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NBSIR 87-3649

Effects of Varying the Austenitizing Temperature on the Ability of HSLA-80 Steel to Achieve A Yield Strength of 689.5 MPa and Toughness Comparable to HSLA-100

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Administrative Information

The investigation reported herein was funded by the Surface Ship and Technology Block Program sponsored by the Materials Block Program (DTNSRDC code 012.5) and funded under Program Element 62234N, Task Area RS-3 -S50, Work Unit 1-2803-117-13, FY87. The effort was monitored by Mr. E. J. Czyryca, David Taylor Naval Ship R & D Center (Code 2814).

Executive Summary

This is the first of two reports on maximizing the mechanical properties of HSLA-80 steel by heat treatment. This report concentrates on the optimization of the austenitization treatment and cooling rate. The optimum austenitization temperature was found to vary with plate thickness: 899°C for 19 mm (3/4 in) thick plate, 927°C for 32 mm (1 1/4 in) thick plate, and 954°C for 51 mm (2 in) thick plate. In all cases the time-at-temperature was 60 minutes followed by an immersion quench in water. Double austenitization and other quenching rates did not significantly improve the mechanical properties. Even at this preliminary stage, a heat treatment was found for 19 mm thick HSLA-80 plate that improved this plate's tensile and impact properties beyond those specified for HSLA-100.

Introduction

Metallurgical evaluations are currently being conducted by the U. S. Navy on a high strength-low alloy, precipitation hardenable steel, HSLA-80. Because of its exceptional yield strength and impact properties, this steel is being considered as a replacement for HY-80. In addition to the excellent mechanical properties, another advantage this steel appears to have over HY-80 is that no pre-or post-weld heat treatments are required.

Currently research and development is simultaneously being conducted on a new steel, designated as HSLA-100. This steel is projected to possess yield strength and impact properties superior to those of the current HSLA-80. The question arose as to whether the HSLA-80 steel could be heat treated in such a manner that resulted in mechanical properties equal to or better than those of HSLA-100. It was concluded that heat treating experiments should be conducted on HSLA-80 in order to determined whether this was attainable.

Hicho and Fields (1) in a previous paper had shown the effects of various heat treatments on the mechanical properties of HSLA-80. In that work, it was shown that HSLA-80 approaches the peak aged condition at 482°C, and was termed overaged at temperatures of 538°C and above. These conditions were found to occur at precipitation hardening times of 30 minutes and longer. It was also shown that the time at the austenitizing temperature, be it 30, 60, or 90 minutes, had no significant effect on the plate's mechanical properties. Plate sizes of 19 mm, 32 mm, and 51 mm were evaluated in that paper.

The objective of the present research was to optimize the mechanical properties of HSLA-80 steel by heat treatment. This paper presents the effects of different austenitizing temperatures on the mechanical properties of this steel. The precipitation hardening temperatures were held constant at 482°C and 538°C.

The effects of multiple austenitizing treatments were also examined here. Niobium (2,3) was shown to help retard austenite recrystallization during hot rolling and to make grain refinement possible. Jesseman and Murphy (4) reported that grain size control during austenitizing was also provided by niobium carbonitride precipitates. It was concluded that if a plate was water quenched from a temperature greater than 982°C, and then quenched from a second austenitizing temperature (double austenitizing), then it may be possible to produce fine grained ferrite, and also both fine niobium carbonitrides and copper precipitates. These three, in combination, could possibly lead to a yield strength greater than 689.5 MPa, and an increase in toughness equal to or greater than that obtained for HSLA-100.

The effects of cooling from the austenitizing temperature using oil and air on the mechanical properties of 19 mm thick plates were also examined and these results are also presented in this paper. Finally, the effects of the cooling rates on two 51 mm thick plates that were quenched in room temperature brine, and ice and brine will also be presented.

Background

HSLA-80 steel is a precipitation hardening ferritic steel containing about 1.2 percent copper which is used to obtain strength and toughness by the precipitation of copper on aging. The primary element responsible for strengthening in this steel, copper, was found (5) to have a maximum solubility of 3% at the austenitizing temperature, and limited solubility at room temperature. When the steel is rapidly quenched from the austenitizing temperature, a large amount of copper is retained in the ferrite, and at the appropriate temperature, the copper in the supersaturated ferrite precipitates as epsilon-copper. These fine copper precipitates, being incoherent with the lattice, impede dislocation motion and produce the exceptional yield strength observed in this steel.

Niobium when added to the steel acts as an austenite grain refiner. Because of its limited solubility, niobium allows the formation of niobium carbonitrides which act as nuclei for the formation of the fine ferrite. Aluminum and nitrogen, in combination, also act as austenite grain refiners. They appear to have a somewhat supportive effect on the resultant properties, less than the primary strengthener copper, and the secondary strengthener niobium. In addition to the effects of these elements, Jesseman and Murphy (4) have reported that chromium and molybdenum are used to retard epsilon-copper precipitate nucleation and the subsequent growth in order that reproducible properties can be obtained by conventional, industrial heat treatment.

Material Used and Experimental Procedure

There were three plates of steel received from the Navy (DTNSRDC) for evaluation. The plates were 19 mm, 32 mm, and 51 mm in thickness. Accompanying the plates were manufacturer test reports which identified the plates as to their composition, heat treatment, and mechanical properties. The manufacturer's test reports indicated that the 19 mm thick plate was "ASTM, A710, Grade A, Class 3 steel, austenitized at 899°C for 45 minutes, water quenched, and precipitation hardened at 593°C for 30 minutes and air cooled." The 32 mm thick plate, also A710, was austenitized at 899°C for 60 minutes, water quenched, and precipitation hardened at 593°C for 30 minutes, and then air cooled. The 51 mm plate was reported to be "ASTM A710, Grade A, Class 3 plate austenitized at 899°C to meet above properties." The chemical composition of the test plates is shown in Table 1.

Prior to the sectioning of the test coupons from the larger plates, an investigation was conducted to determine the coupon size needed to simulate a full plate quench. Quenching or cooling rates are difficult to control in the laboratory, and even more difficult in the producing mill. Hence, specifying anything other than full immersion or spray quenching would probably not be commercially feasible at this time. To simulate a full mill quench, all of the test plate coupons were sectioned so that they were at least three to five times the plate thickness in length and width. The size of the test coupons were as follows. The 19 mm thick plate's coupons were .162 m^2, (6-3/8 in. by 6-3/8 in.); the 32 mm thick plate's coupons were .152 m by .178 m, (6 in. x 7 inch) ; and the 51 mm thick plate's coupons were .238 m by .264 m, (9-3/8 in.

by 10-3/8 in.).

Standard ASTM 12.7 mm (0.500") diameter tensile specimens were machined from as close as possible the quarter-thickness location in each test coupon. The specimens were dimensioned and tested according to ASTM specification A370-84.

Standard Charpy V-notch impact specimens were also sectioned as close as possible from the quarter-thickness location in all the plates, and were dimensioned and tested according to ASTM Specification E23-84.

The tensile specimens had their tensile axes parallel to the rolling direction, and the impact specimens were taken from a direction so that the plane of fracture would be normal to the rolling direction.

The austenitizing and precipitation hardening heat treatments were performed in air furnaces with no protective atmosphere. Three plates were placed in the furnace one on top of the other. The 51 mm thick plate was placed on the bottom, the 32 mm thick plate on top of it, and the 19 mm thick plate placed on top of it. The plates were separated by spacers so that heating would be uniform. Thermocouples were inserted to a depth of 51 mm in the 51 mm thick plate, and 32 mm in the other plates. The thermocouples were used to monitor the heat up, soak, and cooling temperatures.

The austenitizing temperatures chosen for this investigation were: 843°C, 871°C, 899°C, 954°C, and 1010°C. The identifications assigned to the specimens taken from the 19 mm thick plate were as follows: 843°C - G1, G2; 871°C-G3, G4; 899°C-G5, G6; 954°C-G7, G8; and 1010°C-G9, G10. The coding repeats itself for the other plates FUQ and GFF.

After the appropriate heat up time, determined previously,the test coupons were held at the austenitizing temperature for 60 minutes. The coupons were then quenched in a 100 liter tank filled with room temperature water. The water temperature was constantly monitored and was changed after each heat treating cycle. The water temperature never exceeded 32°C. Following this treatment, the coupons were precipitation hardened at the appropriate time and temperature, then were air cooled.

Quenching plates of different thicknesses obviously produces different cooling rates. Therefore additional experiments were conducted on the 19 mm thick plates in order to determine the effects of quenching in oil or air, after austenitizing, on the mechanical properties. Two 19 mm thick coupons were austenitized at 899°C for the appropriate time, and then quenched in oil. Two additional 19 mm thick coupons were also austenitized at 899°C for the appropriate time, but cooled in air. Following both of these heat treatments, two coupons were precipitation hardened at 482°C for 90 minutes, and the other two at 538°C for 60 minutes.

Additional cooling rate effects were conducted on the 51 mm thick plate material. Two plates were austenitized at 954°C. One plate was cooled in room temperature brine, while the other plate was cooled in iced brine.

Double austenitizing treatments were also conducted on the 19 mm thick plates.

The double austenitizing temperatures chosen were 899°C/899°C, 1066°C/899°C, and 1204°C/899°C. Each coupon was held at each austenitizing temperature for 60 minutes, then quenched in water. Precipitation hardening was at 482°C and 538°C for 90 and 60 minutes, respectively, followed by air cooling.

Tensile Test Results

The tensile test results for the specimens receiving single austenitizing treatments are shown in Figures 1 and 2, and in Tables 2,3, and 4. The tensile results for the specimens receiving double austenitizing treatments are shown in Figures 3 and 4, and in Table 5. The results for the specimens that received a single austenitizing treatment and then oil quenched or air cooled are shown in Figure 5 and in Table 5.

Impact Test Results

The impact test results for the specimens given single austenitizing treatments are shown in Figures 6, 7, and 8, and Tables 6, 7,and 8. The impact results for those specimens double austenitized and water quenched, and those single austenitized and quenched in either oil or air, are shown in Figures 9 and 10, and in Table 9.

Cooling Rate Effects

The effects of cooling from the austenitizing temperature on various plate thicknesses are shown in Figures 11 and 12, and in Table 10. The cooling rate curves for the 19 mm plates that were water, oil, or air cooled is shown in Figure 13. A comparison of the cooling rates on 51 mm thick plates quenched in either water, room temperature brine, or ice and brine, are shown in Figure 14.

General Observations

The purpose of this study was to determine if any of the three plate thicknesses - 19 mm, 32 mm, or 51 mm - could be heat treated in a manner which resulted in a minimum yield strength of 689.5 MPa and impact properties at -17.8°C and -84°C equal to or better than HSLA-100. The austenitizing temperatures were varied here in hopes of obtaining an optimum temperature where these two property requirements could be simultaneously achieved by subsequent aging treatments.

For comparison purposes, the yield strength results were considered initially. Figures 1 and 2 were examined and the optimum austenitizing temperature which produced a yield strength of 689.5 MPa or greater was determined for each plate thickness.

Examination of these figures showed that the optimum austenitizing temperature, which produced a yield strength equal to or better than 689.5 MPa, was a function of plate thickness. The tensile test results, Figure 1, for specimens taken from the 19 mm thick plate GAG, and austenitized at temperatures between 885°C and 1010°C, then precipitation hardened at 482°C, indicated that the optimum austenitizing temperature was 899°C. Figure 1 also shows that the optimum yield strength can be achieved in 32 mm thick plate after austenitizing at a temperature of at least 927°C, and precipitation hardening at 482°C. A peak strength or optimum temperature was determined for the 51 mm thick plate, but unlike the plate thicknesses of 19 and 32 mm, this plate attained a maximum yield strength of only about 650 MPa after austenitizing at 1010°C and precipitation hardening at 538°C. Once the yield strength analyses were completed, the Charpy V-notch impact data for each plate exceeding the optimum yield strength of 689.5 MPa was examined.

For reference purposes, the impact acceptance criteria is as follows. The desired specification requires that at the test temperature of -17.8°C, the minimum of the average of three impact values is to be 74.6J (55 ft-lb), and at -84°C, 40.6J (30 ft-lb). In addition, no single energy absorbed value shall be below the minimum average values of 74.6J and 40.6J by more than 6.85J.

Figure 6 shows the impact data for the 19 mm thick plate tested at -17.8°C and -84°C. It was concluded from these data that impact properties <u>with</u> an acceptable yield strength could be obtained in the 19 mm thick plate when it was austenitized at 899°C and precipitation hardened at 482°C. For additional specimens taken from the 19 mm thick plate, but tested at -84°C, it was observed that only with the following heat treatments was the impact criteria met. The treatments were: 843°C and precipitation hardened at only 482°C; and austenitized between 954°C and 1010°C, and precipitation hardened at either 482°C or 538°C. The optimum austenitizing temperature chosen for the 19 mm plates was 899°C.

For the 32 mm thick plate, the desired yield strength of 689.5 MPa was obtained when the plates were austenitized at temperatures ranging from 954°C to 1010°C, but only when they were precipitation hardened at 482°C. Using these heat treatments for comparison, the impact values shown in Figure 7 for the 32 mm plate tested at -17.8°C were found to be acceptable for the plate austenitized at 1010°C, but not for the plate when it was austenitized at 954°C. Figure 7 also shows that for the specimens austenitized at temperatures from 843°C to 954°C, precipitation hardened at either 482 or 538°C, and tested at -17.8°C, the impact values were found to be acceptable. After observing these figures and associated data, 927°C was chosen as the optimum austenitizing temperature for the 32 mm thick plate.

For the 51 mm thick plate, Figure 1 shows that the 689.5 MPa yield strength was not attained at any of the austenitizing temperatures. In Figure 8, it can be seen that at 954°C, and at either a precipitating hardening temperature of 482 or 538°C, the impact values were acceptable. At -17.8°C, the impact values, with the exception of those treated at 1010°C and 482°C, were found to be representative of a tough material, and acceptable. However for those specimens tested at -84°C, the impact values were such that a majority were found to be unacceptable. Even though the desired yield strength of 689.5 MPa was not obtained for the 51 mm thick plate, the austenitizing temperature where both the optimum yield and impact strengths occurred was chosen, and that temperature was 954°C.

Examination of the impact results for these three plate thicknesses indicates that the desired combination was obtained in the 19 mm thick plate. But one must accept a "trade-off" in either yield strength or impact toughness when the 32 mm or 51 mm thick plates are considered. That is, one must either accept good yield strength, i.e. 689.5 MPa, or greater, and lower impact properties, or vice versa. The combination of these two does not appear to be attainable in the plate thicknesses of 32 mm and 51 mm for the two aging conditions studied in this part of the project. It appears this is due to the cooling rate these plates encounter, and what appears to be a significant effect of cooling rate on the resultant properties of 32 mm and 51 mm thick plates. Because of this recognizable effect of plate thickness, investigations were conducted on plates that were double austenitized in order to determine if the double austenitizing could improve the resultant mechanical properties.

Double Austenitizing Results

Tests were conducted on the effects of double austenitizing and water quenching, followed by precipitation hardening at 482 or 538°C, on 19 mm thick plate. Figure 3 shows the tensile results, and in Table 5 the data. Figure 9 shows the impact results, and in Table 9 the data for those specimens.

In the examination of the tensile data, it was noted that the yield strength did not reach the desired value of 689.5 MPa in any of the austenitizing treatments. A comparison of this data and the data for the 19 mm plates that were singly austenitized reveals that the double austenitizing did not improve the yield strength. In fact, it lowered the yield strength.

Of all the impact specimens that were double austenitized and then tested at-17.8°C, the only ones that did not meet impact specifications were those austenitized at 1204°C/899°C and precipitation hardened at 482°C. Using this treatment, the yield strength was about 675 MPa. Examination of the impact results of the double austenitized specimens tested at -84°C revealed that they all failed to meet the specification. Hence, the double austenitizing treatments were not able to raise both the yield and impact values to where they were comparable to HSLA-100.

Plates Quenched in Oil and Air

Figure 5 shows the results for the tensile tests conducted on the 19 mm plates that were air or oil cooled after receiving a single austenitization. For comparison purposes, the plate that was water quenched is also shown. The figure shows that the desired yield strength was not attained for those specimens that were oil or air cooled.

Examination of the impact data, Table 9, and curves, Figure 10, for the same plates revealed that for those specimens tested at -17.8°C, the values were acceptable. However for those specimens tested at -84°C, the impact values were unacceptable, with the exception of one heat treatment. The only plate to meet specification was that austenitized at 899°C and precipitation hardened at 538°C.

Cooling Rates of the Three Plate Thicknesses When Water Quenched

Figures 11 and 12 show the cooling rates obtained for the plates cooled in water from their respective optimum austenitizing temperatures. Noteworthy is the increase in cooling rate, up to 899°C (a maximum), for the 19 mm thick plate. Thereafter for example at 954°C and 1010°C, the cooling rate decreased drastically. It should be noted that at the austenitizing temperature of 899°C, a cooling rate of about 115 deg C/s was obtained. This cooling rate was similar to the one that produced the optimum mechanical properties in the 19 mm thick plate. Such cooling rates could not be obtained in the 32 mm and 51 mm thick plates, a possible reason for the reduced yield strength and toughness.

Cooling Rates for 51 mm Plate Quenched in Various Brines

Figure 14 shows the curves for the 51 mm thick plates that were cooled in water, room temperature brine, and a combination of ice and brine. A curve was drawn connecting only the ice and brine data. The cooling rates for the plates that were quenched in these media were essentially the same, approximately 10 deg.C /sec.

Tensile and impact tests were conducted on specimens taken from the plate that was austenitized at 954°C for 60 minutes, quenched in ice and brine, and precipitation hardened at 510°C. The yield strengths were 673 and 686 MPa (680 MPa average); the ultimate strengths were 761 and 768 MPa (765 MPa average), the reduction of areas, 72.1 and 72.3 % (72.2 % average), and the elongation in 51 mm 25.6 and 25 % (25.3 % average).

Impact tests were also conducted on specimens taken from the plate and tested at -17.8 and -84°C. At -17.8°C the impact values were 101 and 93J (97J average), and at -84°C, 39J and 52.8J (46J average).

The results indicated that even the use of an ice and brine quench did not allow the 51 mm plate to attain a cooling rate which would lead to improved impact properties. The yield strength did not reach the desired value, and only those impact specimens that were tested at -17.8°C proved to be acceptable within the requirements for HSLA-100.

The effects of the cooling rate on a similar steel were addressed by Creswick (6). He has stated that as the level of supersaturated copper increases, the cooling rate necessary to present primary copper precipitation becomes very important. He also states that below 2% copper, the minimum cooling rate for a similar steel needed to obtain optimum properties should be no less than 28 deg C/s. This cooling rate, according to Creswick, will lead to maximum copper solution and maximum age hardness. Looking at Table 12, one sees that for the 51 mm thick plate this cooling rate is never obtained, and it is somewhat questionable if it could be obtained in the 32 mm thick plate.

Creswick has also stated that if the cooling rate is too slow, it is possible to get an agglomeration and precipitation of copper. The effect of the agglomerated copper precipitate is to reduce the degree of supersaturation, and therefore the strength that can be obtained in the subsequent precipitation hardening treatment.

Discussion

HSLA-80 is a precipitation hardenable steel. The steel obtains its strength primarily from the presence of copper in this steel. It was reported by Speich (3) that the solubility of copper in pure iron at 899°C was found to be about 3%. When this steel is held at the austenitizing temperatures reported in this paper, the maximum amount of copper is dissolved in the gamma iron. With a rapid quench into water, the copper is preserved in supersaturated solution. The full hardness of the steel, i.e. yield strength, is developed during the precipitation hardening treatment. Generally, the yield strength properties tend to attain higher values at low precipitation times, as was observed in this paper. The hardness and corresponding yield strength reach a maximum value at a given precipitation hardening temperature, and then slowly decreased as a result of overaging.

Conclusions

The object of this investigation was to determine if three plate thicknesses, 19 mm, 32 mm, and 51 mm, of HSLA-80 could be heat treated in a manner where they would posses yield and impact properties equivalent to or better than HSLA-100. The path chosen to follow was to vary the austenitizing temperature, holding the time at that temperature constant, followed by precipitation hardening at 482°C and 538°C.

The results presented here have identified optimum austenitizing temperatures for significantly increasing the yield strength of HSLA-80 with a minimum reduction in toughness. These optimum temperatures were found to be dependent on plate thickness: 899°C for 19 mm thick plate, 927°C for 32 mm, and 954°C for 51 mm thicknesses.

In addition to the findings on the variation of austenitizing temperatures, cooling rate studies showed water immersion or spray quenching to be a major prerequisite for high strength in this alloy. It does appear that the desired properties could be achieved in the 19 mm thick plate, but could not be obtained in the 32 mm and 51 mm thick plates. The cooling rate did not appear to be sufficient in these plate thicknesses to produce the desired properties. Cooling the 51 mm thick plates in ice and brine also did not improve the mechanical properties. Multiple austenitizing was not found to be superior to a single austenitizing treatment.

Having determined the optimum austenitizing temperatures, a second phase of the investigation will be undertaken: the optimization of the precipitation hardening temperatures and times (7) in order to determine if HSLA-80 could achieve HSLA-100 properties.

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Table 1. Chemical composition of test plates. Values are in weight percent.

Element	ASTM A710, Gr. A	Plate GAG	Plate FUQ	Plate GFF
Carbon (max)	0.07	.05	.05	.04
Manganese	.40-.70	.53	.61	.59
Phosphorus (max)	.025	<.005	.006	.006
Sulfur (max)	.025	.008	<.005	.005
Silicon (max)	.40	.29	.28	.25
Nickel	.70-1.00	.94	.90	.88
Chromium	.60-.90	.67	.67	.68
Molybdenum	.15-.25	.21	.18	.20
Copper	1.00-1.30	1.18	1.18	1.12
Niobium (min)	.02	.037	.043	.031
Aluminum	NR*	.040	.024	.036
Nitrogen	NR*	.014	.014	.021

* not reported

Table 2. Tensile test results for the specimens taken from 19 mm thick plate GAG. Odd numbered specimens were precipitation hardened at 482°C, and even numbered at 538°C.

Coupon Identity	UTS (MPa)	YS (.2%) (MPa)	Elong. 51 mm(%)	Red. of Area (%)	Av. Hardness HRA
ARG*	703.3	604.0	23.4	72.0	58.2
G1	760.5	644.0	26.5	68.2	60.8
G2	684.0	590.2	26.9	73.9	61.6
G3	766.7	679.2	22.9	67.1	59.9
G4	732.2	649.5	25.2	70.3	59.9
G5	797.7	710.9	23.5	63.8	61.5
G6	738.5	644.7	25.2	71.1	60.1
G7	801.2	719.8	25.0	64.1	61.6
G8	751.6	659.2	26.6	70.6	60.3
G9	805.3	701.2	21.5	64.2	61.5
G10	766.7	673.0	22.7	68.1	60.4

*As received plate

Table 3. Tensile test results for the specimens taken from the 32 mm thick plate FUQ. Odd numbered specimens were precipitation hardened at 482°C, and even numbered at 538°C.

Coupon Identity	UTS (MPa)	YS (.2%) (MPa)	Elong. 51 mm,%	Red. of Area (%)	Ave. Hardness HRA
ARQ*	675.7	575.7	28.5	76.7	58.2
Q1	749.5	620.6	29.8	73.3	60.6
Q2	686.1	584.7	26.1	77.6	58.5
Q3	752.9	666.7	28.5	72.9	61.5
Q4	719.8	626.1	27.4	75.6	59.9
Q5	779.1	677.8	26.3	73.0	61.1
Q6	735.0	647.4	28.5	74.8	60.7
Q7	785.3	696.4	25.2	72.6	62.5
Q8	755.7	668.1	25.9	72.6	61.3
Q9	829.5	724.0	22.6	68.7	62.1
Q10	763.3	660.5	24.3	70.4	61.0

* As received plate

Table 4. Tensile test results for specimens taken from the 51 mm thick plate GFF. Odd numbered specimens were precipitation hardened at 482°C, even numbered at 538°C.

Coupon Identity	UTS (MPa)	YS (.2%) (MPa)	Elong. 51 mm, %	Red. of Area (%)	Ave. Hardness HRA
ARF*	618.5	519.9	25.5	77.9	56.1
F1	699.2	570.9	28.6	74.3	58.9
F2	657.8	542.6	29.7	77.3	57.9
F3	706.0	584.7	29.3	75.6	59.5
F4	701.2	584.7	28.1	75.7	58.6
F5	719.8	615.0	27.6	74.4	59.5
F6	704.7	612.3	28.0	75.6	59.2
F7	724.7	632.3	28.0	74.4	60.5
F8	728.1	647.4	27.4	74.8	60.3
F9	757.1	659.2	23.2	71.6	61.3
F10	734.3	635.7	25.7	73.4	60.8

* As received plate

Table 5. Tensile test results for specimens taken from the 19 mm thick plate. This includes coupons which were double austenitized and water quenched, and those that were single austenitized, quenched in oil or air, then precipitation hardened. Odd numbered specimens were precipitation hardened at 482°C, even numbered at 538°C.

Coupon Identity	Heat Treatment	UTS (MPa)	YS (0.2%) (MPa)	Elong. 51 mm.%	Red. of Area(%)	Ave.Hardness HRA
G11	DA(1)	761.9	679.8	27.2	71.4	61.8
G12	DA	727.4	640.5	27.4	73.6	59.9
G13	DA	764.7	688.8	23.9	70.9	61.2
G14	DA	734.3	659.2	95.6	26.1	60.2
G15	DA	770.2	671.6	97.4	22.1	61.2
G16	DA	736.4	643.3	93.3	24.8	60.4
G17	SO(2)	708.8	586.8	28.1	70.9	59.5
G18	SO	689.5	561.3	28.9	73.9	58.6
G19	SA(3)	651.6	504.7	29.9	69.0	56.5
G20	SA	652.3	506.8	29.6	72.6	56.5

1) DA - double austenitizing , water quenched
   G11, G12: 899°C/899°C
   G13, G14: 1066°C/899°C
   G15, G16: 1204°C/899°C
2) SO - single (899°C), oil quenched
3) SA - single (899°C), air cooled

Table 6. Impact test results for specimens taken from the 19 mm thick plate GAG. Odd numbered specimens were precipitation hardened at 438°C, even numbered at 538°C. There were two specimens tested at each temperature. ARG, as received plate specimen.

Test Temperature, -17.8°C			Test Temperature, -84°C		
Specimen Identity	En. Abs. J	Lat. Exp. mm	Specimen Identity	En. Abs. J	Lat. Exp. mm
ARG1	147.8	2.0	ARG3	78.6	1.1
ARG2	147.8	2.0	ARG4	94.9	1.3
1G1	84.1	1.1	1G3	10.2	0.2
1G2	74.6	1.1	1G4	10.2	0.1
2G1	132.9	1.9	2G3	44.7	0.6
2G2	150.5	1.9	2G4	65.1	0.8
3G1	55.6	0.8	3G3	16.9	0.2
3G2	75.9	1.1	3G4	16.3	0.3
4G1	131.5	1.7	4G3	38.0	0.5
4G2	128.8	1.8	4G4	62.4	0.8
5G1	82.7	1.1	5G3	47.5	0.6
5G2	84.1	1.1	5G4	33.9	0.5
6G1	141.0	1.9	6G3	80.0	1.0
6G2	127.4	1.7	6G4	58.3	0.7
7G1	88.1	1.1	7G3	32.5	0.6
7G2	84.1	1.1	7G4	18.3	0.2
8G1	101.7	1.4	8G3	14.2	0.1
8G2	109.8	1.5	8G4	86.8	1.1
9G1	31.2	0.4	9G3	7.5	0.1
9G2	24.4	0.4	9G4	6.1	0.1
10G1	62.4	0.1	10G3	14.2	0.2
10G2	78.6	1.1	10G4	8.8	0.0

Table 7. Impact test results for specimens taken from the 32 mm thick plate FUQ. Odd numbered specimens were tested at 482°C, even numbered at 538°C. There were two specimens tested at each temperature. ARQ, as received plate specimen.

Test Temperature, -17.8°C			Test Temperature, -84°C		
Specimen Identity	En. Abs. J	Lat. Exp. mm	Specimen Identity	En. Abs. J	Lat. Exp. mm
ARQ1	253.5	2.5	ARQ3	172.2	2.3
ARQ2	250.8	2.3	ARQ4	146.4	1.9
1Q1	181.7	2.1	1Q3	44.7	0.6
1Q2	181.7	2.2	1Q4	77.3	0.9
2Q1	290.1	2.5	2Q3	184.4	2.2
2Q2	298.3	2.4	2Q4	234.6	2.4
3Q1	149.1	1.7	3Q3	103.0	1.5
3Q2	170.8	2.0	3Q4	115.2	1.6
4Q1	272.5	2.5	4Q3	160.0	2.0
4Q2	284.7	2.3	4Q4	184.4	2.3
5A1	161.3	2.1	5Q3	104.4	1.5
5Q2	162.7	2.0	5Q4	55.6	0.8
6Q1	254.9	2.5	6Q3	157.3	2.0
6Q2	235.9	2.4	6Q4	119.3	1.6
7Q1	122.0	1.5	7Q3	8.8	0.1
7Q2	71.9	0.9	7Q4	16.3	0.2
8Q1	235.9	2.5	8Q3	40.7	0.7
8Q2	160.0	1.9	8Q4	19.7	0.3
9Q1	35.3	0.4	9Q3	12.2	0.3
9Q2	47.5	0.6	9Q4	9.5	0.1
10Q1	108.5	1.5	10Q3	35.3	0.4
10Q2	104.4	1.4	10Q4	29.8	0.4

Table 8. Impact test results for specimens taken from the 51 mm thick plate GFF. Odd numbered specimen were tested at 482°C, and even numbered at 538°C. There were two specimens tested at each temperature. ARF, as received plate specimen..

Test Temperature, -17.8°C			Test Temperature, -84°C		
Specimen Identity	En. Abs. J	Lat. Exp. mm	Specimen Identity	En. Abs. J	Lat. Exp. mm
ARF1	294.2	2.3	ARF3	282.0	2.4
ARF2	310.5	2.3	ARF4	273.9	2.3
1F1	151.9	1.9	1F3	99.0	1.4
1F2	216.9	2.3	1F4	50.2	0.7
2F1	254.9	2.3	2F3	138.3	2.0
2F2	260.3	2.3	2F4	184.4	2.1
3F1	187.1	2.2	3F3	16.3	0.3
3F2	260.3	2.5	3F4	46.1	0.5
4F1	260.3	2.4	4F3	143.7	1.8
4F2	257.6	2.3	4F4	149.1	2.0
5F1	208.8	2.3	5F3	61.0	0.9
5F2	206.1	2.2	5F4	19.0	0.3
6F1	192.5	2.2	6F3	39.3	0.6
6F2	184.4	2.1	6F4	19.7	0.3
7F1	189.9	2.2	7F3	6.1	0.1
7F2	150.5	2.0	7F4	29.8	0.4
8F1	176.9	2.0	8F3	124.7	1.7
8F2	196.6	2.2	8F4	138.3	1.9
9F1	32.5	0.4	9F3	6.8	0.1
9F2	89.5	0.4	9F4	20.3	0.2
10F1	131.5	1.7	10F3	33.9	0.4
10F2	131.5	1.8	10F4	16.3	0.2

Table 9. Impact test results for the double austenitized (DA) and water quenched. The single austenitized specimens which were either oil (SO), or air (SA) quenched. The odd numbered specimens were precipitation hardened at 482°C, and the even numbered at 538°C.

Test Temperature, -17.8°C				Test Temperature, -84°C		
Specimen Identity	Heat Treatment	En. Abs. J	Lat. Exp. mm	Specimen Identity	En. Abs. J	Lat. Exp. mm
11G1	DA	123.4	1.6	11G3	26.4	0.5
11G2	DA	105.8	1.4	11G4	27.8	0.5
12G1	DA	155.9	2.0	12G4	58.3	0.7
12G2	DA	161.3	1.9	12G4	86.8	1.0
13G1	DA	113.9	1.4	13G3	36.6	0.5
13G2	DA	100.3	1.5	13G4	35.3	0.5
14G1	DA	131.5	1.7	14G3	27.1	0.4
14G2	DA	118.0	1.5	14G4	70.5	1.0
15G1	DA	44.7	0.7	15G3	6.8	0.1
15G2	DA	40.7	0.6	15G4	8.1	0.5
16G1	DA	123.4	1.6	16G3	12.9	0.2
16G2	DA	97.6	1.4	16G4	8.8	0.1
17G1	SO	111.2	1.5	17G3	40.7	0.1
17G2	SO	82.7	1.2	17G4	26.4	0.4
18G1	SO	170.8	2.1	18G3	36.6	0.5
18G2	SO	116.6	1.5	18G4	58.3	0.8
19G1	SA	97.6	1.3	19G3	9.5	0.1
19G2	SA	124.7	1.8	19G4	16.9	0.3
20G1	SA	158.6	1.9	20G3	26.4	0.5
20G2	SA	146.4	2.0	20G4	23.0	0.3

Table 10. Cooling rates in water from various austenitizing temperatures for the 19 mm, 32 mm, and 51 mm thick plates. Rates are in deg C/S.

Aust. Temperature, °C	19 mm (GAG)	32 mm (FUO)	51 mm(GFF)
843	102	30	14
871	78	22	11
899	115	37	12
954	48	48	12
1010	31	24	8

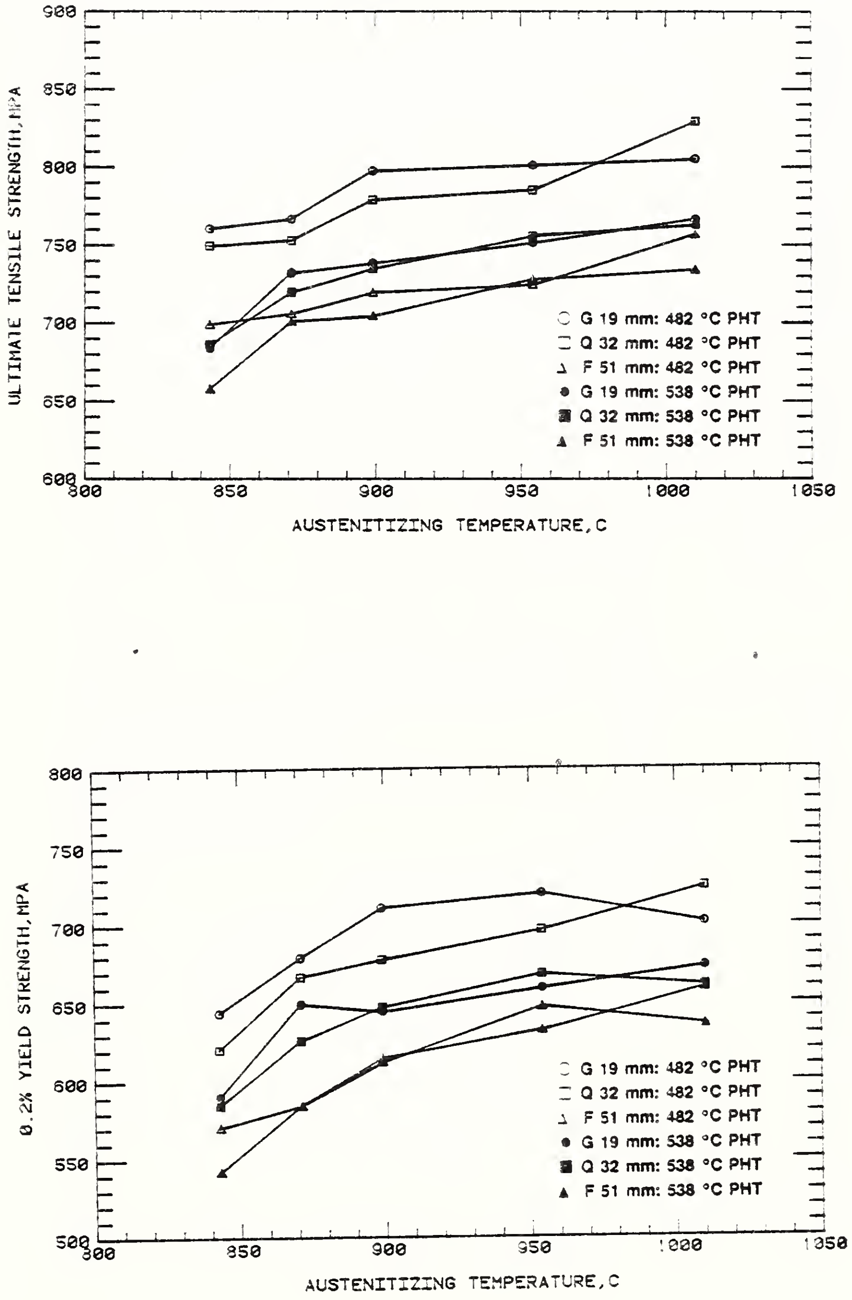
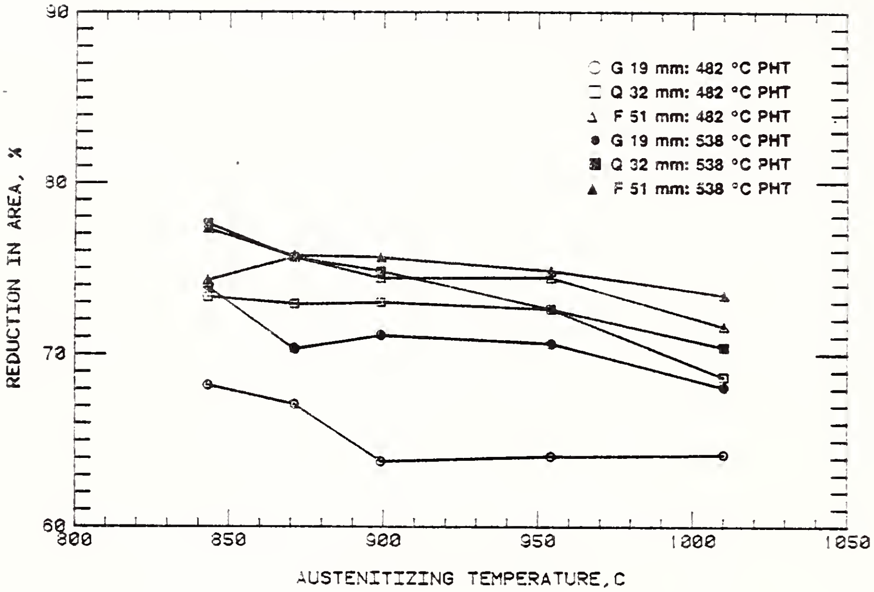


Figure 1. Ultimate tensile and 0.2% yield strength versus austenitizing temperature for specimens precipitation hardened at either 482°C or 538°C.



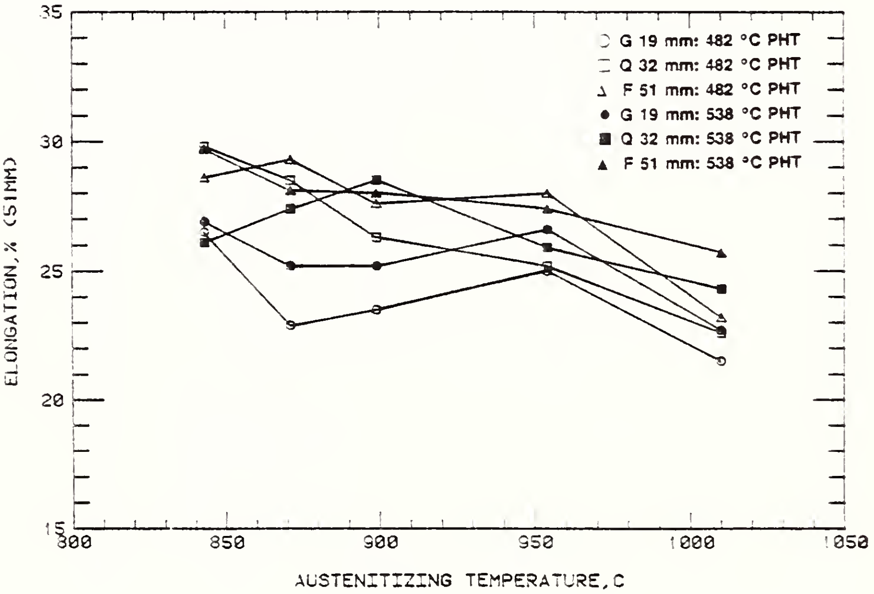


Figure 2. Reduction in area and elongation, % versus austenitizing temperature for specimens precipitation hardened at either 482°C or 538°C.

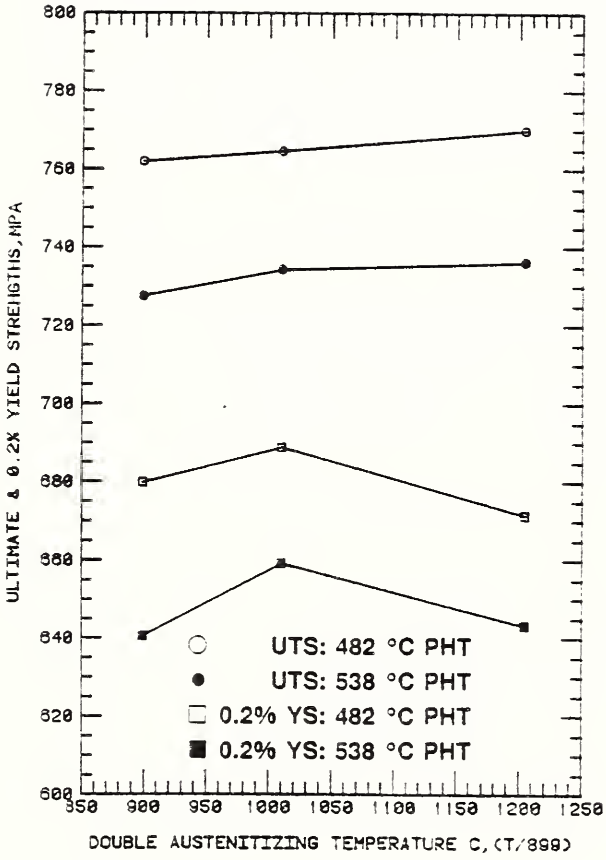


Figure 3. Ultimate tensile and 0.2% yield strength versus austenitizing temperature for double austenitized specimens precipitation hardened at either 482°C or 538°C.

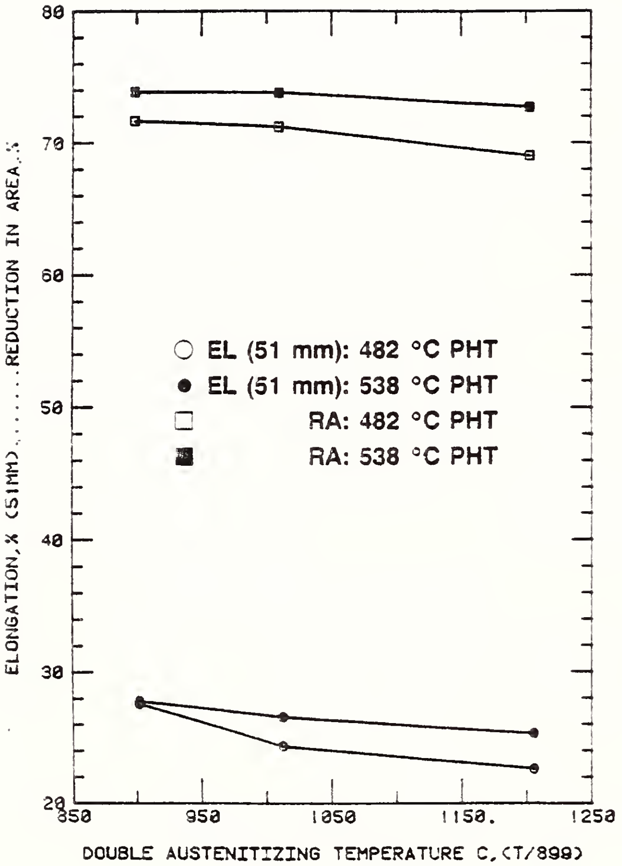
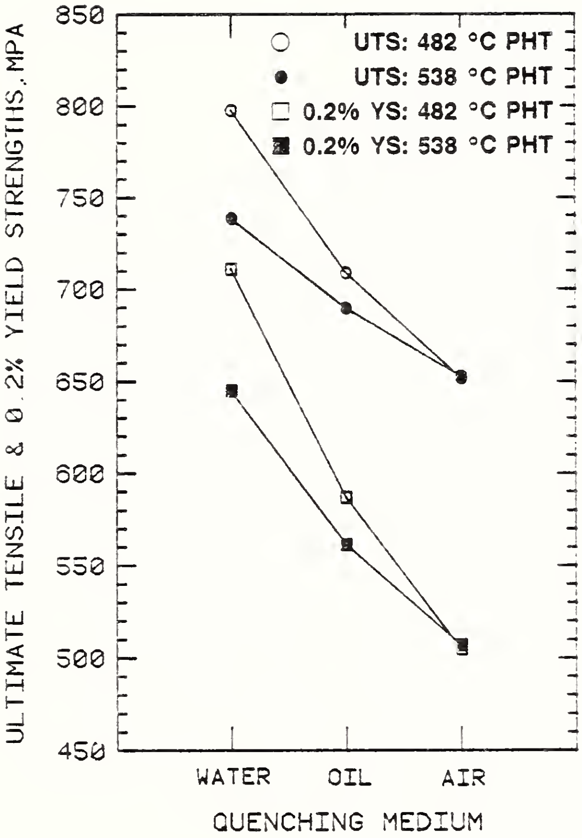


Figure 4. Reduction in area and elongation, % versus austenitizing temperature for double austenitized specimens precipitation hardened at either 482°C or 538°C.



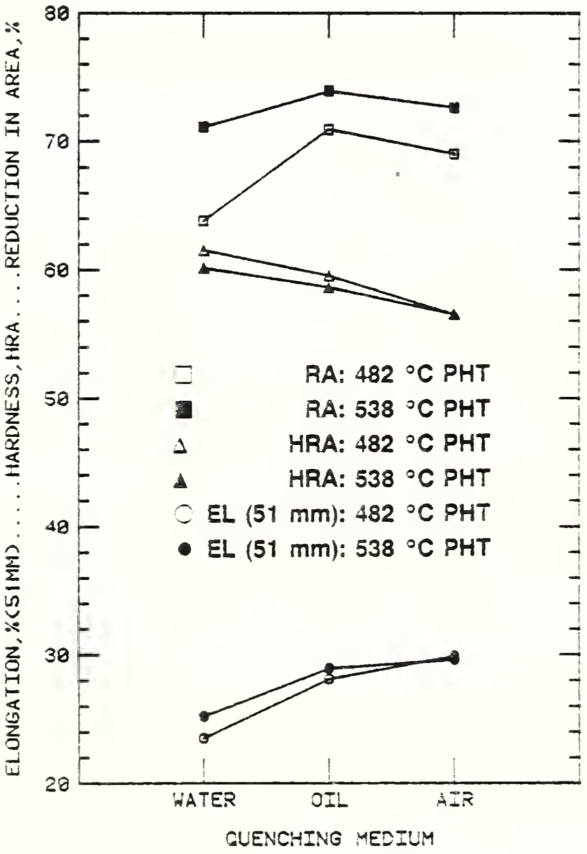


Figure 5. Ultimate tensile, 0.2% yield strength, reduction in area, elongation,% and hardness versus quenching medium. Data are for 19 mm thick plate GAG.

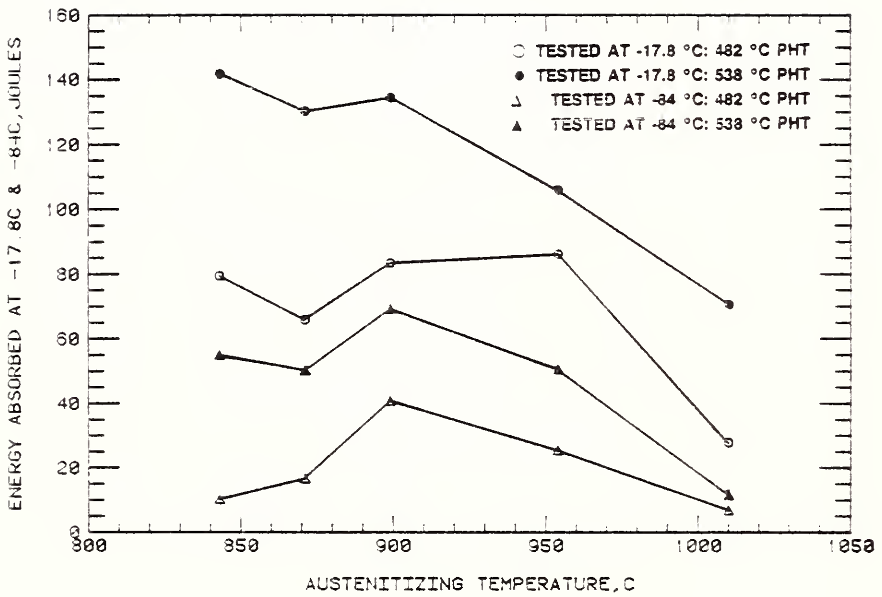


Figure 6. Energy absorbed versus austenitizing temperature for specimens taken from 19 mm thick plate GAG and tested at -17.8°C and -84°C. The solid line connects the average value.

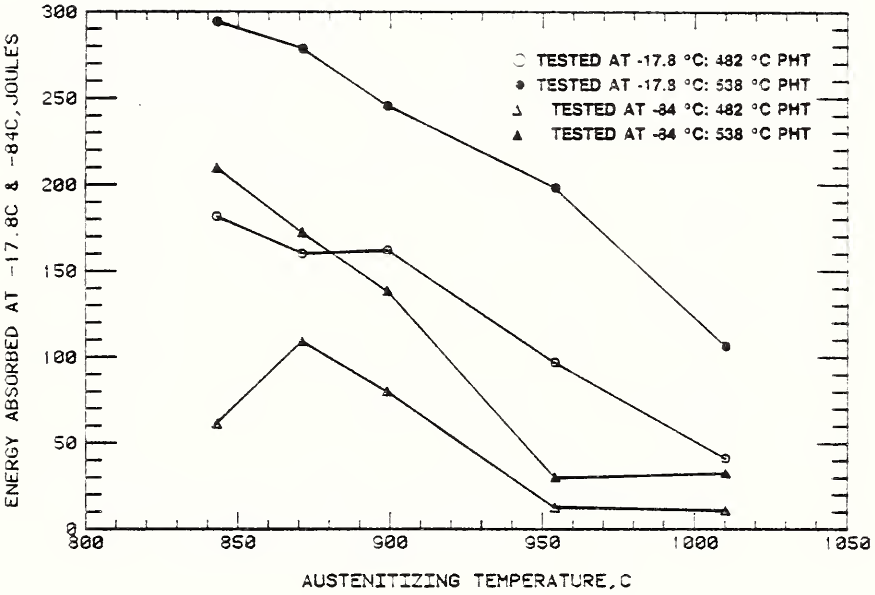


Figure 7. Energy absorbed versus austenitizing temperature for specimens taken from 32 mm thick plate FUQ and tested at -17.8°C and -84°C. The solid line connects the average value.

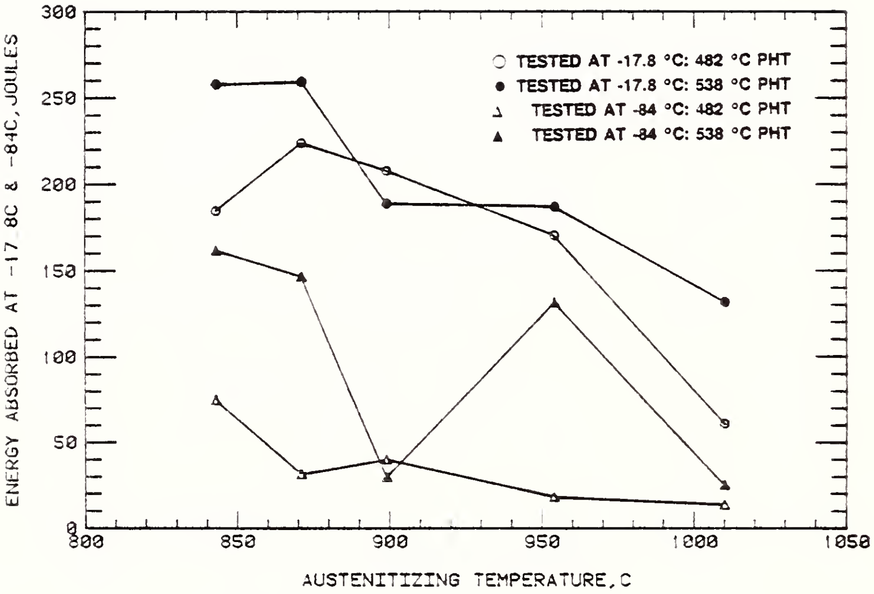


Figure 8. Energy absorbed versus austenitizing temperature for specimens taken from 51 mm thick plate GFF and tested at -17.8°C and -84°C. The solid line connects the average values.

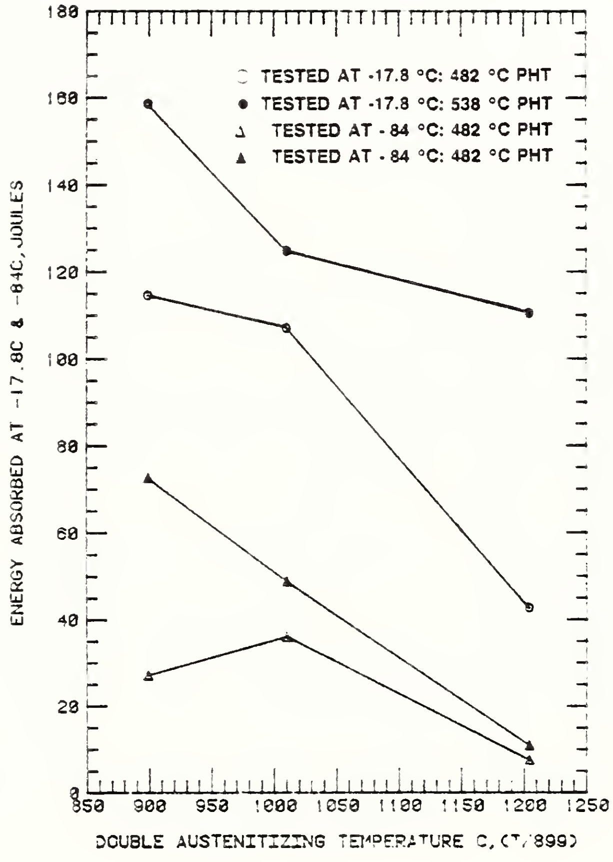


Figure 9. Energy absorbed versus double austenitizing temperatures for specimens taken from 19 mm thick plate GAG and tested at -17.8°C and -84°C. The solid line connects the average values.

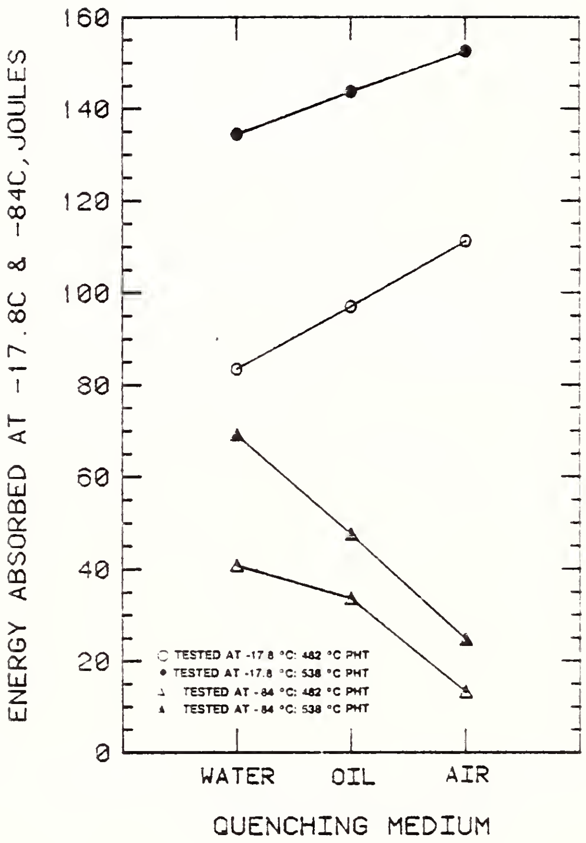


Figure 10. Energy absorbed versus quenching medium for specimens taken from 19 mm thick plate GAG and tested at -17.8°C and -84°C. The solid line connects the average values.

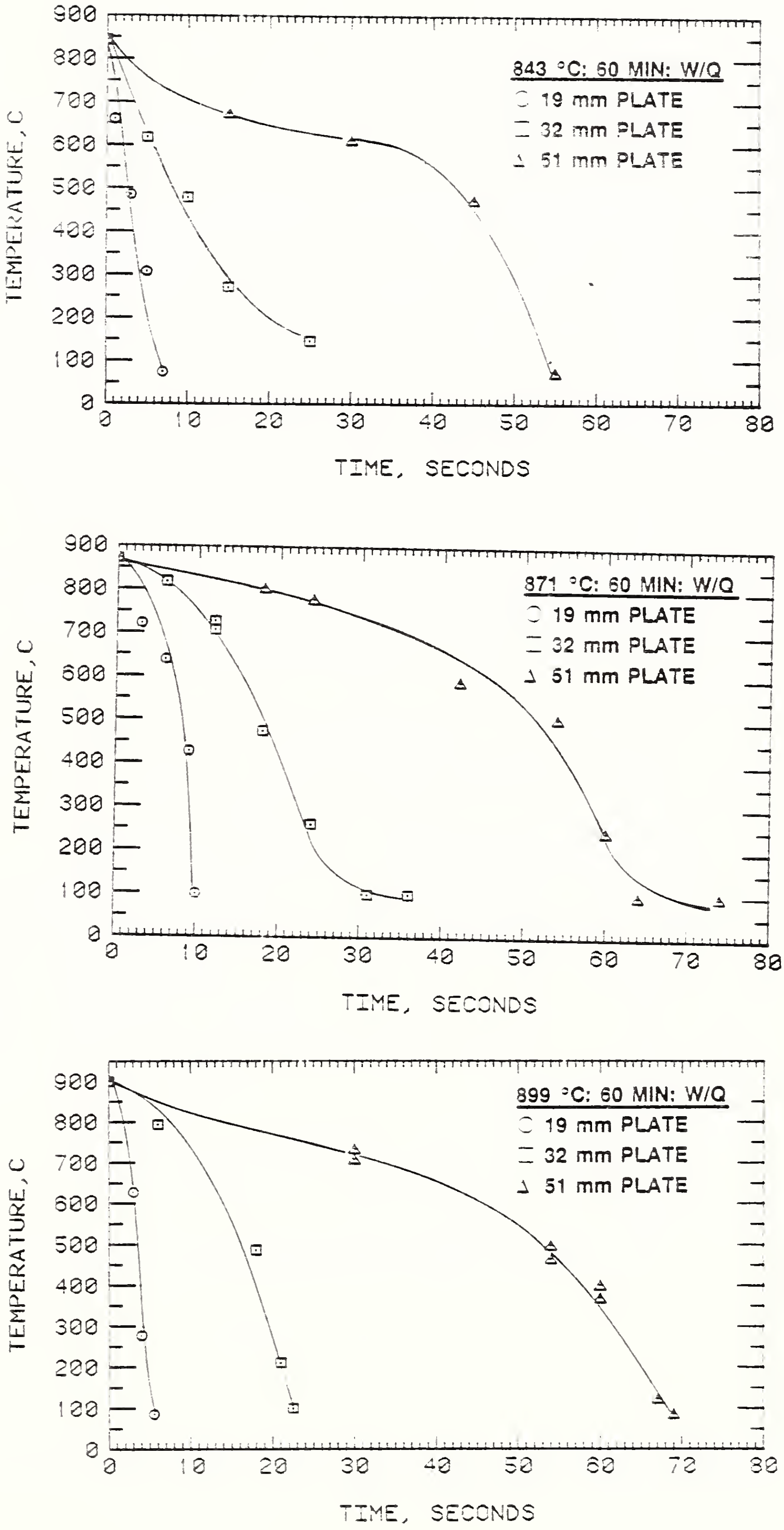
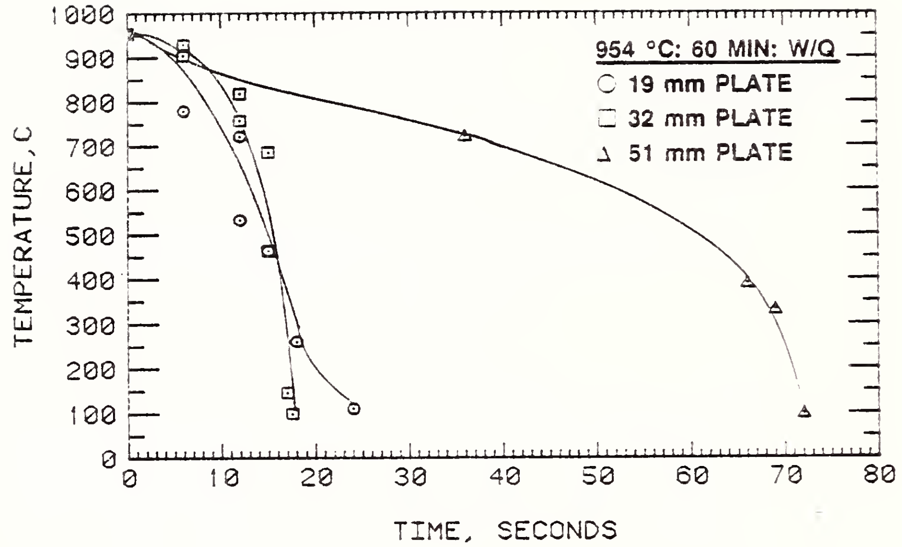


Figure 11. Cooling curves for 19 mm, 32 mm, and 51 mm plates, each water cooled from the austenitizing temperatures of 843°C, 871°C, and 899°C.



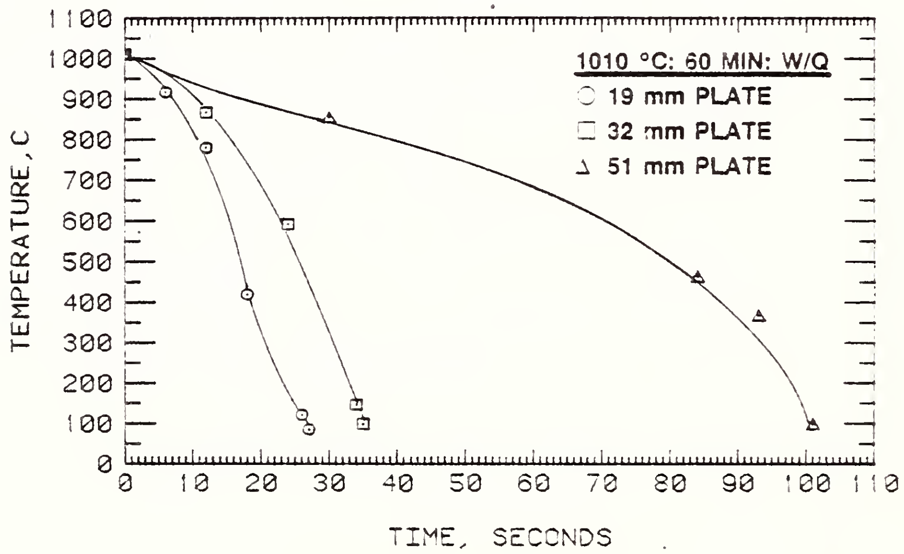


Figure 12. Cooling curves for 19 mm, 32 mm, and 51 mm plates, each cooled from austenitizing temperatures of 954°C and 1010°C.

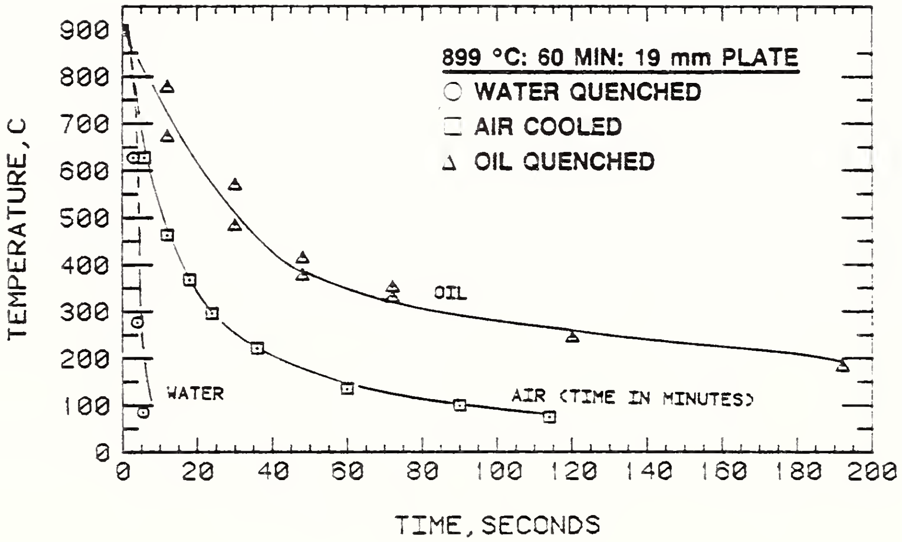


Figure 13. Cooling curves for 19 mm plates cooled in water, oil, or air.

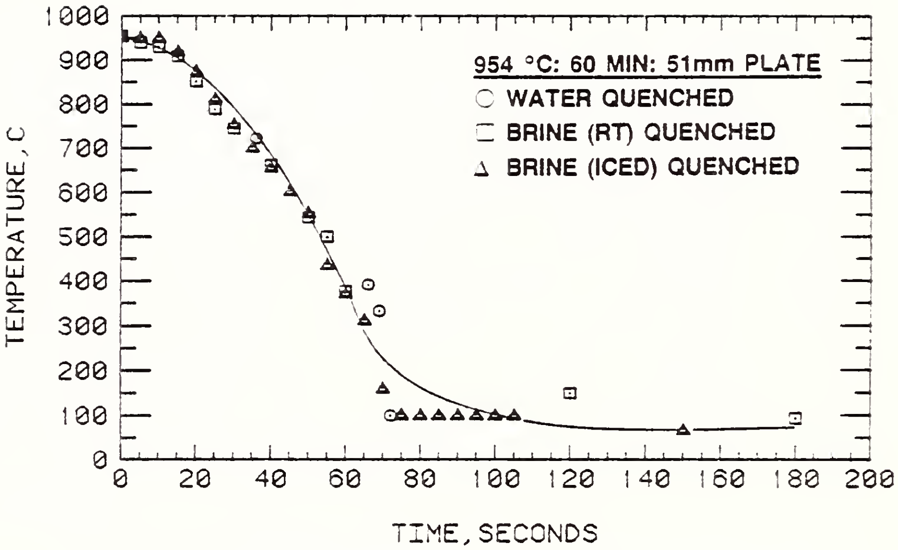


Figure 14. Cooling curves for 51 mm plates cooled in water, room temperature brine, or ice and brine.

NBS-114A (REV. 2-8C)

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BIBLIOGRAPHIC DATA SHEET *(See instructions)*

1. PUBLICATION OR REPORT NO. NBSIR 87-3649

2. Performing Organ. Report No.

3. Publication Date OCTOBER 1987

4. TITLE AND SUBTITLE

Effects of Varying the Austenitizing Temperature of the Ability of HSLA-80 to Achieve a Yield Strength of 689.5 MPa and Toughness Comparable to HSLA-100

5. AUTHOR(S)

G.E. Hicho, C.H. Brady, L.C. Smith, and R.J. Fields

6. PERFORMING ORGANIZATION *(If joint or other than NBS, see instructions)*

NATIONAL BUREAU OF STANDARDS
U.S. DEPARTMENT OF COMMERCE
GAITHERSBURG, MD 20899

7. Contract/Grant No.

8. Type of Report & Period Covered

9. SPONSORING ORGANIZATION NAME AND COMPLETE ADDRESS *(Street, City, State, ZIP)*

David Taylor Naval Ship R&D Center
Code 2814
Annapolis, MD

10. SUPPLEMENTARY NOTES

☐ Document describes a computer program; SF-185, FIPS Software Summary, is attached.

11. ABSTRACT *(A 200-word or less factual summary of most significant information. If document includes a significant bibliography or literature survey, mention it here)*

This is the first of two reports on maximizing the mechanical properties of HSLA-80 steel by heat treatment. This report concentrates on the optimization of the austenitization treatment and cooling rate. The optimum austenitization temperature was found to vary with plate thickness: 899°C for 19 mm (3/4 in) thick plate, 927°C for 32 mm (1-1/4 in) thick plate, and 954°C for 51 mm (2 in) thick plate. In all cases the time-at-temperature was 60 minutes followed by an immersion quench in water. Double austenitization and other quenching rates did not significantly improve the mechanical properties. Even at this preliminary stage, a heat treatment for 19 mm thick HSLA-80 plate was found that improved this plate's tensile and impact properties beyond those specified for HSLA-100.

12. KEY WORDS *(Six to twelve entries; alphabetical order; capitalize only proper names; and separate key words by semicolons)*

austenitizing temperature; cooling rate; double austenitizing; impact; steel; tensile

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14. NO. OF PRINTED PAGES

15. Price