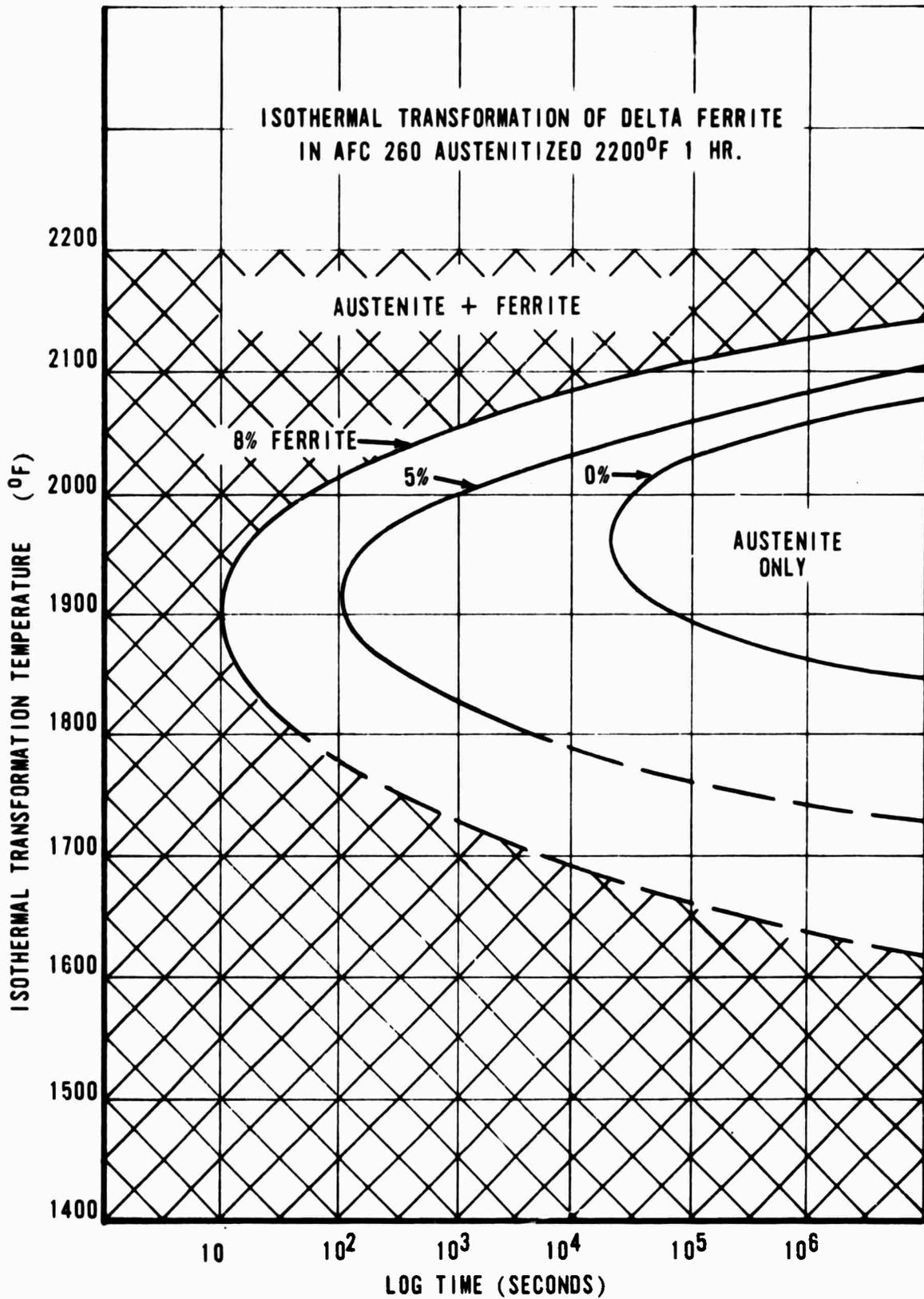


FIGURE 3 - ISOTHERMAL TRANSFORMATION OF DELTA FERRITE IN LOW-CARBON
AFC 77 SHEET AUSTENITIZED 1 HR AT 2200 F



**FIGURE 4 - ISOTHERMAL TRANSFORMATION OF DELTA FERRITE IN AFC 260
PLATE AUSTENITIZED 1 HR AT 2200 F**



FIGURE 5 AFC 77 SHEET AUSTENITIZED 1 HR AT 2200^oF AND WATER QUENCHED, SHOWING DELTA FERRITE (x 800)



FIGURE 6 AFC SHEET AUSTENITIZED 1 HR AT 2200^oF FOLLOWED BY 100 HRS AT 1900^oF. THE DELTA FERRITE SHOWN IN FIGURE 5 HAS BEEN REMOVED AND THE AUSTENITE GRAIN SIZE HAS INCREASED. (x 800).

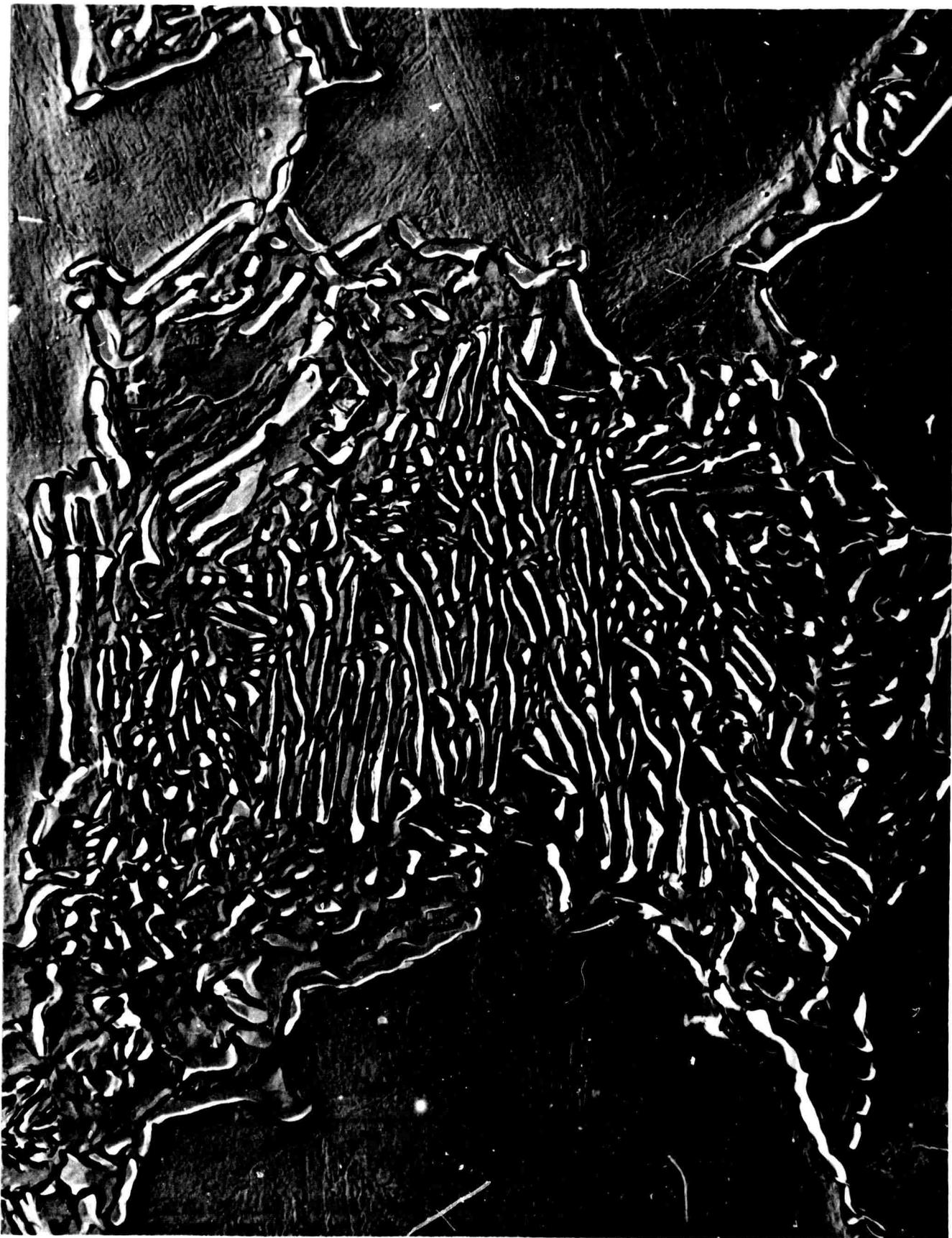


FIGURE 7 EUTECTIC-LIKE REMAINS OF A LARGE BLOCK OF DELTA FERRITE IN AFC 77 SHEET AT 1600° F (x 6000).

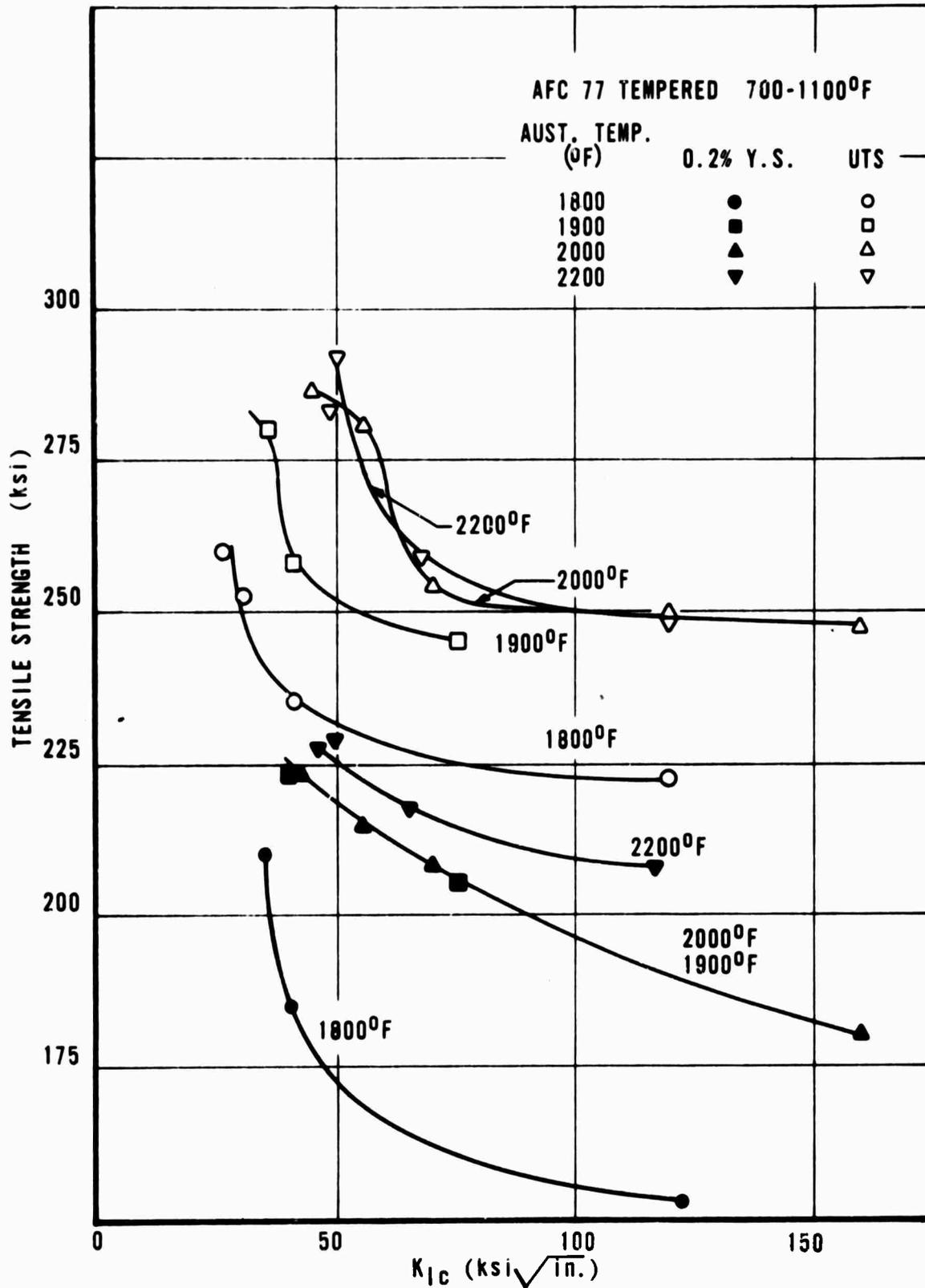


FIGURE 8 - SUMMARY OF THE STRENGTH-TOUGHNESS VALUES OBTAINED ON AFC 77 BAR AUSTENITIZED AT TEMPERATURES BETWEEN 1800 AND 2200 F.

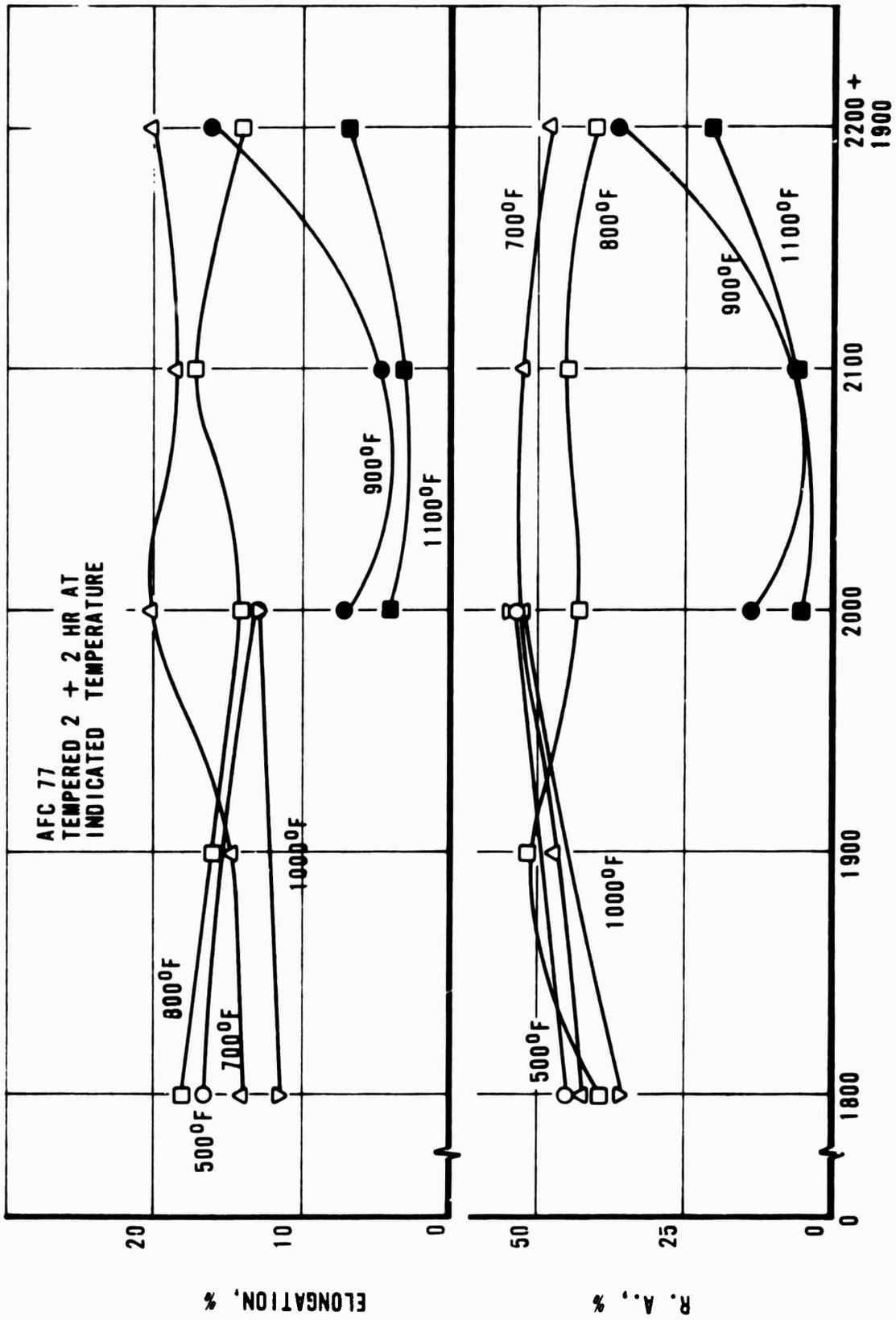


FIGURE 9 - DUCTILITY OF AFC 77 BAR AS A FUNCTION OF AUSTENITIZING AND TEMPERING TEMPERATURES

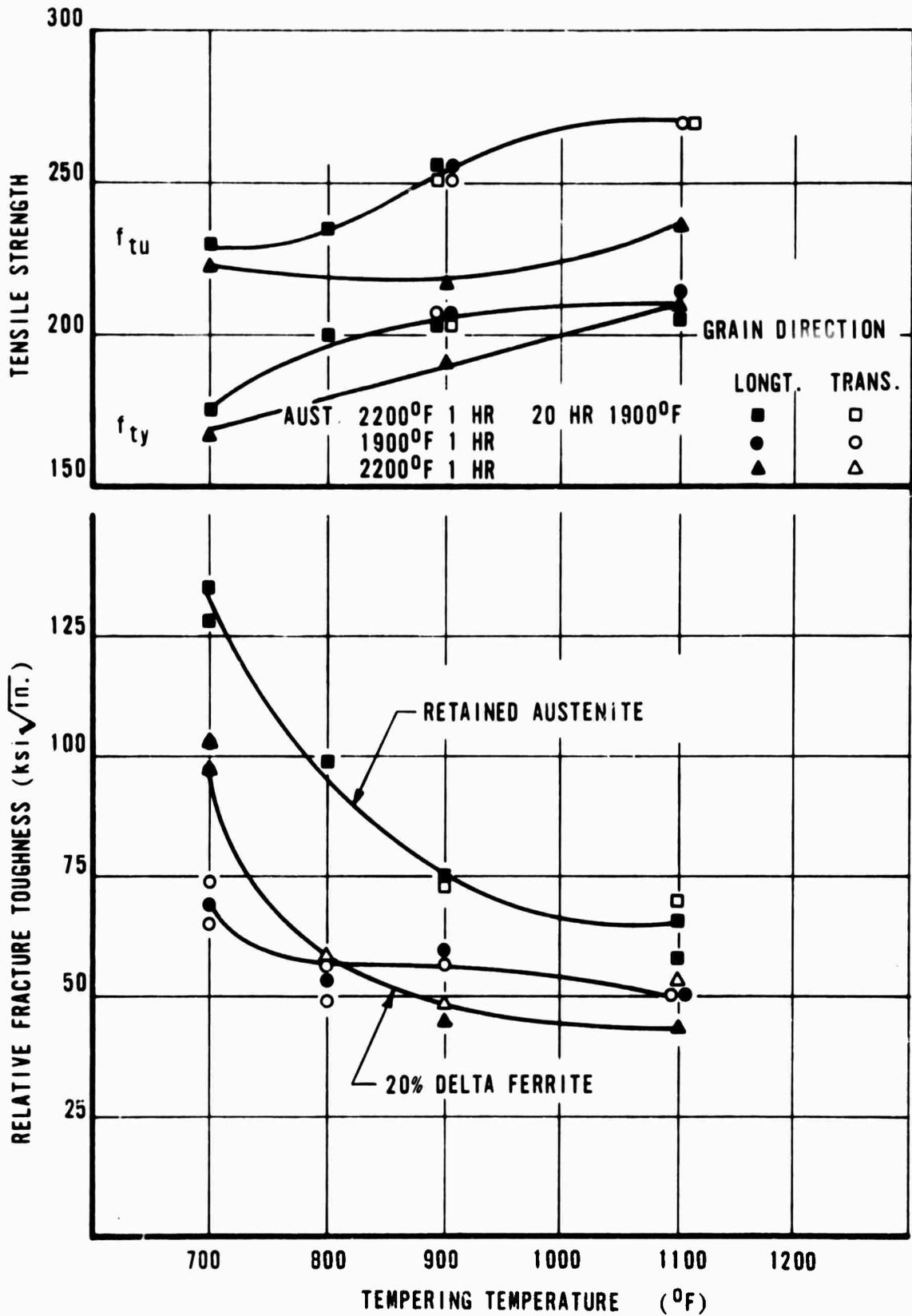


FIGURE 10 - STRENGTH AND TOUGHNESS OF LOW CARBON AFC 77 SHEET

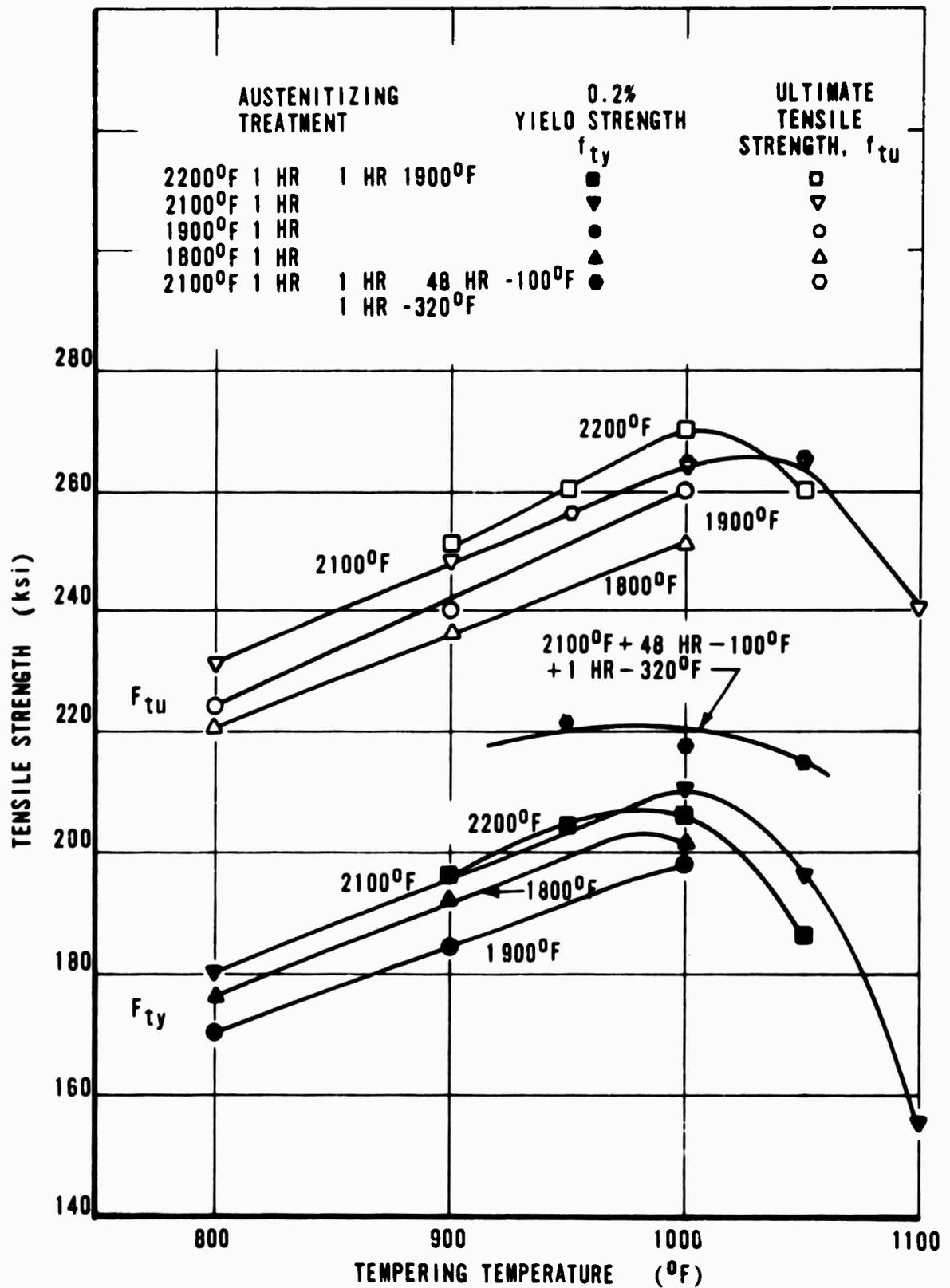


FIGURE 11 - STRENGTH OF AFC 260 AS A FUNCTION OF AUSTENITIZING AND TEMPERING TEMPERATURES.

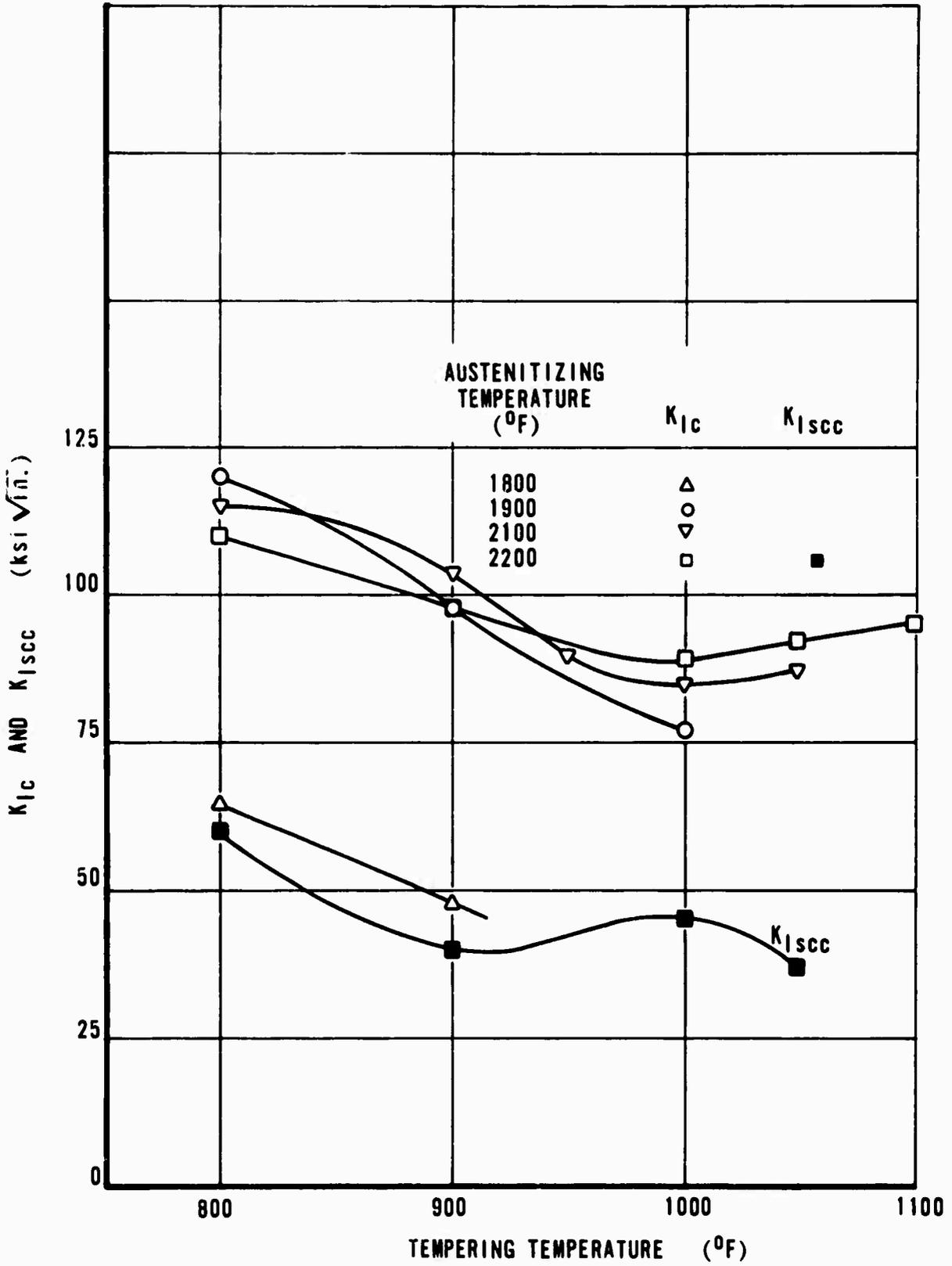
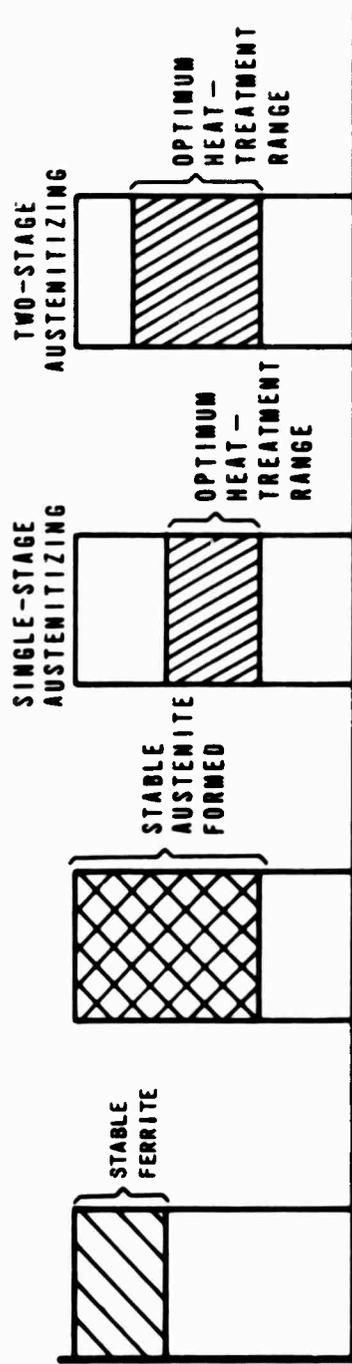


FIGURE 12 - TOUGHNESS AND STRESS-CORROSION RESISTANCE OF AFC 260 AS A FUNCTION OF AUSTENITIZING AND TEMPERING TEMPERATURES

HIGH RATIO OF AUSTENITE/FERRITE FORMING ELEMENTS



LOW RATIO OF AUSTENITE/FERRITE FORMING ELEMENTS

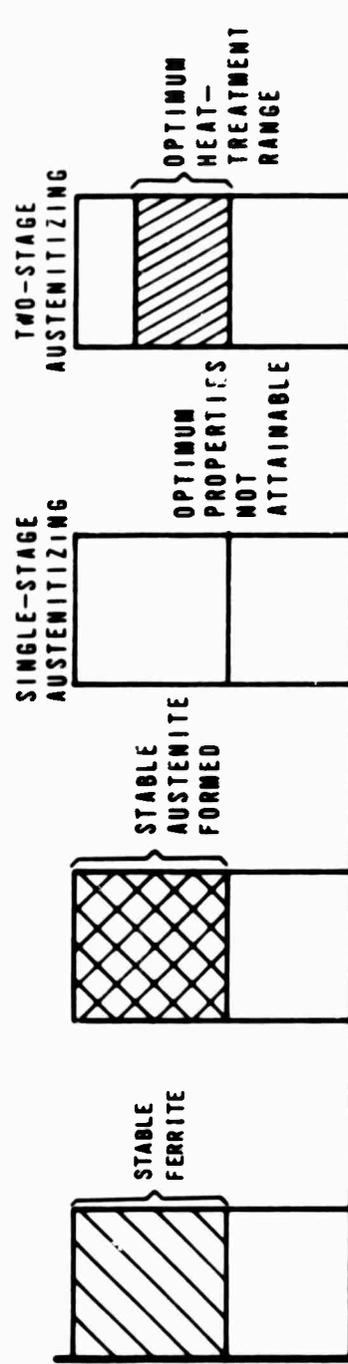


FIGURE 13 - SCHEMATIC ILLUSTRATION SHOWING HOW A TWO-STAGE AUSTENITIZING TREATMENT INCREASES THE TEMPERATURE RANGE IN WHICH OPTIMUM MECHANICAL PROPERTIES CAN BE OBTAINED.

AUSTENITIZING TEMPERATURE

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High Strength Stainless Steels Increased Strength and Toughness Isothermal Transformation of Delta Ferrite						