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Effects of Varying Precipitation Hardening Temperatures and Times on the Ability of HSLA-80 to Achieve A Yield Strength of 689.5 MPa and Impact Properties Comparable to HSLA-100

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G.E. Hicho, C.H. Brady, L.C. Smith, and R.J. Fields
Fracture and Deformation Division
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Administrative Information

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Executive Summary

The second of two reports on optimizing the mechanical properties of HSLA-80 steel by heat treatment, concentrates on the precipitation hardening temperatures and times. Optimum properties, comparable to HSLA-100, were found when the 19 mm thick plates were precipitation hardened at 482°C for 90 minutes, and the 32 mm thick plates were precipitation hardened at either 454°C for 90 minutes, 482°C for 300 minutes, or 510°C for 30 minutes. There was no precipitation hardening treatment for the 51 mm thick plate where the desired mechanical properties were achieved.

Introduction

In the previous paper by Hicho and Fields (1), austenitizing treatments were conducted on three plate thicknesses of HSLA-80 steel in order to optimize the mechanical properties. In that paper, temperatures ranging from 843°C to 1010°C were used to determine the optimum austenitizing temperature for each plate thickness. In addition, the plates were precipitation hardened at 482°C for 90 minutes, and 538°C for 60 minutes. The results indicated that optimum mechanical properties were obtained when the 19 mm thick plate was austenitized at 899°C, the 32 mm thick plate at 927°C, and the 51 mm thick plate at 954°C.

Having determined these austenitizing temperatures, it was proposed that heat treating experiments should be conducted on the optimization of the precipitation hardening temperature and time for each plate thickness. The purpose of the research was to find a combination of precipitation hardening temperature and time for each plate thickness that would raise the yield strength to at least 689.5 MPa, yet maintain the impact properties at a level comparable to those specified for HSLA-100. This paper presents the results of these hardening experiments.

General Information

The plates evaluated here were identified in accordance with the DTNSRDC system as follows: 19 mm - GAG; 32 mm - FUQ; and 51 mm - GGN. The chemical compositions of these plates, as well as that of ASTM A710, the standard composition, are shown in Table 1.

Test coupons, identical in width and length to those used in the first paper (1), were sectioned from the larger plates and prepared for heat treatment. Care was taken to maintain specimen orientation, i.e. parallel or normal to the rolling direction. Air type furnaces with no protective atmosphere were used for both the austenitizing and precipitation hardening treatments. Thermocouples were inserted into each plate in order to monitor the heating rate, soak temperature, and cooling rate.

The plates were loaded into the furnace with the 51 mm plate on the bottom, the 32 mm plate on top of it, and finally the 19 mm plate on top of the 32 mm plate. Spacers were placed in between each plate in order to allow each plate to be heated uniformly. Check thermocouples monitored the heat up rate for each plate, and the time to reach the soak temperature was added to subsequent heat treatments. The coupons were given the optimum austenitizing time depending on their plate thickness, and then quenched in a large trough of water which was changed after each heat treatment. The coupons were then removed from the bath, and inserted into an air furnace for the precipitation hardening treatment. The thermocouples previously inserted into the plates were again used to monitor the heat up rate and soak temperature. The heat treatment matrix and specimen identification are shown in Table 2.

The precipitation hardening temperatures chosen to be evaluated in this study were: 427, 454, 482, 510, and 538°C, and the times at these temperatures were: 30, 90, 300, and 900 minutes. In addition to these heat treatments, there were three treatments performed on the 19 mm thick plate, GAG. Following the austenitizing treatment at 899°C for 60 minutes and water quenching, each plate was precipitation hardened at 482°C for 60 minutes. Normally following the precipitation hardening treatment, the plates are air cooled. However, following these precipitation hardening treatments, the plates were either water quenched, oil quenched, or furnace cooled. The purpose of these treatments was to determine if cooling rate after precipitation hardening had an effect on the resultant mechanical properties. In addition to these treatments, one coupon of each plate thickness was austenitized at its optimum temperature and quenched in water. These plates did not receive any precipitation hardening treatment. Following the heat treatments, test specimens (two tensiles and four impacts) were machined from the quarter-thickness location in each plate.

Tensile Test Results

Figures 1, 2, 3, and 4 show plots of the 0.2% offset yield strength and ultimate tensile strength versus the precipitation hardening temperature for specimens held at temperature for 30, 90, 300, and 900 minutes. The data used to develop these plots are shown in Tables 3,4, and 5.

One of the aims of these heat treating variations was to determine if this steel, in plate thicknesses of 19 mm, 32 mm and 51 mm, could be heat treated to a yield strength of at least 689.5 MPa. These figures show that there are heat treatments where this can be achieved.

Both the tables and figures show that, for the 19 mm thick plate, the desired yield strength was obtained when the following precipitation hardening treatments were performed: 427°C for 900 minutes; 454°C for 300 or 900 minutes;and 510°C for 30 minutes. As for the 32 mm thick plate, the yield strength was obtained when the plate was precipitation hardened at 454°C for 30 or 90 minutes. And finally the optimum yield strength was achieved in the 51 mm thick plate when it was precipitation hardened at 482°C for 90 or 300 minutes.

Comparing Figures 1, 2, 3, and 4 it was seen that as the precipitation hardening time increased, the yield strength curves for all the thicknesses reached their maximum at a lower precipitation hardening temperature. For example the optimum was reached after 30 minutes at 510°C, 90 minutes at 482°C, 300 minutes between 454 and 482°C, and after 900 minutes at 454°C. Examination of the yield strength curves for the 32 and 51 mm thick plates show similar trends. This "peaking" of the curves is believed to be associated with the copper precipitation. (2,3,4)

The ultimate tensile strength curves show the same trend as the yield strength curves. The difference between the yield and ultimate tensile strengths remains essentially the same over all the entire range of precipitation hardening temperatures and times tested.

The reduction-of-area and elongation results were independent of heat treatment for all of the plate thicknesses examined. The overall reduction-of-area was about 72%, and the elongation was about 26%. The hardness results were also found to be relatively insensitive to heat treatment when all of the plates thicknesses were compared.

Investigation of Cooling Rate Effects after Precipitation Hardening

An investigation of the effects of cooling rate after precipitation hardening on the mechanical properties was also conducted on three coupons taken from the 19 mm thick plate. The coupons were austenitized at 899°C, quenched in water, and precipitation hardened at 482°C. Following precipitation hardening, they were individually cooled in water or oil, or furnace cooled.

The tensile results for these specimens indicated that the yield strength of 689.5 MPa was not obtained for any of these treatments. The yield strength using these cooling rates was about 650 MPa ± 7 MPa. The cooling rate of the plate after precipitation hardening does not appear to have a significant effect on its resultant mechanical properties.

Investigation of Cooling Rate Effects with no Precipitation Hardening

Three additional specimens taken from the 19, 32, and 51 mm thick plates which were austenitized at their optimum temperature and water quenched. These plates were not precipitation hardened. The yield strengths obtained were not greater than 460 MPa. The reduction-of-areas and elongations were not significantly different than for those specimens that were precipitation hardened. These data provide a baseline for separating the strengthening due to grain size effects and that due to precipitation during aging.

Impact Requirements

In addition to the attainment of a minimum yield strength of 689.5 MPa, a toughness comparable to that specified for HY-100 was desired for naval applications. The toughness was determined by means of Charpy impact tests conducted at two temperatures, -17.8°C and -84°C. Two specimens were tested at each temperature and heat treatment. The requirements set forth in the specification for HY-100 was that at -17.8°C, the minimum average energy absorbed value should be 74.6 J, and at -84°C, 41 J. In addition, no single energy absorbed value was to be below these minimum average values of 74.6 J and 41 J by more than 7 J.

Comparison of Impact Results as a Function of Time and Temperature

Figures 5,6,7,8,9, and 10 show a comparison of energy absorbed versus precipitation hardening temperature for times of 30, 90, 300, and 900 minutes. The impact results are for specimens tested at -17.8°C and -84°C.

Figure 5, results for the 19 mm thick plate, shows that the impact requirement of 74 J at -17.8°C was obtained for those specimens precipitation hardened for all the times at temperatures greater than 470°C. Similarly in Figure 6, the impact results for the 32 mm thick plate also tested at -17.8°C, showed that the impact requirement was met at all temperatures and times. Figure 7 shows the impact results for the 51 mm thick plate tested at -17.8°C. The figure shows that at times of 30, 90, and 900 minutes the impact requirements were met, and it was only at 482°C for 300 minutes that the requirement was not met.

It is noteworthy that, unlike the 19 and 32 mm thick plates, precipitation hardening at all the temperatures for 900 minutes yielded impact properties that were indicative of a tough material. In addition, at short precipitation hardening times, and at all temperatures, the impact properties were found to be superior to those that were precipitation hardened for 900 minutes. Figures 8,9, and 10 show the impact results for the three plate thicknesses that were tested at -84°C. The figures show that it was quite difficult for the material to attain the requirement of 40 J at that test temperature. The requirement was met by specimens from selected temperatures and times, but not to the extent that was found for the same thicknesses tested at -17.8°C.

Impact Test Results for Specimens Tested at -17.8°C

An examination of impact test data for the specimens taken from the 19 mm thick plate GAG, Table 6, revealed that with the exception of two heat treatments (G14 and G17), the impact energy absorbed requirement,74.6 J, was met for all heat treatments. For those specimens taken from the 32 mm thick plate FUQ, Table 8, all of the heat treatments met the 74.6 J criteria. And finally for those specimens taken from the 51 mm thick plate GGN, Table 10, all of the treatments but three (N7, N10, and N11) met the 74.6 J criteria.

Impact Test Results for Specimens Tested at -84°C

In a similar comparison of specimens taken from the three plates and impact tested at -84°C, the following was observed. For the 19 mm thick plate, Table 7, eleven heat treatments met the 41 J requirement,and for the 31 mm thick plate, Table 9, sixteen met the requirement. For the 51 mm thick plate, Table 11, only five treatments (N1, N12, N15, N16, and N20) met the energy absorption requirement of 41 J at -84°C.

Examination of the impact data for all the plate thicknesses tested revealed that if the specimens met the requirement at -84°C, they met the requirement at -17.8°C.

Summary Figures

Figures 11 through 22 are summary figures which show the room temperature 0.2% yield strength, and the average energy absorbed values at -17.8 and -84°C versus the precipitation hardening temperature and time for each plate thickness. There were two impact specimens tested at each indicated temperature, and the average of these two values was plotted.

In Figures 11, 12, 13, and 14, which summarize the energy absorbed and yield strength results for the 19 mm thick plate, the desired yield strength of 689.5 MPa was obtained using the following heat treatments: 510°C for 30 minutes; 482°C for 90 minutes; 454°C to 482°C for 300 minutes; and 427 to

460°C for 900 minutes.

The impact curves and the data for the 19 mm thick plate were examined. A single heat treatment was found where both the impact and yield strength requirements were met. At a heat treatment of 90 minutes at 482°C, the impact values for those specimens tested at -17.8°C and -84°C, and the room temperature yield strength were found to meet or exceed the specifications for HY-100.

Similar summary figures were plotted for the 32 mm thick plate and the results are shown in Figures 15, 16, 17, and 18. Examination of Figure 17, in particular those specimens precipitation hardened for 300 minutes at temperatures between 454 and 482°C, reveals that the desired yield strength was obtained. Examination of the impact properties for those same heat treatments shows that for 300 minutes at 454°C, the HY-100 specifications were met.

Another heat treatment was found which possibly yielded acceptable results. Using specimens with a 689.5 minimum yield strength, the average energy absorbed value for those specimens tested at -17.8°C was found to be over 149 J for a heat treatment of 30 minutes at 510°C. The average impact value obtained was acceptable, but the scatter (134 and 165 J) in these values prevented them from being acceptable. At -84°C, and using the same precipitation hardening treatment, the impact specimens met both requirements. We believe that if additional specimens we tested at -17.8°C, acceptable impact behavior would be found.

Figures 19, 20, 21, and 22 show the summary results for the 51 mm thick plate. For those specimens treated 90 minutes at 482°C, Figure 20, the yield strength was satisfactory, but the impact values at -17.8°C and -84°C were not acceptable. For those specimens held for 300 minutes at temperatures from 454°C to 482°C, the yield strengths were acceptable, but the impacts tested at -17.8°C and -84°C were again unacceptable.

Examination of the yield strength and impact data for the 51 mm thick plate repeatedly showed that only one of these criteria could be obtained using any of the heat treatments. We concluded that there was no heat treatment for the 51 mm plate where both the strength and impact values, together, satisfied the requirements of the HY-100 specifications.

Impact Results for Specimens Quenched in Various Medium

The impact values for those specimens taken from the 19 mm thick plate, and quenched in various media after precipitation hardening were also examined. These specimens are identified as G29, G30, and G31 in the tables. The impact toughness results for all of the specimens tested at -17.8°C were found to be acceptable, but the results for those tested at -84°C were found not to be acceptable. The yield strengths for these heat treatments were also found to be below the desired value of 689.5 MPa.

Additional impact tests were conducted on specimens taken from each plate of each thickness, austenitized and water quenched, but not given any precipitation hardening treatment. These specimens are identified in the tables as G32, Q11, and N21. The impact results indicate that only the 32 mm thick plate met the impact criteria at both test temperatures of -17.8 and-84°C. The 19 mm thick plate met the criteria at -17.8°C, but not at -84 °C, and the 51 mm thick plate did not meet <u>any</u> of the requirements. The average yield strength for these three plates was found to be about 460 MPa.

DISCUSSION

The steel investigated in this paper is designated as HSLA-80, and achieves its specified properties when it is mill austenitized at 899°C for 30 minutes, water quenched, and precipitation hardened at 593°C for about 70 minutes. Following these treatments, the steel possesses a room temperature yield strength of about 551 MPa and impact properties, at -17.8 and -84°C, of 81 J and 47 J respectively.

During the testing of the HSLA-80, questions arose as to whether this steel could be heat treated in a manner that resulted in the yield and impact properties being equivalent to a steel currently being developed, HSLA-100. Hence, research was initiated in order to determine if, indeed, this was possible with the HSLA-80 steel.

Experiments have already been conducted on establishing the effects of variations of the austenitizing temperature on the mechanical properties of this steel, and the results have been reported in an earlier paper (1). The optimum austenitizing temperature for each plate thickness, where the best yield and impact properties were obtained, had been determined. These temperatures were then used to evaluate the effects of a variation in precipitation hardening temperatures and times on the three plate thicknesses.

The effects of different cooling rates following the precipitation hardening treatment was found to have no significant effect on the resultant mechanical properties. The tensile results for the 19 mm thick plates that were either water or furnace cooled after precipitation hardening were comparable. The tensile test results for the plate that was oil quenched after precipitation hardening showed a higher yield strength than that obtained for those specimens that were water quenched or furnace cooled. The impact results for the plates that were water, oil, or furnace cooled after precipitation hardening were comparable.

No difference was observed in the yield strengths of those plates that were not given any precipitation hardening treatment. The three plate thicknesses possessed essentially the same yield strength, 460 MPa, after the austenitizing. The impact properties were as follows: for the 19 mm plate, 165 J; for the 32 mm plate, 215 J; and for the 51 mm plate, 155 J when they were tested at -17.8°C. At -84°C, the impact properties were: for the 19 mm plate, 75 J; for the 32 mm plate 83 J; and for the 51 mm plate, 26 J. It can be concluded from these results that the steel has to be precipitation hardened in order for it to achieve its high yield strength.

In examining these results, one feature which stands out is the effect of plate thickness on the resultant mechanical properties. It was observed that as plate thickness increased, the yield strength decreased, and the impact toughness increased.

Conclusions

In the optimization of the precipitation hardening temperature, it was found that HSLA-80, in the plate thicknesses evaluated, could indeed be heat treated in a manner which produced a yield strength of 689.5 MPa. However, with the achievement of an acceptable yield strength, deficiencies in the corresponding impact toughness were revealed. For most heat treatments, the desire for both the tensile and impact results being comparable or superior to HSLA-100 requirements was not attainable. However, there were some heat treatments where both requirements were achieved simultaneously, and they are as follows.

For the 19 mm thick plate material, the requirements were achieved when the plate was precipitation hardened at 482°C for 90 minutes. It was also achieved in the 32 mm thick material when given the following treatments: 454°C for 900 minutes; 482°C for 300 minutes; and 510°C for 30 minutes. There was no precipitation hardening treatment for the 51 mm thick plate which resulted in the requirements being met simultaneously.

References

1) G.E.Hicho and R.J. Fields, Effects of Varying the Austenitizing Temperature on the Ability of HSLA-80 to Achieve a Yield Strength of 689.5 MPa and Toughness Comparable to HY-100, (to be published).

2) E.Hornbogen, Aging and Plastic Deformation of an Fe-0.9% Alloy, Transactions of the ASM, Vol. 57,1964, pp.120-132.

3) J.L.Hurley and C.H.Shelton, Age-Hardenable Nickel-Copper Steels, Metals Engineering Quarterly,ASM, May 1966, pp.25-31.

4) M.R.Krishnadev and A.Galibois, Some Aspects of Precipitation of Copper and Columbium (Nb) Carbide in an Experimental High Strength Steel, Metallurgical Transactions, vol. 6a, January,1975. pp.222-224.

Table 1. Chemical compositions, in weight percent, for the plates used in this study. Also shown is the specification and composition for ASTM A710.

	ASTM A710, Grade A	GAG (19 mm)	FUQ (32 mm)	GGN (51 mm)
Carbon (max)	.07	.05	.05	.06
Manganese	.40-.70	.53	.61	.45
Phosphorus (max)	.025	<.005	.006	.007
Sulfur (max)	.025	.008	<.005	.005
Silicon (max)	.40	.29	.28	.28
Nickel	.70-1.00	.94	.90	.87
Chromium	.60-.90	.67	.67	.78
Molybdenum	.15-.25	.21	.18	.21
Copper	1.0-1.30	1.18	1.18	1.15
Niobium (min)	.02	.037	.043	.035
Aluminum	NR[1]	.040	.024	.035
Nitrogen	NR[1]	.014	.014	.014

1) Not reported

Table 2. Test matrix showing sample identification and precipitation hardening temperatures and times.

Precipitation Hardening Temperature, °C

Plate GAG (19 mm)

Minutes	427	454	482	510	538
30	G11	G15	G19	G22	G26
90	G12	G16	A	G23	ND
300	G13	G17	G20	G24	G27
900	G14	G18	G21	G25	G28

Plate FUQ (32 mm)

Minutes	427	454	482	510	538
30	Q14	Q18	Q23	Q26	G26
90	Q15	Q19	ND	Q27	ND
300	Q16	Q20	Q24	Q28	Q31
900	Q17	Q21	Q25	Q29	Q13

Plate GGN (51 mm)

Minutes	427	454	482	510	538
30	N1	N5	N9	N13	N17
90	N2	N6	N10	N14	N18
300	N3	N7	N11	N15	N19
900	N4	N8	N12	N16	N20

G29 - water quenched - 482°C - 60 minutes - water quenched
G30 - water quenched - 482°C - 60 minutes - oil quenched
G31 - water quenched - 482°C - 60 minutes - furnace cooled
G32 - water quenched - no precipitation hardening treatment
Q11 - water quenched - no precipitation hardening treatment
N21 - water quenched - no precipitation hardening treatment
A - Results presented in a previous report (1).
ND- not done

Table 3. Tensile and hardness results for specimens taken from plate GAG which was 19 mm thick.

Specimen Identity	UTS (MPa)	0.2% Ys (MPa)	RA (%)	Elong (51 mm) (%)	Hardness* (Av., HRA)
G11	647.4	537.1	71.7	26.2	57.5
G12	669.5	557.8	72.2	25.1	57.7
G13	715.7	621.9	72.5	26.4	58.6
G14	787.4	705.4	68.4	26.2	61.7
G15	679.2	579.9	72.5	26.7	58.6
G16	715.7	621.9	72.7	25.5	60.1
G17	785.3	698.5	69.2	25.3	62.1
G18	799.8	718.5	69.1	30.0	61.2
G19	747.4	665.4	71.2	28.2	60.9
G20	774.3	687.4	69.6	26.0	61.7
G21	756.4	667.4	71.5	27.3	61.1
G22	779.1	696.4	70.6	24.8	61.4
G23	750.9	657.1	71.1	26.7	60.6
G24	723.3	635.0	71.0	25.2	59.7
G25	682.6	596.4	73.6	30.4	59.2
G26	743.3	655.7	70.4	25.6	60.8
G27	674.3	586.1	74.4	25.8	58.5
G28	661.2	561.9	72.1	27.3	57.8
G29	741.9	646.7	73.4	24.3	61.1
G30	737.1	648.8	71.1	24.2	60.1
G31	741.9	654.3	70.2	25.0	60.6
G32	672.3	454.4	73.9	28.4	57.8

*Readings taken over entire thickness of coupon.

Table 4. Tensile and hardness results for specimens taken from plate FUQ which was 32 mm thick.

Specimen Identity	UTS (MPa)	0.2% Ys (MPa)	RA (%)	Elong (51 mm) (%)	Hardness* (Av., HRA)
Q11	692.9	456.4	70.1	27.7	58.8
Q13	646.1	557.8	76.9	30.5	58.1
Q14	621.9	499.9	73.5	28.5	56.8
Q15	634.3	530.2	75.1	26.4	56.9
Q16	655.7	546.1	75.6	28.6	58.1
Q17	738.5	645.4	72.4	26.6	60.3
Q18	673.6	579.2	73.2	26.7	58.8
Q19	698.5	604.0	73.8	26.3	59.9
Q20	773.6	684.7	69.4	25.6	61.4
Q21	787.4	688.1	70.0	25.6	62.0
Q23	744.0	661.2	70.5	26.3	61.4
Q24	777.1	689.5	72.1	26.7	61.6
Q25	748.1	666.7	71.8	26.0	61.0
Q26	780.5	704.7	74.0	25.7	62.1
Q27	781.2	700.5	74.8	27.5	62.1
Q28	742.6	661.2	73.1	28.1	60.3
Q29	679.8	592.3	75.7	30.5	59.3
Q30	746.7	664.7	72.6	26.3	61.0
Q31	679.2	597.1	76.6	27.6	59.1

*Readings taken over entire thickness of coupon.

Table 5. Tensile and hardness results for specimens taken from plate GGN which was 51 mm thick.

Specimen Identity	UTS (MPa)	0.2% Ys (MPa)	RA (%)	Elong (51 mm) (%)	Hardness* (Av., HRA)
N1	660.5	538.5	76.9	25.8	58.1
N2	659.9	539.2	77.3	26.0	58.8
N3	685.4	580.6	75.7	24.8	60.1
N4	726.0	639.2	75.1	25.5	61.6
N5	661.9	552.3	77.0	26.7	59.2
N6	682.6	590.2	77.4	25.0	60.3
N7	783.3	697.1	72.7	25.7	62.2
N8	766.7	680.5	72.9	26.3	62.2
N9	718.5	637.8	75.6	25.0	61.6
N10	775.7	689.5	71.5	24.1	62.1
N11	785.3	692.9	71.1	30.5	62.2
N12	721.2	628.1	75.2	27.8	61.1
N13	733.6	653.0	72.6	28.5	61.3
N14	769.5	681.2	74.1	26.2	61.6
N15	722.6	630.9	74.4	27.3	61.2
N16	700.5	614.3	75.9	27.4	59.9
N17	746.0	659.2	73.1	26.9	61.7
N18	103.0	618.5	75.7	28.3	60.8
N19	684.7	603.3	75.8	26.2	60.1
N20	670.2	583.3	76.7	32.4	59.4
N21	677.8	459.9	71.9	25.9	58.8

*Readings taken over entire thickness of coupon.

Table 6. Impact test results for plate GAG (19 mm). Specimens were tested at -17.8°C. Two specimens were tested at each condition, i.e. 1, 2.

Specimen Identity	En Ab. Joules	Lat. Exp. X10^-3 M	Specimen Identity	En Ab. Joules	Lat Exp. X10^-3 M
G11-1	169.5	2.34	G22-1	96.3	1.24
G11-2	160.0	2.18	G22-2	77.3	1.04
G12-1	169.5	2.16	G23-1	119.3	1.63
G12-2	160.0	2.08	G23-2	103.0	1.40
G13-1	122.0	1.78	G24-1	127.4	1.78
G13-2	101.7	1.42	G24-2	147.8	1.83
G14-1	70.5	0.99	G25-1	157.3	2.11
G14-2	51.5	0.76	G25-2	168.1	2.01
G15-1	150.5	2.16	G26-1	112.5	1.58
G15-2	130.2	2.03	G26-2	122.0	1.70
G16-1	105.7	1.37	G27-1	157.3	2.13
G16-2	93.6	1.30	G27-2	161.3	2.23
G17-1	67.8	0.94	G28-1	179.0	2.29
G17-2	69.1	0.91	G28-2	184.4	2.24
G18-1	80.0	1.09	G29-1	84.1	1.19
G18-2	82.7	1.07	G29-2	97.6	1.45
G19-1	101.7	1.47	G30-1	86.8	1.22
G19-2	99.0	1.47	G30-2	103.0	1.40
G20-1	89.5	1.32	G31-1	78.6	1.12
G20-2	99.0	1.40	G31-2	84.1	1.14
G21-1	126.1	1.73	G32-1	169.5	2.13
G21-2	116.6	1.68	G32-2	166.8	2.31

Table 7. Impact test results for plate GAG (19 mm). Specimens were tested at -84°C. Two specimens were tested at each condition, i.e. 3, 4.

Specimen Identity	En Ab. Joules	Lat. Exp. X10^-3 M	Specimen Identity	En Ab. Joules	Lat. Exp. X10^-3 M
G11-3	100.3	1.32	G22-3	38.0	0.46
G11-4	77.8	1.07	G22-4	32.5	0.41
G12-3	96.3	1.27	G23-3	62.4	0.81
G12-4	96.3	1.30	G23-4	43.4	0.61
G13-3	56.9	0.64	G24-3	58.3	0.69
G13-4	23.7	0.20	G24-4	77.3	0.94
G14-3	23.7	0.41	G25-3	108.5	1.50
G14-4	38.0	0.38	G25-4	94.9	1.19
G15-3	83.4	1.07	G26-3	38.0	0.43
G15-4	86.8	1.17	G26-4	52.9	0.64
G16-3	46.1	0.53	G27-3	81.3	0.96
G16-4	33.9	0.48	G27-4	107.1	1.35
G17-3	22.4	0.28	G28-3	119.3	1.65
G17-4	20.3	0.41	G28-4	119.3	1.60
G18-3	20.3	0.18	G29-3	8.8	0.13
G18-4	33.9	0.33	G29-4	43.4	0.53
G19-3	21.0	0.25	G30-3	10.8	0.05
G19-4	29.8	0.48	G30-4	25.8	0.25
G20-3	38.0	0.41	G31-3	11.5	0.18
G20-4	24.4	0.31	G31-4	28.5	0.36
G21-3	58.3	0.69	G32-3	63.7	0.81
G21-4	55.6	0.79	G32-4	92.2	1.04

Table 8. Impact test results for plate FUQ (32 mm). Specimens were tested at -17.8°C. Two specimens were tested at each condition, i.e. 1, 2.

Specimen Identity	En Ab. Joules	Lat. Exp. X10^-3 M	Specimen Identity	En Ab. Joules	Lat.Exp. X10^-3 M
Q11-1	210.2	2.34	Q23-1	151.8	1.91
Q11-2	225.1	2.44	Q23-2	146.4	1.83
Q13-1	230.5	2.52	Q24-1	135.6	1.78
Q13-2	221.0	2.31	Q24-2	147.8	1.85
Q14-1	216.9	2.56	Q25-1	200.7	2.41
Q14-2	216.9	2.34	Q25-2	187.1	2.11
Q15-1	219.6	2.39	Q26-1	134.2	1.65
Q15-2	225.1	2.59	Q26-2	165.4	2.03
Q16-1	221.0	2.49	Q27-1	135.6	1.67
Q16-2	202.0	2.36	Q27-2	197.9	2.44
Q17-1	124.7	1.65	Q28-1	208.8	2.46
Q17-2	149.1	1.85	Q28-2	149.1	1.91
Q18-1	208.8	2.41	Q29-1	225.1	2.39
Q18-2	200.7	2.36	Q29-2	246.7	2.26
Q19-1	203.4	2.46	Q30-1	179.0	2.24
Q19-2	199.3	2.26	Q30-2	208.8	2.46
Q20-1	122.0	1.50	Q31-1	235.9	2.01
Q20-2	136.9	1.75	Q31-2	223.7	2.39
Q21-1	128.8	1.60			
Q21-2	122.0	1.60			

Table 9. Impact test results for plate FUQ (32 mm). Specimens were tested at -84°C. Two specimens were tested at each condition, i.e. 3,4.

Specimen Identity	En Ab. Joules	Lat. Exp X10^-3 M	Specimen Identity	En Ab. Joules	Lat. Exp. X10^-3 M
Q11-3	88.1	1.04	Q23-3	36.6	0.43
Q11-4	78.6	1.04	Q23-4	74.6	1.14
Q13-3	155.9	2.01	Q24-3	67.8	1.07
Q13-4	162.7	1.98	Q24-4	48.8	0.66
Q14-3	122.0	1.70	Q25-3	96.3	1.24
Q14-4	128.8	1.80	Q25-4	111.2	1.42
Q15-3	127.4	1.78	Q26-3	38.0	0.61
Q15-4	113.9	1.65	Q26-4	50.2	0.64
Q16-3	123.4	1.68	Q27-3	61.1	0.76
Q16-4	97.6	1.37	Q27-4	15.6	0.10
Q17-3	73.2	0.94	Q28-3	113.9	1.47
Q17-4	71.6	0.86	Q28-4	113.9	1.50
Q18-3	135.6	1.78	Q29-3	154.6	1.83
Q18-4	107.1	1.47	Q29-4	108.5	1.45
Q19-3	99.0	1.27	Q30-3	69.1	0.94
Q19-4	99.0	1.37	Q30-4	88.1	1.12
Q20-3	18.3	0.20	Q31-3	158.7	1.98
Q20-4	51.5	0.79	Q31-4	157.3	2.06
Q21-3	51.5	0.61			
Q21-4	39.3	0.51			

Table 10. Impact test results for plate GGN (51 mm). Specimens were tested at -17.8°C. Two specimens were tested at each condition, i.e. 1,2.

Specimen Identity	En Ab. Joules	Lat. Exp X10^-3 M	Specimen Identity	En Ab. Joules	Lat. Exp. X10^-3 M
N1-1	230.5	2.59	N12-1	218.3	2.36
N1-2	238.6	2.49	N12-2	184.4	2.31
N2-1	183.0	2.34	N13-1	153.2	2.01
N2-2	196.6	2.46	N13-2	160.0	2.11
N3-1	170.3	2.21	N14-1	123.4	1.63
N3-2	149.1	1.88	N14-2	123.4	1.70
N4-1	155.9	2.06	N15-1	225.1	2.44
N4-2	146.4	1.98	N15-2	173.5	2.26
N5-1	192.5	2.36	N16-1	226.4	2.29
N5-2	235.9	2.64	N16-2	200.7	2.34
N6-1	185.7	2.39	N17-1	176.3	2.24
N6-2	118.0	1.52	N17-2	149.1	1.80
N7-1	38.0	0.43	N18-1	200.7	2.39
N7-2	122.0	1.70	N18-2	230.5	2.41
N8-1	151.8	2.06	N19-1	174.9	2.11
N8-2	136.9	1.83	N19-2	230.5	2.39
N9-1	161.3	2.18	N20-1	221.0	2.41
N9-2	147.8	1.78	N20-2	192.5	2.34
N10-1	104.4	1.42	N21-1	145.1	1.83
N10-2	48.8	0.64	N21-2	164.1	2.08
N11-1	54.2	0.64			
N11-2	15.6	0.15			

Table 11. Impact test results for plate GGN (51 mm). Specimens were tested at -84°C. Two specimens were tested at each condition, i.e. 3, 4.

Specimen Identity	En Ab. Joules	Lat. Exp. X10^-3 M	Specimen Identity	En Ab. Joules	Lat. Exp. X10^-3 M
N1-3	115.2	1.60	N12-3	92.2	1.22
N1-4	75.9	1.07	N12-4	103.0	1.32
N2-3	29.8	0.41	N13-3	69.1	0.91
N2-4	107.1	1.55	N13-4	12.2	0.18
N3-3	14.9	0.28	N14-3	21.0	0.23
N3-4	54.2	0.79	N14-4	39.3	0.46
N4-3	14.9	0.18	N15-3	52.9	0.76
N4-4	38.0	0.46	N15-4	71.9	1.09
N5-3	16.9	0.18	N16-3	59.7	0.91
N5-4	38.0	0.51	N16-4	67.8	0.89
N6-3	22.4	0.31	N17-3	8.1	0.10
N6-4	55.6	0.81	N17-4	23.0	0.33
N7-3	18.3	0.20	N18-3	124.7	1.75
N7-4	6.1	0.03	N18-4	7.5	0.13
N8-3	10.1	0.03	N19-3	23.7	0.15
N8-4	71.8	1.07	N19-4	20.3	0.36
N9-3	31.2	0.41	N20-3	135.6	1.80
N9-4	33.9	0.43	N20-4	116.6	1.50
N10-3	13.6	0.46	N21-3	21.0	0.28
N10-4	8.8	0.10	N21-4	32.5	0.46
N11-3	23.7	0.25			
N11-4	22.4	0.23			

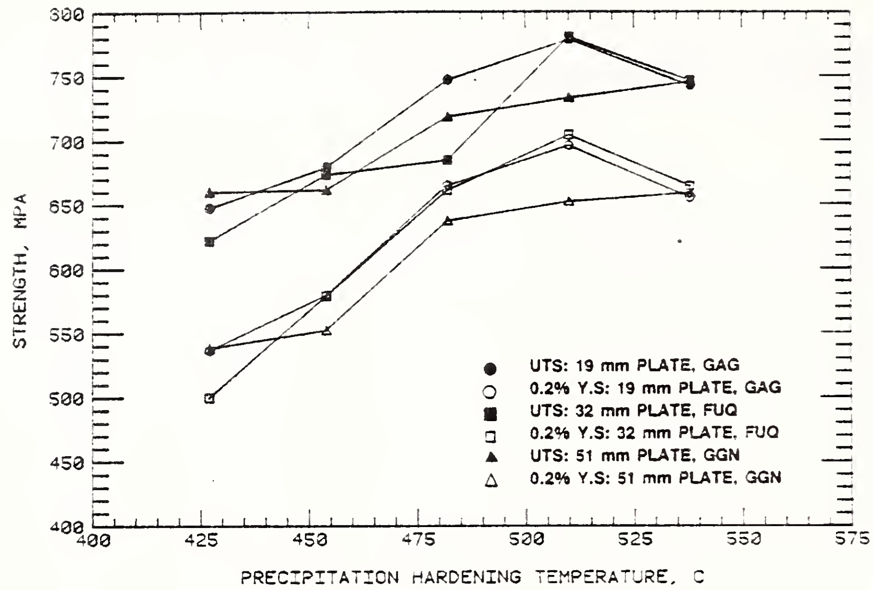

Figure 1. Ultimate and yield (0.2%) strengths versus precipitation hardening temperature. Plates were held 30 minutes at temperature.

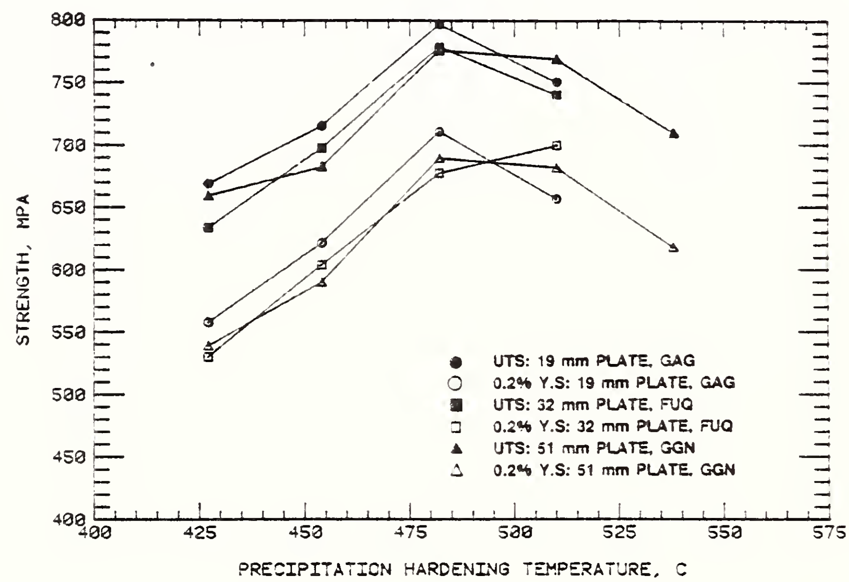

Figure 2. Ultimate and yield (0.2%) strengths versus precipitation hardening temperature. Plates were held 90 minutes at temperature.

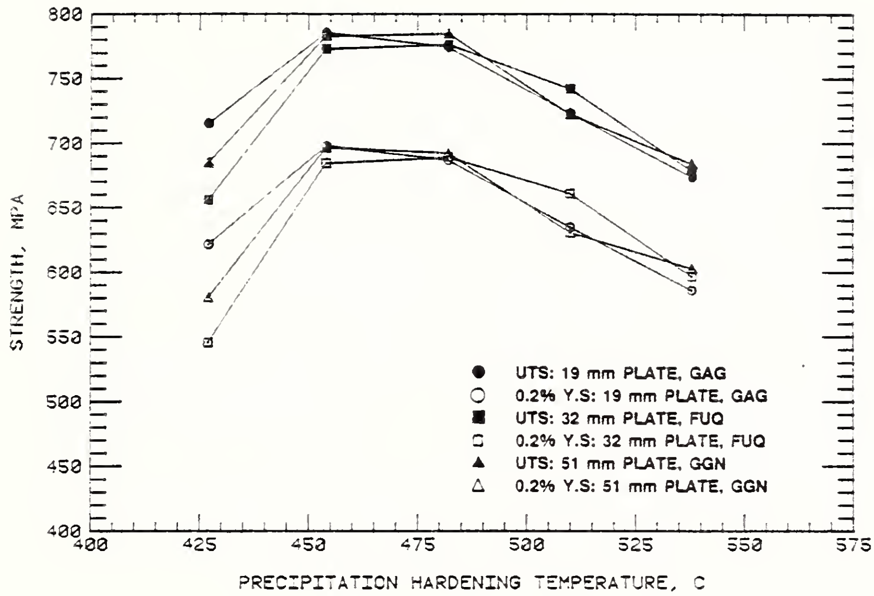

Figure 3. Ultimate and yield (0.2%) strengths versus precipitation hardening temperature. Plates were held 300 minutes at temperature.

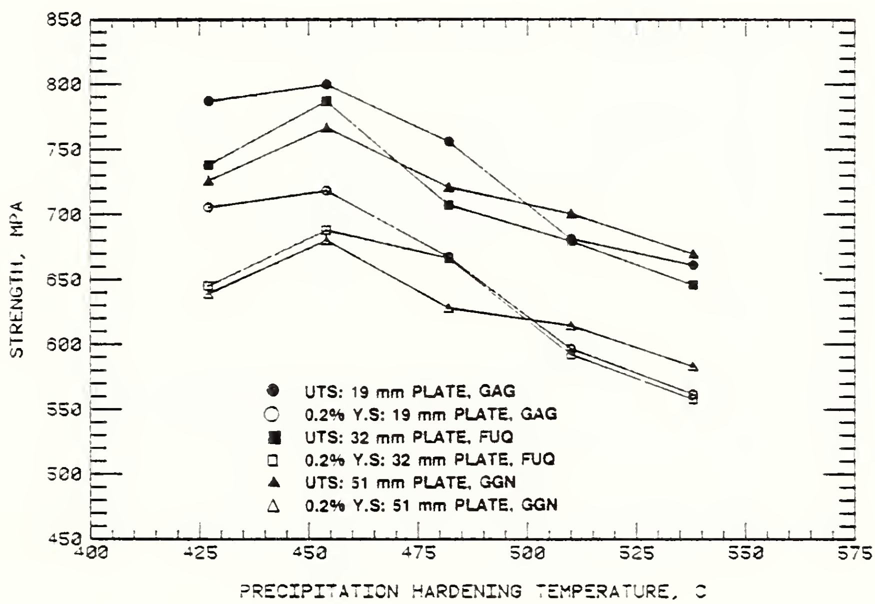

Figure 4. Ultimate and yield (0.2%) strengths versus precipitation hardening temperature. Plates were held 900 minutes at temperature.

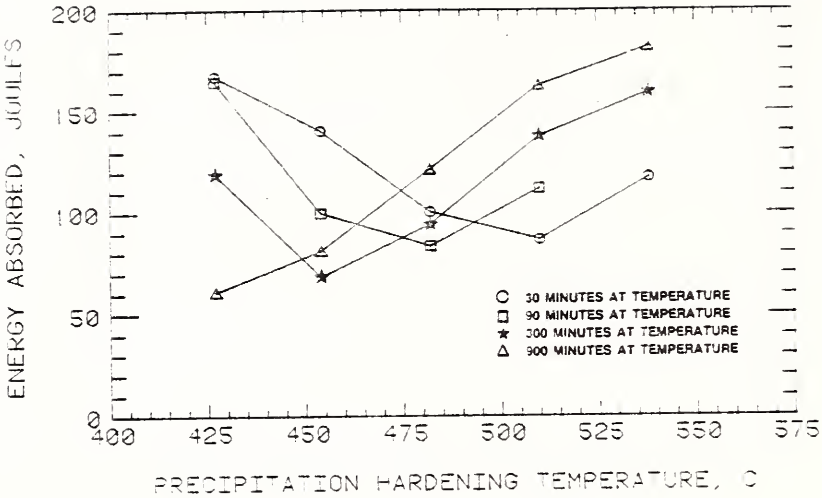

Figure 5. Energy absorbed versus precipitation hardening temperature for specimens taken from the 19 mm thick plate GAG and precipitation hardened for the times shown. Impact tests were conducted at -17.8°C

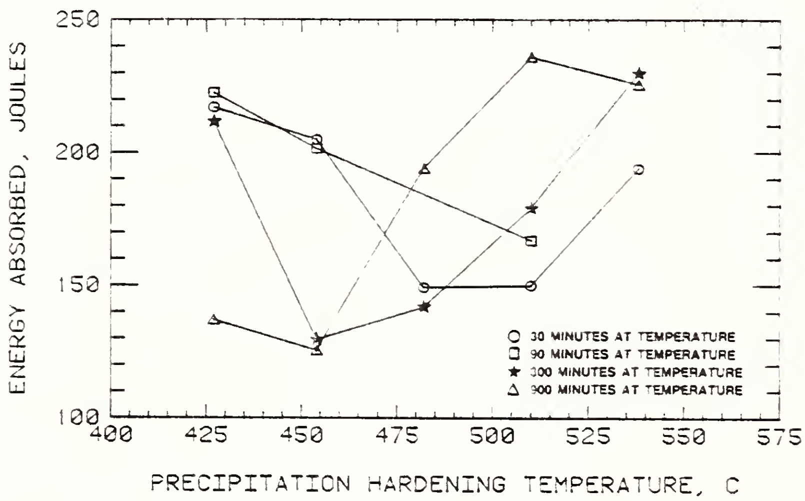

Figure 6. Energy absorbed and precipitation hardening temperature for specimens taken from the 32 mm thick plate FUQ and precipitation hardened for the times shown. Impact tests were conducted at -17.8°C.

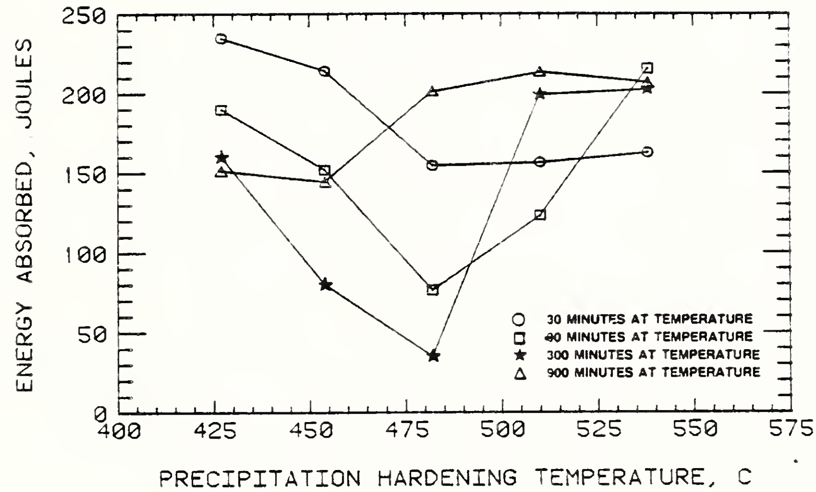

Figure 7. Energy absorbed versus precipitation hardening temperature for specimens taken from the 51 mm thick plate GGN and precipitation hardened for the times shown. Impact tests were conducted at -17.8°C.

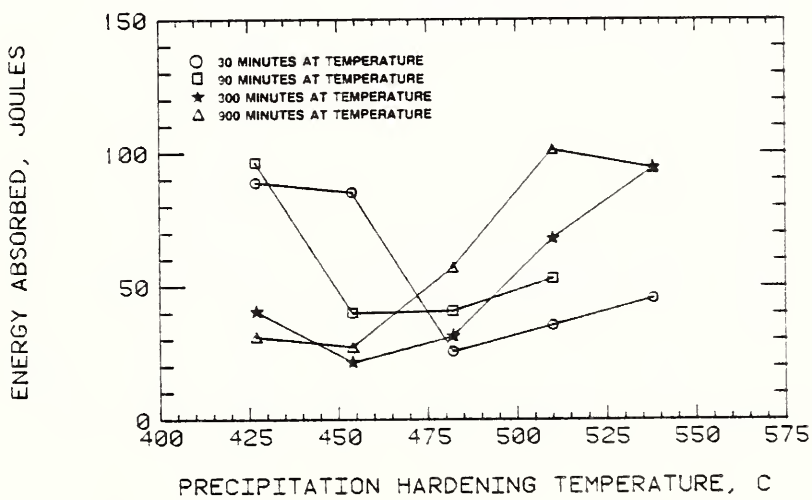

Figure 8. Energy absorbed versus precipitation hardening temperature for specimens taken from the 19 mm thick plate GAG and precipitation hardened for the times shown. Impact tests were conducted at -84°C

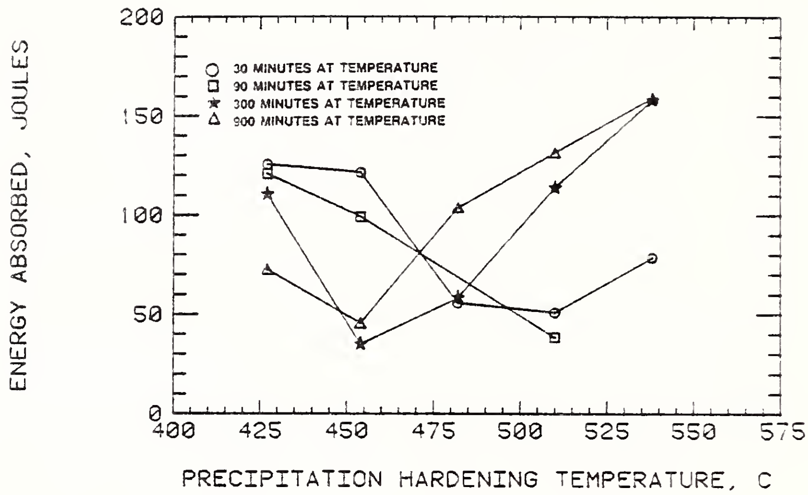

Figure 9. Energy absorbed versus precipitation hardening temperature for specimens taken from the 32 mm thick plate FUQ and precipitation hardened for the times shown. Impact tests were conducted at -84°C.

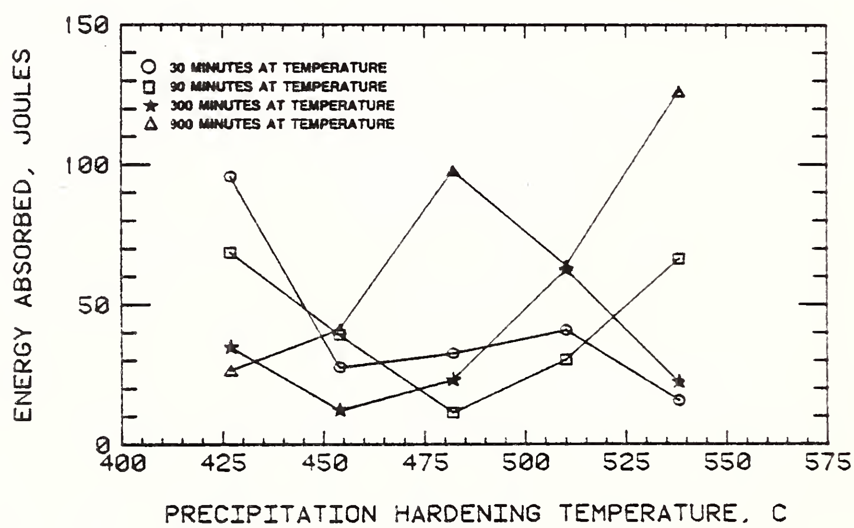

Figure 10. Energy absorbed versus precipitation hardening temperature for specimens taken from the 51 mm thick plate GGN and precipitation hardened for the times shown. Impact tests were conducted at -84°C.

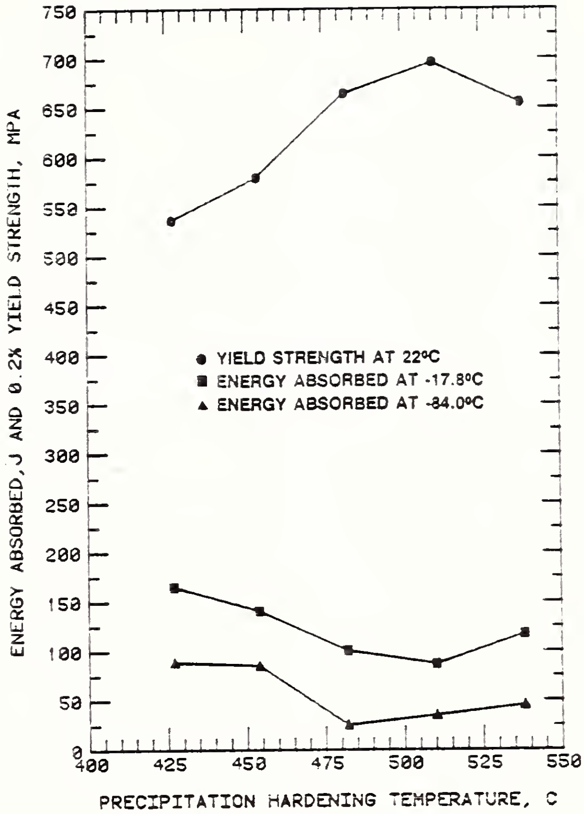

Figure 11. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 30 minutes and specimens were taken from the 19 mm thick plate GAG.

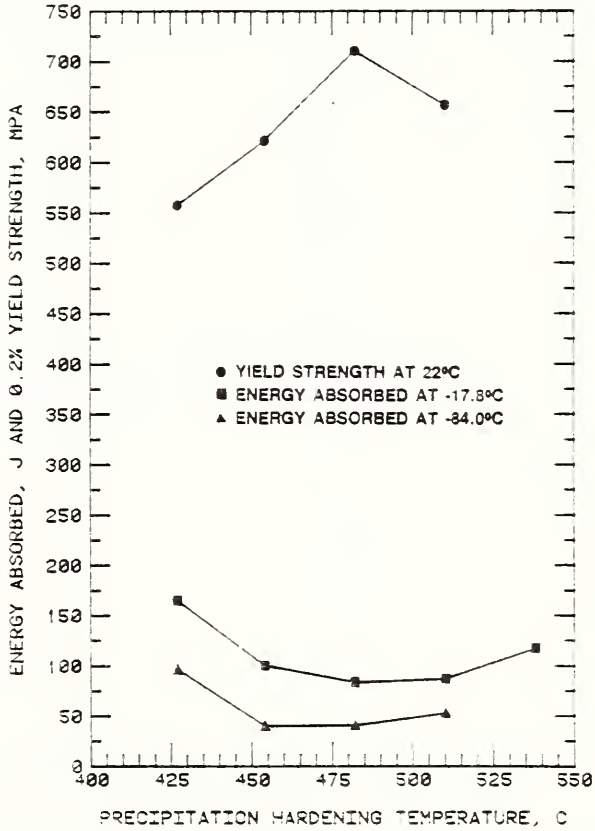

Figure 12. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 90 minutes an specimens were taken from the 19 mm thick plate GAG.

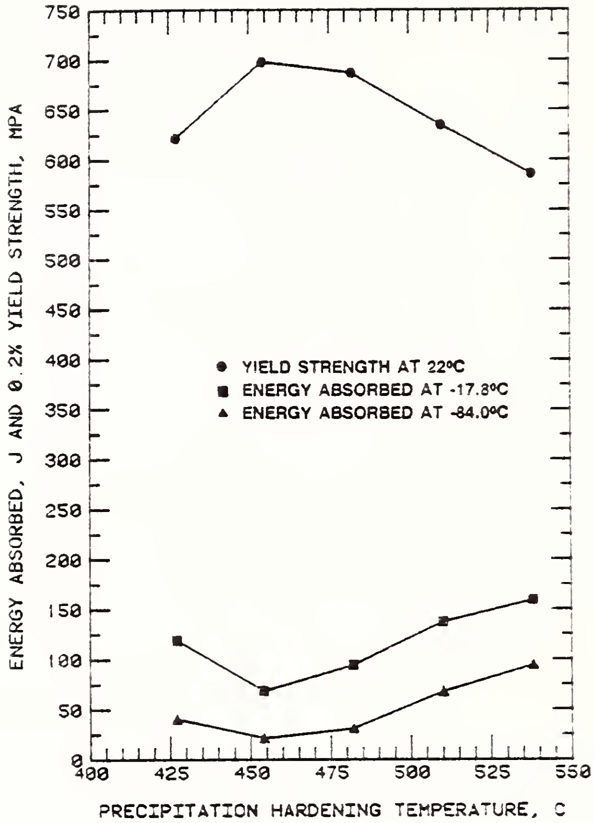

Figure 13. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 300 minutes and specimens were taken from the 19 mm thick plate GAG.

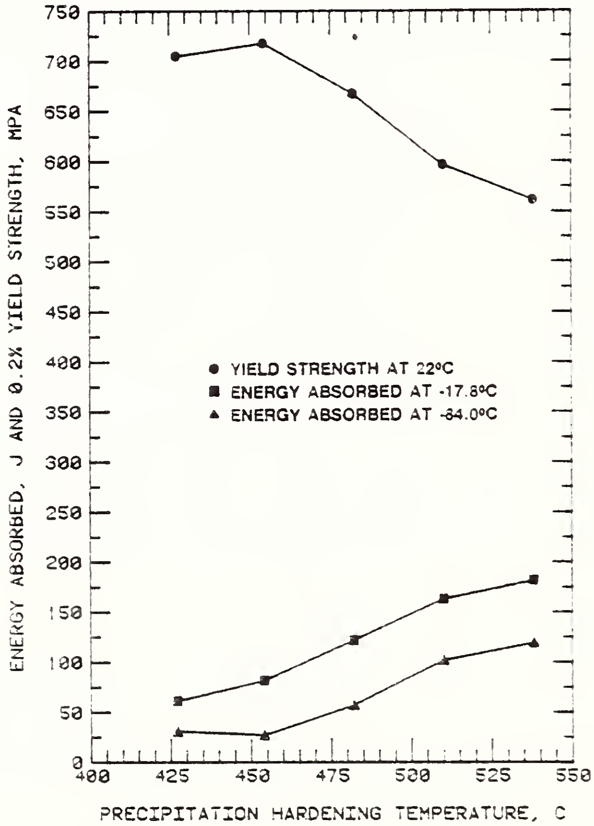

Figure 14. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 900 minutes and specimens were taken from the 19 mm thick plate GAG.

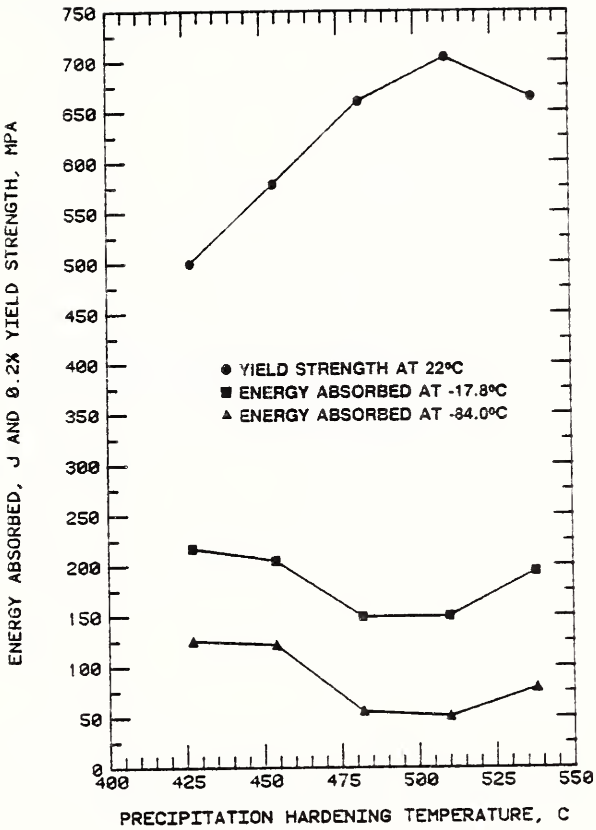

Figure 15. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 30 minutes and specimens were taken from the 32 mm thick plate FUQ.

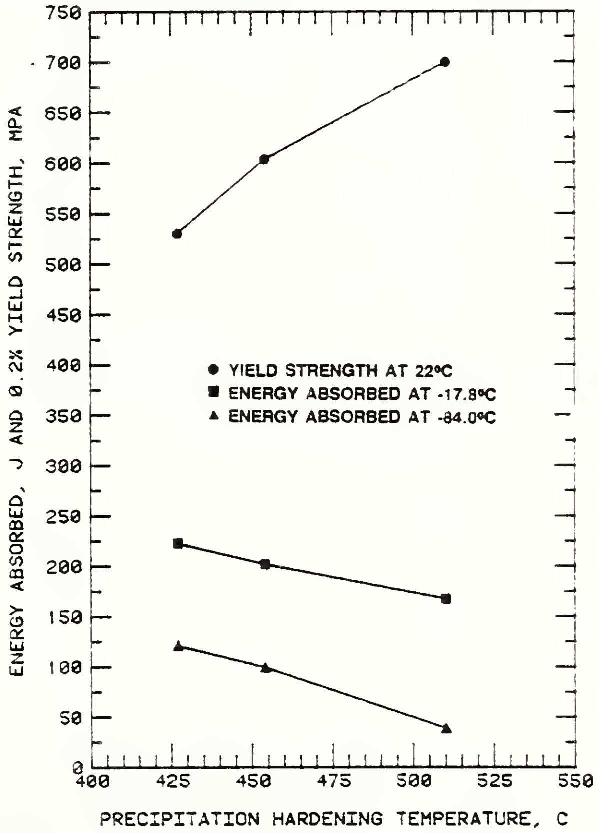

Figure 16. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 90 minutes and specimens were taken from the 32 mm thick plate FUQ.

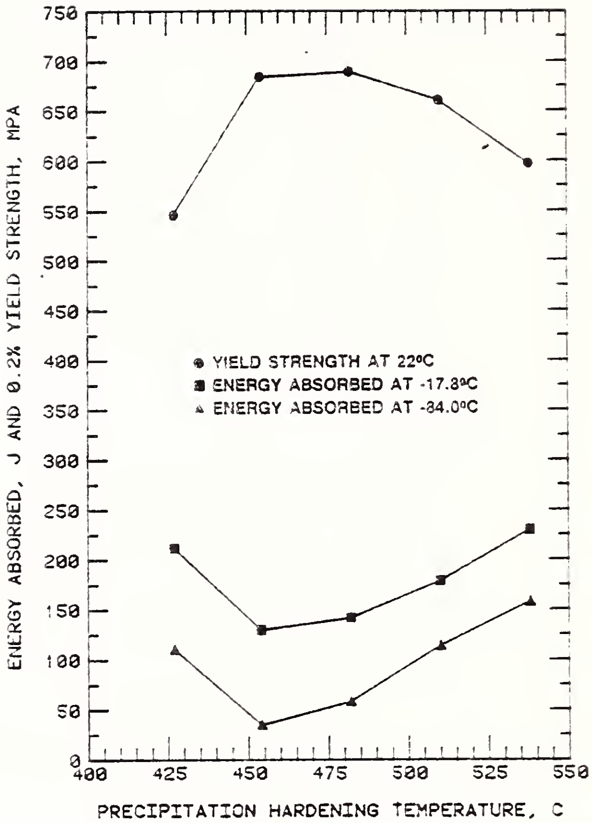

Figure 17. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 300 minutes and specimens were taken from the 32 mm thick plate FUQ.

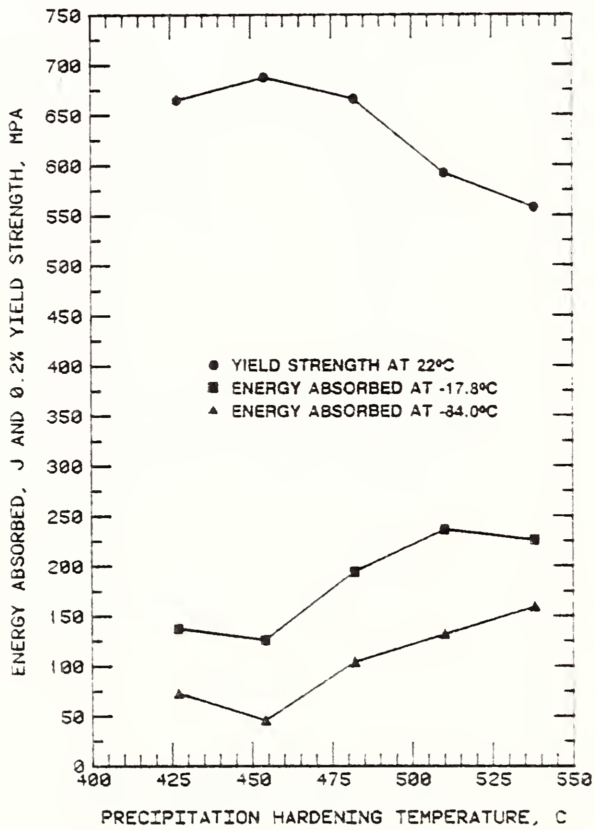

Figure 18. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 900 minutes and specimens were taken from the 32 mm thick plate FUQ.

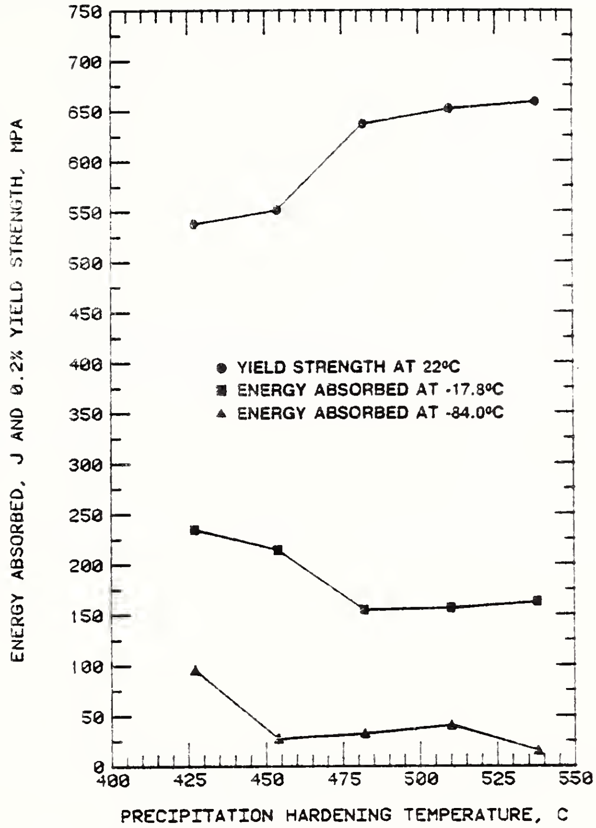

Figure 19. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 30 minutes and specimens were taken from the 51 mm thick plate GGN.

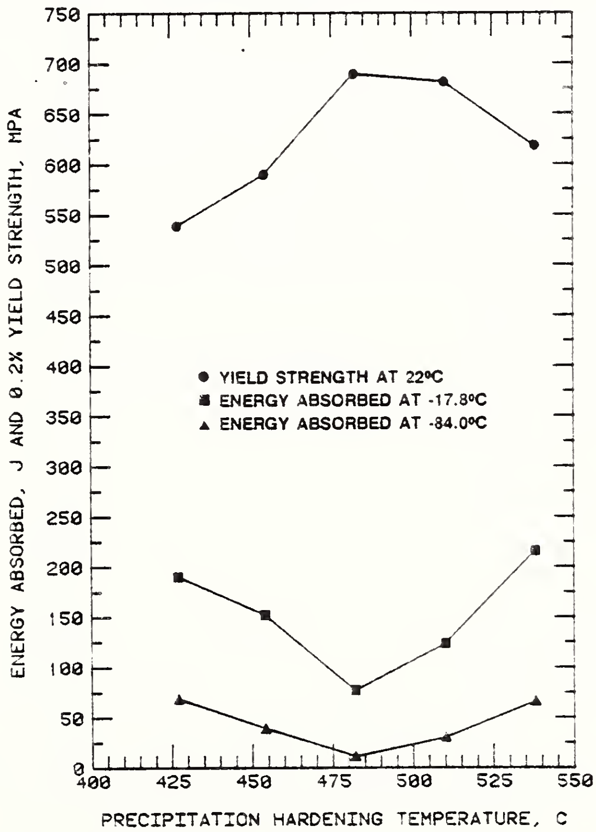

Figure 20. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 90 minutes and specimens were taken from the 51 mm thick plate GGN.

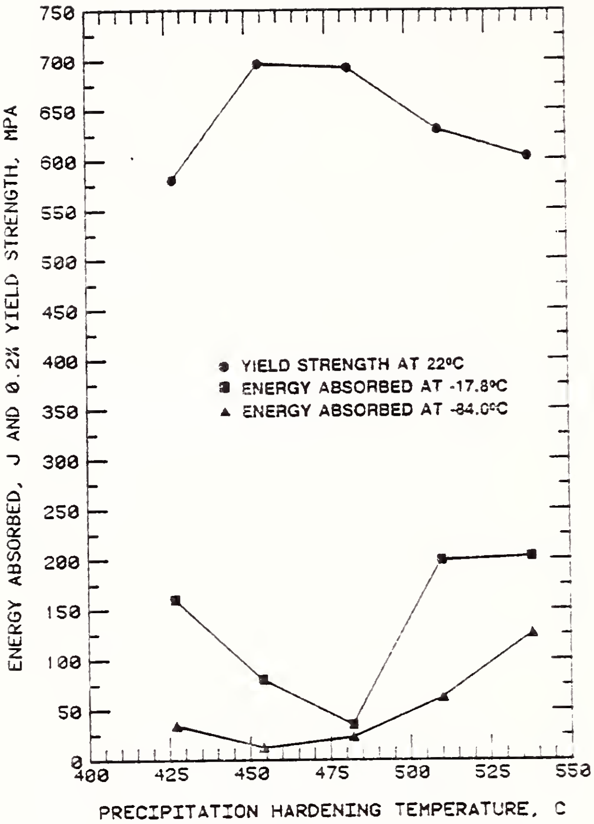

Figure 21. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 300 minutes and specimens were taken from the 51 mm thick plate GGN.

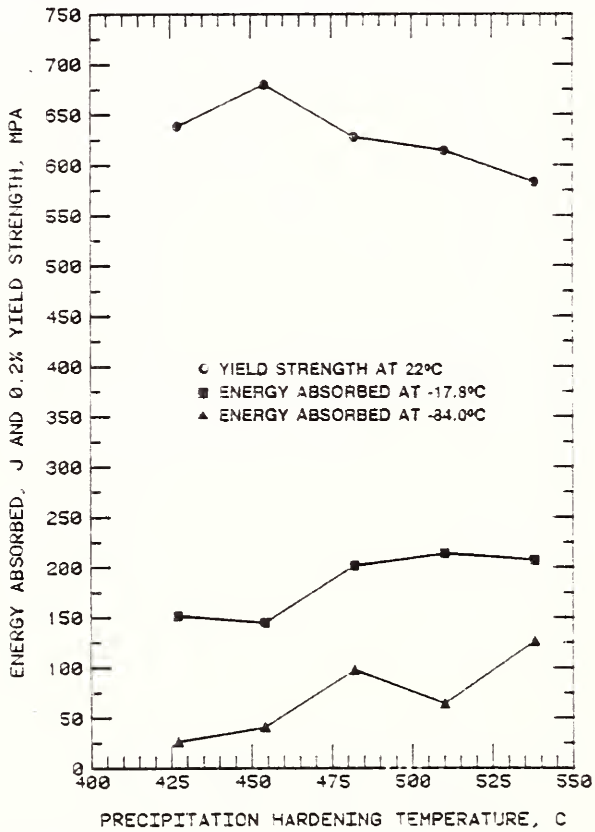

Figure 22. Yield strength (0.2%) and energy absorbed versus precipitation hardening temperature. Time at temperature was 900 minutes and specimens were taken from the 51 mm thick plate GGN.

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5. AUTHOR(S)

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

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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)*

The second of two reports on optimizing the mechanical properties of HSLA-80 steel by heat treatment, concentrates on the precipitation hardening tempertures adn times. Optimum properties, comparable to HSLA-100, were found when the 19 mm thick plates were precipitation hardened at 482°C for 90 minutes, and the 32 mm thick plates were precipitation hardened at 454°C for 90 minutes; 482°C for 300 minutes; and 510°C for 30 minutes. There was no precipitation hardening treatment for the 51 mm thick plate where the desired mechanical properties were achieved.

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

Impacts; precipitation hardening temperatures; precipitation hardening times; steel; tensiles

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