UNCLASSIFIED

AD 444806

DEFENSE DOCUMENTATION CENTER

FOR

SCIENTIFIC AND TECHNICAL INFORMATION

CAMERON STATION, ALEXANDRIA, VIRGINIA

UNCLASSIFIED

DEPARTMENT OF THE NAVY

HYDROMECHANICS

○

AERODYNAMICS

○

STRUCTURAL MECHANICS

○

APPLIED MATHEMATICS

○

ACOUSTICS AND VIBRATION

EVALUATION OF COMMERCIALLY PRODUCED HY-80 STEEL

by

A. R. Willner and M. L. Salive

STRUCTURAL MECHANICS LABORATORY

RESEARCH AND DEVELOPMENT REPORT

July 1964

Report 1850

PRNC–TMB–648 (Rev 1–64)

EVALUATION OF COMMERCIALLY PRODUCED
HY-80 STEEL

by

A. R. Willner and M. L. Salive

July 1964

Report 1850
S-R011 01 01

TABLE OF CONTENTS

37

LIST OF FIGURES

LIST OF TABLES

ABSTRACT

The purpose of this investigation was to obtain a better understanding of some of the variables which may affect the properties of HY-80 steel. The data indicate that hardenability is increased with plate thickness. Generally, plates above 3-in. thick contain less than 80 percent martensite. As the percent martensite decreases, so do the Charpy V-notch impact values at -120 F. HY-80 steel made under military specifications MIL-S-16216E and F had lower phosphorous and sulphur content than the HY-80 produced under MIL-S-16216D. The data presented herein will be used by the Model Basin for determining the individual or combined metallurgical variables which may have an effect on the mechanical properties of HY-80 steel used in model and prototype construction.

INTRODUCTION

This is the fourth in a series of preliminary reports[1-3] on the factors which affect the mechanical properties of high-strength steel melted to the HY-80 specification.[4]

This work was initiated under Bureau of Ships sponsorship[5,6] and completed under the Model Basin's fundamental research program.[7]

All of the planned studies depicted in Figure 1 have been completed with the exception of the welding investigation. Voluminous data have been compiled and are being prepared for publication. A partial summary of the data is presented in this report for immediate dissemination. These data were accumulated for the purpose of obtaining an understanding of the producers variables which may have an effect on the metallurgical transformation characteristics and mechanical properties of HY-80 steel.

The chemistry ranges used in producing HY-80 steel can have a pronounced effect on its transformation characteristics. Accordingly, the Model Basin has to know the effect that variations in chemistry and methods of different steelmaking processes will have on mechanical properties in order to interpret and extrapolate mechanical property data for analysis of HY-80 steel used in model construction to the HY-80 steel used in prototype construction.

---

[1]References are listed on page 37.

Data presented herein are obtained from investigative steps (included within the broken line in Figure 2) which correlate the effects of various factors influencing the mechanical properties of commercially produced HY-80 steel. For this evaluation, data were taken from INSMAT's Form INM-16 and from the quality control sheets of two producers herein designated as "X" and "Y."

BACKGROUND

When this investigation was initiated, HY-80 specification MIL-S-16216D[4] was in effect. This specification indicated two chemistries, one for plates up to 56.1 lb/ft^2 and the other for plates above 51 lb/ft.^{2} The MIL-S-16216D specification[4] permitted considerable overlapping between the two chemistry ranges.

The effects that a given chemistry can have on the metallurgical transformation characteristics are shown in Figure 3 which depicts the isothermal transformation diagrams[8] for low and high chemistry ranges of HY-80 steel. The Model Basin checked the validity of these diagrams, and the check points are superimposed upon the TTT diagrams. In addition, Figure 3 shows the rate of isothermal transformation for the low and high chemistries.

Since the Model Basin initiated its metallurgical studies of HY-80 steels, the HY-80 specification[4] has been superseded three times: by MIL-S-16216E,[9] by MIL-S-16216F,[10] and now by MIL-S-16216G.[11] The chemistry specified for HY-80 steels in the latter specifications[9,10,11] are the same. Instead of specifying chemical composition for two different thickness ranges, the newer specifications give only one range. The differences in chemical composition requirements between MIL-S-16216D and MIL-S-16216G are compared in Table 1. In the newest specification,[11] the carbon, phosphorous, and sulphur maximums are lower than formerly and maximums are specified for the residual elements titanium, copper, and vanadium.

In order to economically meet the chemical and mechanical property requirements of the HY-80 specifications, the steel companies have set up their own "in-house ordered chemistry ranges." The composition ranges used by these producers for making HY-80 steel to the former[4] and to the present[11]

TABLE 1

Comparison of the Chemical Composition Requirements for HY 80 Steel Specified by MIL-S-16216D and MIL-S-16216G

Specification Requirements		Military Specification Percent*		
		MIL-S-16216D		MIL-S-16216G
Plate Thickness lb/ft^2		To 56.1 lb/ft^2	Over 51.0 lb/ft^2	-------
Major Alloying Elements	C	0.22	0.23	0.18
	Mn	0.10-0.40	0.10-0.40	0.10-0.40
	P	0.035	0.035	0.025
	S	0.040	0.040	0.025
	P & S	---	---	0.045
	Si	0.15-0.35	0.15-0.35	0.15-0.35
	Ni	2.00-2.75	2.50-3.25	2.00-3.25
	Cr	0.90-1.40	1.35-1.85	1.00-1.80
	Mo	0.23-0.35	0.30-0.60	0.20-0.60
Residual Elements	Ti	---	---	0.02
	V	---	---	0.03
	Cu	---	---	0.25
Microstructure (Minimum)		---		80 percent Martensite

*Maximum percent unless a range is shown.

specifications are considered proprietary information and will not be included in this report. When the chemistries of MIL-S-16216D were changed to meet the requirements given in modification MIL-S-16216E, the producers changed their ordered chemistry ranges. Since that time, they have made no change in their "in-house" chemistry ranges and have kept the ordered chemistry ranges formulated to meet the requirements of MIL-S-16216E.[9]

MATERIALS AND ANALYTICAL PROCEDURES

As previously stated, the INM-16 cards and the producers quality control sheets were used as the source of data for the analysis. However, at the time this study was made, no commercial data were available for HY-80 steel made to MIL-S-16216G. Since the producers are still using their in-house ordered chemistry ranges developed for MIL-S-16216E and F to manufacture HY-80 steel, the data presented herein can be considered as typical for HY-80 steel currently being made under MIL-S-16216G.

Since the HY-80 specification permits different chemistries for light and heavy gages, the question arises as to the effects of hardenability on the notch toughness. In order to calculate hardenability, the prior austenitic grain size had to be taken into consideration. The commercial data did not report grain size; therefore, to establish a hardenability baseline, grain size measurements were made on approximately 25 as-received ends cropped from commercially produced HY-80 plates. The measured prior austenitic grain sizes from those cropped ends are given in Table 2.

An average austenitic grain size of 6 is used herein for calculating the hardenabilities. The equations developed by the Ad Hoc Committee on Naval Armor[12] were used for converting the ideal critical diameter (D_{I-50M}*) values to equivalent thicknesses (L_{SW-80}**) of plates quenched in still water.[1]

---

*Grossman's factors for obtaining D_{I-50M} are based on a 50 percent martensitic structure at the center of a round bar after an ideal quench.

**L_{SW-80} is the calculated plate thickness based on chemical composition for obtaining 80 percent martensite at center thickness.

TABLE 2

Prior Austenitic ASTM Grain Size of Commercially Produced HY-80 Steels

Laboratory Identification*	Thickness inches	ASTM Micro Grain Size as Received
X- 1	2.0	6
X- 2	6.0	6
X- 3	1.625	5
X- 4	2.0	6
X- 5	2.125	4
X- 6	3.75	7
X- 8	2.0	5
X- 9	1.5	6
X-10	1.75	4
X-11	2.125	6
X-12	1.5	8
X-13	4.5	6
X-15	4.5	7
X-16	1.8	5
X-17	6.0	6
X-18	2.0	-
Y- 1	0.6875	7
Y- 2	2.0	7
Y- 3	0.75	7
Y- 4	2.625	5
Y- 5	2.25	6
Y- 6	2.0	5
Y- 7	1.5	5
Y- 8	2.0	8
Y- 9	2.0	5
Y-10	2.5	7
Y-11	3.625	4

*X and Y indicate the two major producers.

The question may arise whether the calculated hardenability factors have any significance when dealing with an HY-80 composition. Typical plots of experimental and calculated end-quench hardenability curves are shown in Figure 4. The experimental ASTM end-quench hardenability curves[13,14] for HY-80 steels were obtained from Naval Weapons Laboratory (NWL), Dahlgren, Virginia; as can be seen from Figure 4, the calculated values closely approximated the NWL experimental test data. Some nonmartensitic transformation took place during the end quenching as indicated by the inflections on the experimental curves.

The 80 percent martensite criterion is used throughout this report since HY-80 was developed to the Ad Hoc Committee on Naval Armor's criterion of 80 percent martensite at the center of the plate.[12] MIL-S-16216G states that the producers shall use processes which will develop 80 percent martensite.

In order to make the hardenability calculations relative for each producer, the ratio

$$T/L_{SW-80} = \frac{\text{Actual plate thickness}}{\text{Calculated plate thickness to obtain 80 percent martensite at center}}$$

was used. A ratio equal to 1.0 indicates a production plate containing 80 percent martensite; a ratio less than 1.0 indicates a plate containing more than 80 percent martensite; and a ratio greater than 1.0 indicates a plate containing less than 80 percent martensite.

Figure 5* was used to obtain (from calculated D_{I-50M}) the theoretical percent martensite at the center thickness of any plate quenched in still water.

Data representing production heats for each of the two major producers were evaluated statistically, 150 INM-16 cards provided data on HY-80 made

---

*Figure 5 was developed by simultaneous solution of the equations developed by the Ad Hoc Committee[9] for relating Grossman's D_{I-50M} to plate thickness and to the microstructure developed.

under MIL-S-16216D. Since the chemistry requirements of MIL-S-16216E and MIL-S-16216F are the same and, at the time of this analysis, neither of the two major producers had made 150 heats in accordance with the "F" specification, a combination of 150 heats made under the E and F specification were analyzed as a single unit and compared to the "D" data. These data were analyzed by the use of least-squares method and relative frequency distributions. The relative frequency distribution curve shows the frequency of occurrence on a percentage basis of the variable being studied. All data in the graphical presentations are depicted as a plus or minus one standard deviation band; that is, approximately 67 percent of the data will fall within this band, and approximately 95 percent of the data will fall in a plus or minus two standard deviation band.

Since Producer X makes the majority of its HY-80 steel using open hearth process and Producer Y uses electric furnace process, comparison between producers for the various metallurgical properties will be made on this basis.

ANALYSIS OF DATA

The producers of HY-80 steel adjust the chemistry of any given heat to fit the purchase requirements of a given order; that is, producer's in-house chemistry ranges are used which will insure that the steel will meet the required mechanical properties for the various plate thicknesses ordered.

Figure 6 is a plate thickness frequency distribution of the data used in this analysis. The frequency depicted was not preselected but represents the distribution of the data the Model Basin received for analysis. It is interesting to note that the mean plate thickness is approximately 2 in. in all cases. Since only limited data are available for the thicker plates, the plate thickness distribution has to be considered when analyzing the least-squares fit of the variables being related; that is, the best least-squares fit for a given variable was found by selecting the fit which gave the minimum residual.

PERCENT CHEMISTRY versus PLATE THICKNESS

Carbon

Carbon is the major element contributing to hardenability. It is interesting to note that MIL-S-16216D calls for a maximum percent carbon of 0.22 to 0.23 depending upon the plate thickness, whereas the later specifications (MIL-S-16216E, F, and G) have a maximum of 0.18 percent carbon, except for plates over 6-in. thick where an additional 0.02 percent carbon is permitted. The producer is allowed to have a check analysis variation of 0.02 percent over the limit.

Figure 7 shows the correlation between check analysis for carbon and plate thickness for the various specifications. Carbon content for HY-80 plates made to MIL-S-16216D can be considered to be the same for both producers. The general trend was to increase carbon content with increasing plate thickness; however, the spread in data indicates that the carbon content for HY-80 steel made under MIL-S-16216D averaged approximately 0.16 percent for both producers.

In making HY-80 steel to MIL-S-16216E and F, Producer Y showed a closer control of carbon content, with carbon content increasing with plate thickness; Producer X appeared to use the same broad carbon range as used in the superseded specification MIL-S-16216D.

Phosphorus and Sulphur

The major change in chemistry requirements between MIL-S-16216D and superseding specifications MIL-S-16216E, F, and G, is in the permissible phosphorus and sulpher content; see Table 3.

Figure 8 compares the ladle or melt to the check chemical analysis taken from finished plates for percent phosphorus, sulpher, and combined phosphorus plus sulpher by relative frequency distribution for HY-80 steel made by Producer X. At the time of the analysis, this producer used open hearth practice for the majority of the HY-80 melts, however, some heats were produced by electric melting practice. Figure 8 includes the relative frequency distribution of these elements for both open hearth and electric

TABLE 3

Comparison of Specified Maximum Phosphorus and Sulphur Contents for Various HY-80 Specifications

Element	Permissible Content (percent)	
	MIL-S-16216D	MIL-S-16216E, F, G
Phosphorus	0.035	0.025*
Sulphur	0.040	0.025
P plus S	---	0.045

*Phosphorus is permitted to exceed maximum by 0.003 percent upon check analysis.

melts. It can be readily seen that the difference between ladle and check analysis is greatest for the open hearth melts. The phosphorus and sulphur content, individually or in combination, is less for the electric heats than for the open hearth melts of HY-80 steel made by Producer X.

Company Y produces HY-80 steel by electric furnace process and reports only check chemical analysis. Figure 9 shows that the phosphorus and sulphur content of the electric melts of Producer Y are approximately the same as for the open hearth heats of Producer X but that the electric melt heats made by Producer X contain a lower sulphur content than the electric heats made by Producer Y. In any case, the check analyses of phosphorus, sulphur, and the combination of both are below the maximum stated in specifications MIL-S-16216E and F.

Figure 10 compares the individual and combined contents of phosphorus and sulphur as a function of plate thickness for HY-80 plate made by the two major producers under MIL-S-16216D and under MIL-S-16216E and F. The steels made under MIL-S-16216D by Producer Y contained greater phosphorus and sulphur content than that of Producer X. However, under MIL-S-16216E and F, the phosphorus and sulphur content were approximately the same for both producers regardless of plate thickness.

Major Alloying Elements

The major alloying elements (other than carbon) which influence hardenability are nickel (Ni), chromium (Cr), and molybdenum (Mo). Manganese (Mn) is used mainly as a sulphur scavenger but it will be discussed as an alloying element since it also contributes to hardenability.

Figure 11 shows the difference in major alloying elements between the two major producers for various plate thicknesses. In addition, a comparison is made between producer chemistries and the specifications MIL-S-16216D and MIL-S-16216E and F.

As can be seen in Figure 11, the HY-80 steel made by Producer Y tends to have a leaner alloy content than steel made by Producer X. It appears that when MIL-S-16216E and F went into effect, both producers tended to slightly drop their alloying additions. Producer Y had a tendency to increase the manganese content of HY-80 plates made under the newer specifications.

HARDENABILITY

Figure 12 compares the calculated hardenabilities to actual plate thicknesses for both producers. The D_{I-50M} versus plate thickness is higher for Producer X than for Producer Y.

The D_{I-50M} is converted to equivalent theoretical plate thickness that will have 80 percent martensite at the center (L_{SW-80}) and plotted as a function of actual plate thickness. As shown by the 45-deg lines in Figure 12, a one-to-one relationship does not exist between actual plate thickness and the theoretical hardenability thickness for 80 percent martensite. The data to the left of the 45-deg line show that the majority of the plates can be expected to contain more than 80 percent martensite; the plates to the right of the 45-deg line are expected to contain less than 80 percent martensite.

The question arises as to what percentage of martensite is actually present in commercially produced plates of HY-80. Since no microstructure analysis was available, the calculated D_{I-50M} for the plates used in the statistical analysis was converted to determine percent martensite at the center of the plate by the use of Figure 5.

Figure 13 shows that with the advent of MIL-S-16216E and F, the heavier HY-80 plates made by Producer Y contain less martensite than similar plates made by Producer X. Under MIL-S-16216E and F, Producer Y's plates, approximately 3-in. thick, will contain 80 percent martensite; Producer X theoretically produces plates up to 4-in. thick with 80 percent martensite. It should be remembered from the frequency distribution shown in Figure 6 that only a limited number of plates were available for this analysis with thicknesses greater than 4-in. However, chemistry data obtained for heavier plate since the completion of this analysis indicate the calculated percent martensite will fall well within the standard deviation given in Figure 13.

TEMPERABILITY

It was shown in Figure 13 that as the thickness of the HY-80 plate increases, so does the percentage of nonmartensitic products. MIL-S-16216D and MIL-S-16216E, F, and G require that the tempering temperature shall not go below 1100 F for HY-80 steel. The question arises as to what effect does nonmartensitic products have on the temperability of HY-80 steel.

Tempering temperature versus the calculated percent martensite present in HY-80 plates quenched in still water are depicted in Figure 14. This figure shows that there is a wide spread in tempering temperatures for HY-80 steel containing more than 97 percent martensite; the tempering range for Producer X ranges from 1190 to 1310 F, and for Producer Y, ranges from 1200 to 1280 F. For these plates containing more than 97 percent martensite, chemistry and grain size play an important part in the tempering temperatures used by the producers for meeting mechanical property requirements. In a few cases, the upper tempering temperature approaches the theoretical critical A_{e_1} temperature, 1321 F.[1]

As the percentage of martensite decreases, the tempering temperature bands become narrower and approximately equal for both producers, from 1190 to 1220 F. However, the minimum temperatures used in tempering commercially produced HY-80 steel is approximately 100 F above the specification requirements.

IMPACT PROPERTIES

Since Figure 13 showed that the theoretical percent martensite decreased with increasing plate thickness for an HY-80 steel plate quenched in still water, the effects of plate thickness on Charpy V-notch impact values at -120 F were studied. MIL-S-16216 requires that longitudinal Charpy specimens be tested at -120 F; 50 ft-lb are required for plates up to 2-in. thick and 30 ft-lb for plates over 2-in. thick. Figure 15 shows that both producers meet these impact requirements. However, the data depicted in Figure 15 do show a decrease in impact values for increasing plate thicknesses. This decrease in impact energy absorption at -120 F is attributed to the increasing percentage of nonmartensitic products as indicated in Figures 13 and 16.

MECHANICAL PROPERTIES AS A FUNCTION OF HARDENABILITY

Since it is believed that nonmartensitic products play an important role in determining the notch toughness level, a ratio of actual plate thickness (T) to calculated plate thickness having 80 percent martensite at the center (L_{SW-80}) is used to determine the relative effects of nonmartensitic products. This ratio shows (Figure 17) that plates 1 1/2 in. and less made under MIL-S-16216D were melted to a lean HY-80 chemical composition; for plates 1 1/2 in. and above, a rich HY-80 chemical composition was used. However, for plates made under MIL-S-16216E and F, Producer X uses a sliding chemistry range whereas Producer Y has held to the system of using two chemical composition ranges. As previously noted in Figures 12 and 13, Producer Y tends toward leaner chemistries for any given plate thickness.

The mechanical properties are plotted in Figure 18 as a function of T over L_{SW-80} ratio. For HY-80 steel made under MIL-S-16216E and F, the impact values of both producers tend to merge and show the same relationship. It should also be noted that Producer X keeps to lower ratios of T over L_{SW-80} than does Producer Y; the lower the ratio, the greater the percent martensite in the steel.

STRESS-STRAIN CURVE CHARACTERISTICS

The stress-strain curve of a material becomes critical when a structural design is based upon buckling and instability formulae. If the proportional limit of a material is lowered due to process variables or due to fabrication, a premature failure may occur. Therefore, it is necessary for the designer to know the stress-strain limitations of the material he is using in developing a structural design.

Producer X has made available to the Model Basin approximately 1200 stress-strain curves from HY-80 steel plates sold to the government for naval use. These stress-strain curves were obtained when MIL-S-16216B was in effect; examination of HY-80 steel produced under MIL-S-16216D, E, F, and G indicated that the stress-strain data presented herein are representative of current production of plates greater than 1/2 inch thick.

Figure 19 depicts the five types of stress-strain curves which are representative of HY-80 steel, and these curves are defined as follows

a. Discontinuous (D) - This curve represents a proportional stress-strain relationship; the strain is proportional to the applied stress in accordance with Hooke's Law. An increment of stress above Point 1 initiates plastic straining with a sudden drop in the stress-strain curve. Point 1, the inception of plastic strain is called the upper yield point. The termination of this drop in load, Point 2, is called the lower yield point. There is usually an extension of yielding without an increase in stress, Points 2-3; this increase in deformation without additional stress is called the yield-point elongation. At Point 3, the curve commences to rise but the strain is not proportional to the stress although the speciman under test deforms uniformly. The stress-strain curve beyond Point 3 is considered inelastic and since the typical production obtained stress-strain curves do not contain this portion of the curve, the inelastic region will not be discussed.

b. Plateau (P) - The second stress-strain curve also represents a discontinuous yielding curve. At Point 1, there is a sudden plastic strain without a drop in stress. This plateau or nearly horizontal portion of the curve may properly be considered a yield point. Points

1-2 exhibit a yield point elongation and at Point 2 the curve exhibits a plastic yielding characteristic which is similar to that found after Point 3 on the D curve.

c. Semi-Plateau (SP) - The semi-plateau curve is similar to the P curve except there is no sharp demarkation at the initiation of the yield point but a rounding of the curve at Point 1. In addition the yield point elongation Points 1-2 has a slight rise with increasing stress.

d. Semi-Continuous (SC) - The fourth curve has a similar rounding off at the proportional limit, Point 1, as the SP curve. However, the proportional limit yield strength ratio is markedly lower for the SC curve. In addition the yield point elongation slope, Points 1-2, is greater than that demonstrated by the SP curve.

e. Continuous (C) - The final curve shows that there is no definite yield point, but a stress-strain curve which gradually deviates from linearity at Point 1 and becomes curvilinear.

The yield strength of the discontinuous and plateau type of curves are equivalent to the lower yield point of the D curve and to the plateau of the P curve. A 0.2 percent off set is taken as the yield strength for the SP, SC and C types of stress-strain curves.

Figure 20 is the relative frequency distribution of the five types of curves as determined from 1200 HY-80 stress-strain curves obtained from Producer X and representing 600 commercially produced plates. Eighty-two percent of the curves from these production plates had either discontinuous, plateau, or semi-plateau types of stress-strain curves; the remaining 18 percent had either semi-continuous or continuous type stress-strain curves. Figure 20 also shows the stress-strain curve distribution of HY-80 steel used in structural models. It is interesting to note that the distribution of type of stress-strain curve used in models is similar to the distribution obtained for standard production plates.

Approximately 50 percent of the stress-strain curves showing SC or C types of curve were from production plates 3-3/8 inches or more thick; the remaining SC and C curves came from plates less than 1/2-in. thick. Plates less than 1/2-in. thick were usually distorted in quenching and had to be roll straightened after tempering thereby imparting a Bauschinger effect. Since these plates were produced, new heat treating facilities were installed by Producer X and the stress-strain curves for these thin plates are usually of the D and P type.

Figure 21 shows the distribution of proportional limits for each plate thickness used in the analysis of yielding characteristics of production HY-80 plates. The mean proportional limit falls around 80,000 psi with the one standard deviation spread falling between 75,000 and 85,000. These high proportional limits are representative of HY-80 steel having either discontinuous, plateau, or semi-plateau type of stress-strain curves. It should be remembered that the proportional limits were obtained from stress-strain curves representing production inspection techniques and that the proportional limits obtained from these curves can be considered on the conservative side.

FRACTURE CHARACTERISTICS

Military specifications MIL-S-16216E, F, and G state that HY-80 plates can be rejected if their fracture appearance has a partly crystalline structure or a lamination 2 in. or more in length. The steel producers use the fracture appearance quality standards developed for STS armor in reporting fracture characteristics of HY-80 steel. Producer X uses a fracture specimen 6-in. wide and 16-in. long by the plate thickness whereas Producer Y uses a 3-in. by 18-in. by plate thickness. Producer X flame-notches the fracture specimen through the thickness on both sides to a depth of 1/2 in. Producer Y notches the flame cut edge of the fracture specimen by using a mechanical chisel with a 45-deg edge. The specimens are simply supported at both ends, and the load is slowly applied across the width of the specimen by hydraulic pressure through a mandrel having a diameter of 1 in. or 1 1/2 in. depending upon plate thickness.

Fracture specimens are rated by the steel producers as follows:

Ratings	Type of Fracture
F	All-fiber or fibrous
LL	Light lamellar
HL	Heavy lamellar
LS	Light shale
HS	Heavy shale

Generally the fracture ratings can be interpreted as follows:

Fibrous Fracture - an all-fiber or fibrous fracture is characterized by a nonreflecting dark-gray rough surface. The side of the fracture shows the necking-in associated with ductile behavior.

Lamellar Fracture - A lamellar fracture is evidenced within the plate thickness across the plate width by the presence of long areas where the metal has split to form holes or elongated cavities. These holes or elongated cavities are attributed to the separation of the metal from nonmetallic inclusions, such as sulfides, oxides, and silicates, or to the internal shearing of the metal in the rolling sequence; that is, the metal plate is so severely cold-worked in the rolling operation that the ductility of the metal is exceeded.

Shale Fracture - A shale fracture is characterized by the presence of short splits and steps, generally with an eroded, crumbling-wall appearance. This type of failure is attributed to poor open hearth practice resulting in the presence of oxide inclusions of aluminum and silicon within the grain and grain boundaries. Another cause for shale may be that in the solidification of the ingot, many voids may be present due to the occlusion of nonoxidizing gases. In the rolling process, these voids are partially welded together. These partially welded areas can be considered as localized points of weakness. When plates containing inclusions or partially welded voids are subjected to the fracture tests, these planes of weaknesses are evidenced by short splits and steps.

Figure 22 shows the relative distribution of the fracture appearance of HY-80 steel. It should be understood that these are the fracture appearances reported by the steel producers. With the advent of MIL-S-16216E and F, Producer X fracture quality appears to be equally distributed between fibrous and light shale and that of Producer Y is consistently fibrous.

The significance of the fracture characteristics as depicted in Figure 22 cannot be related to the requirements of the HY-80 specification. However ballistic armor containing heavy shale and having low transverse Charpy V-notch energy absorption values (less than 40 ft-lb at -40 F) is considered to be of questionable quality. Laminations can be considered as only localized effects and are usually eliminated by cutting back from the end of the plate. However, none of the fracture characteristic ratings given in Figure 22 would be considered detrimental to the overall quality of the HY-80 plate since those plates having a shale type of appearance had better than average impact properties.

Since there are no data on the effects of fracture characteristics on weldability, no direct comparisons can be made. However, if a shale condition is present and this shale appearance is due to abundance of sulfide or oxide inclusions, weldability may be affected.

DISCUSSION

The analysis shows that the phosphorous and sulphur content of the HY-80 steel made under MIL-S-16216E and F are below those for steels produced under MIL-S-16216D. This reduction should improve weldability.

Both producers have made a slight cutback on the alloying additions to HY-80 steels produced under MIL-S-16216E and F, thereby decreasing the theoretical hardenability of the steel; however, the overall notch toughness for any given plate thickness as measured by Charpy V-notch energy absorbed at -120 F was slightly increased. This increase in Charpy properties is attributed to the general decrease in phosphorous and sulphur content.

The data indicate that HY-80 plates greater than 3-in. thick do not contain the required minimum of 80 percent martensite. It should be remembered that HY-80 is inherently a fine grain steel and that the grain size ASTM-6 used in the hardenability calculations may not be representative of all production heats. Smaller grain sizes, as indicated by ASTM-7 and above, will reduce the hardenability factors used in calculating percent martensite for a given plate thickness. Therefore, the actual plate thicknesses containing 80 percent martensite may be less than the minimums established in Figure 13. A quantitative analysis as to the actual percent martensite for a given plate thickness will be established under an existing Model Basin assignment.[15] However, it should be remembered that the calculated end-quench curves fall on the experimental curves as shown in Figure 4, indicating that the hardenability calculations used in this report are realistic approximations of the hardenability behavior of HY-80 steel. Another corroboration of the use of hardenability calculations is the fact that as the calculated percent of nonmartensitic products increased, the reported Charpy V-notch values for those plates decreased, as is shown in Figure 16.

Figure 14 shows that plates quenched out to 100 percent martensite require higher tempering temperatures; whereas the tempering ranges for HY-80 steel containing nonmartensitic products are lower. If HY-80 steel plates are made to the high side of the chemistry range and are fully quenched out to produce 100 percent martensite, a tempering temperature close to the critical transformation temperature, A_{e_1}, may be required to soften the steel to meet the tensile yield strength requirements of the HY-80 specifications. Due to chemical heterogeneity, the A_{e_1} temperature may be exceeded. The effect of tempering over the A_{e_1} temperature on the mechanical and notch toughness properties will be presented in report in preparation.[16]

Both producers meet the mechanical properties required in the current specification, but Producer X makes a higher quality steel as determined by Charpy V-notch values. Producer Y can improve notch toughness quality by increasing both pearlitic and bainitic hardenability.

Fracture appearance on a macroscale through the thickness of the plate shows a general trend toward better fracture characteristics for HY-80 steels made under MIL-S-16216E and F. However, the effects that fracture appearance may have on notch toughness and on weldability are unknown.

In general, the yielding characteristics of HY-80 steel plates are of the discontinuous, plateau, or semi-plateau type. Structures developed on designs where instability may be a problem, will be benefitted by use of steel having a high proportional limit.

It can be observed from this study that the HY-80 steel plate up to 3-in. thick being produced under military specification MIL-S-16216E and F, and probably for MIL-S-16216G, is of high quality.

A report is in preparation on the effects of selected heat treatments on the mechanical properties of HY-80 steel made by the two producers whose data were used in this report. Approximately 25 different HY-80 heats were selected to represent different chemistry ranges and fracture appearances. This report will correlate calculated or theoretical hardenabilities to the actual microstructures obtained. Preliminary analysis of these data indicates that there is a direct correlation between calculated hardenability and actual microstructure as evidenced by the experimental and calculated end-quench curves shown in Figure 4.

Another report[16] is in progress which discusses the effects of metallurgical transformation products on the mechanical properties and notch toughness of a selected HY-80 steel composition; some of these data have already been published.[1-3]

CONCLUSIONS

1. HY-80 steel produced under military specifications MIL-S-16216E and F had lower phosphorous and sulphur content than HY-80 steel previously produced under MIL-S-16216D.
2. The hardenability of HY-80 steel made to MIL-S-16216D was slightly higher than that produced under MIL-S-16216E and F.
3. The notch toughness of HY-80 steel for a given plate thickness produced under MIL-S-16216E and F is slightly higher than that made under MIL-S-16216D.
4. Hardenability calculations indicate that HY-80 plates greater than 3-in. thick generally contain less than 80 percent martensite.
5. The lower the effective hardenability, the lower the reported longitudinal Charpy V-notch impact energy absorption at -120 F.

6. Eighty percent of production HY-80 steel plates have stress-strain curves with either discontinuous, plateau, or semi-plateau yielding characteristics; increasing the hardenability of heavy plates will tend to increase the percentage of these types of curves.

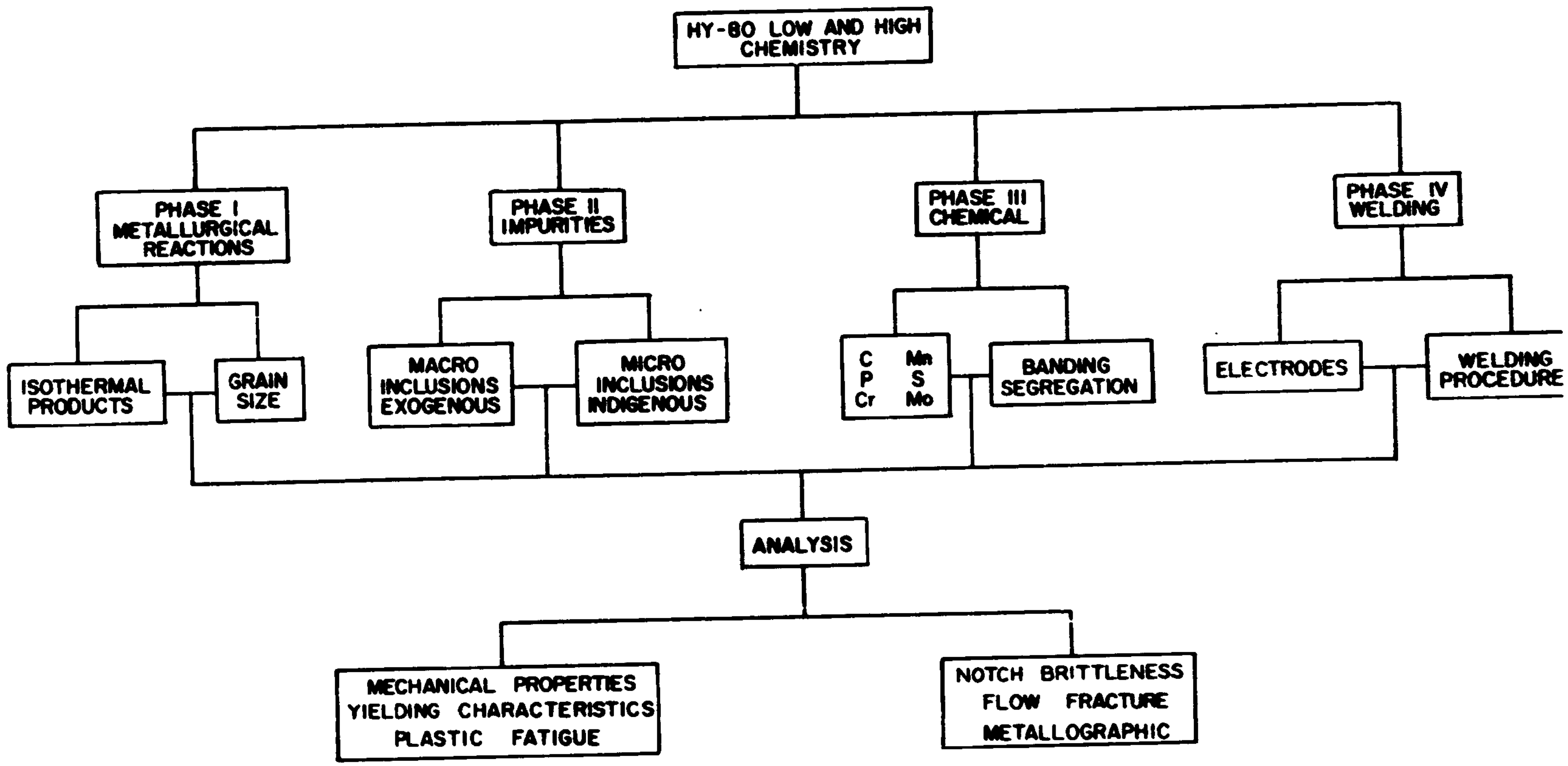


Figure 1 - Investigative Steps in the Study of HY-80 Steels

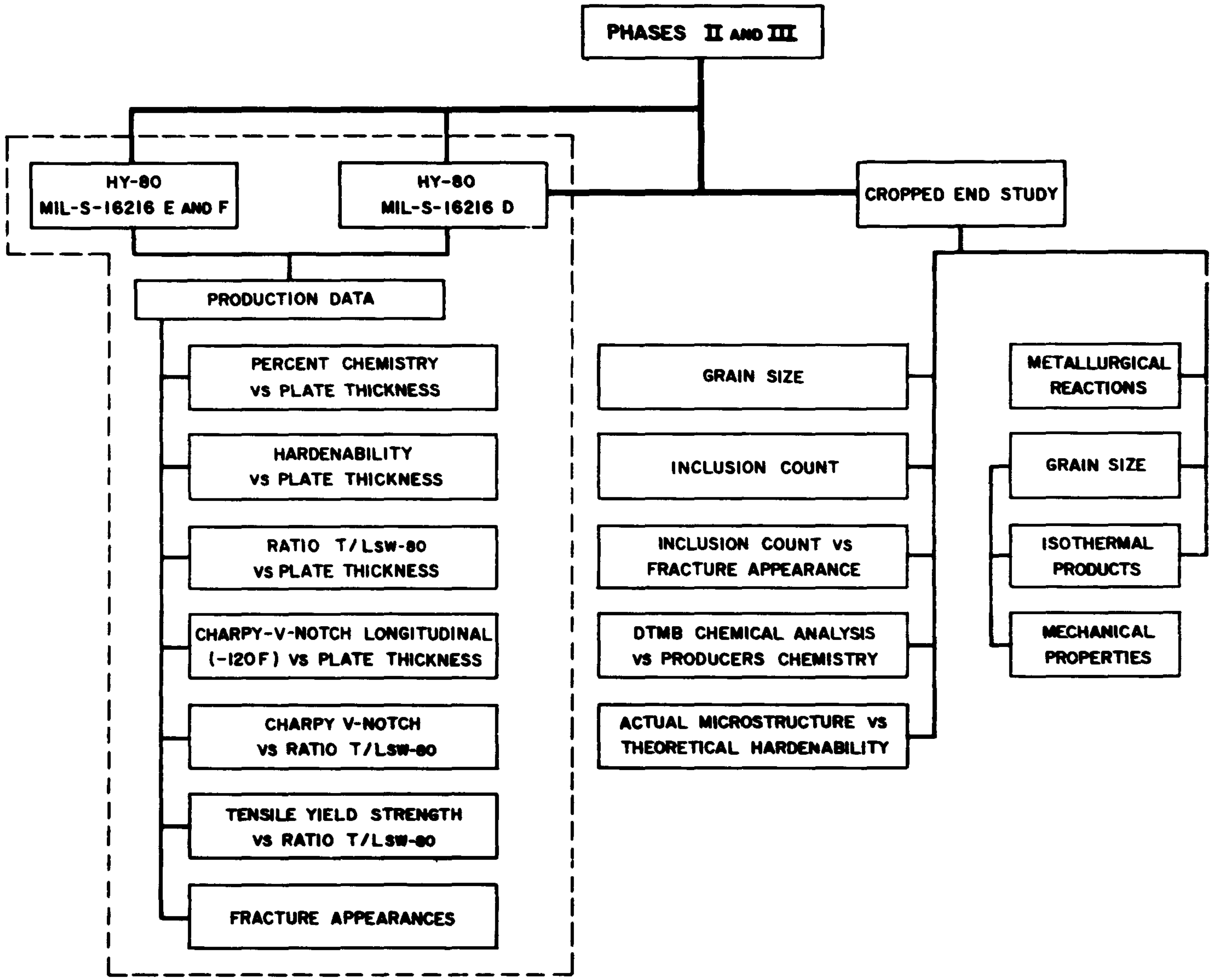


Figure 2 - Investigative Steps in the Study of Commercially Produced HY-80 Steels

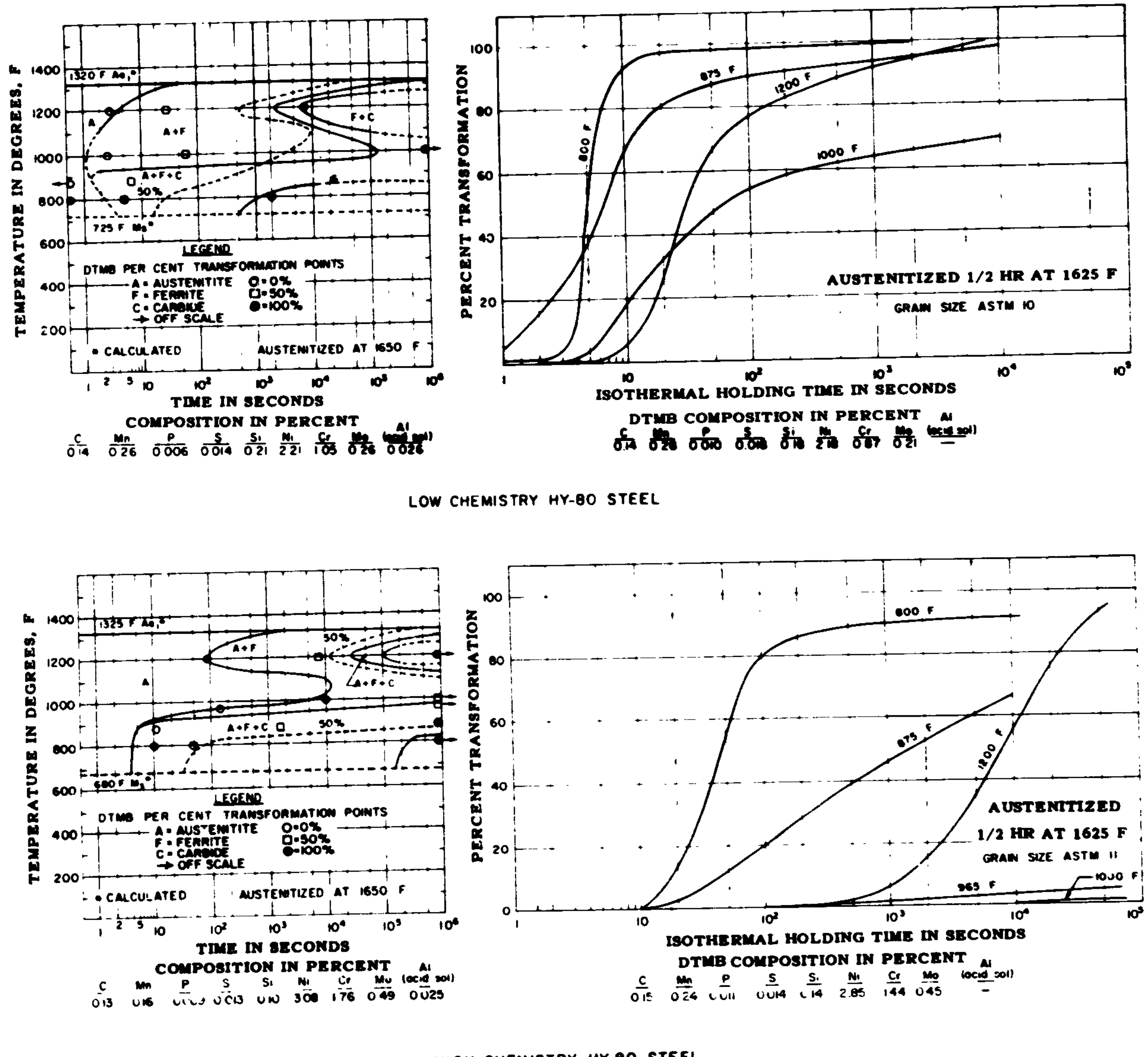


Figure 3 - Isothermal Transformation Diagrams and Rate of Transformation for Lean and Rich HY-80 Steel Compositions

PLATE THICKNESS	ASTM GRAIN SIZE	CHEMICAL COMPOSITION, PERCENT								CALCULATED HARDENABILITY
		C	Mn	P	S	Si	Ni	Cr	Mo	D_I-50 M
1.5	6 *	0.16	0.27	0.012	0.02	0.26	2.9	1.75	0.50	9.5

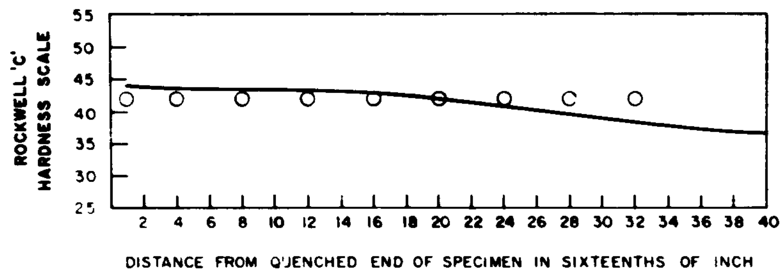
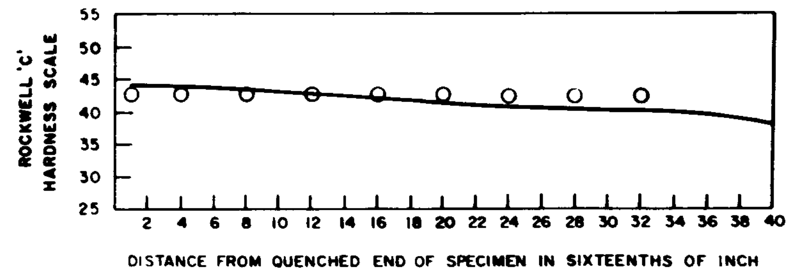


PLATE THICKNESS	ASTM GRAIN SIZE	CHEMICAL COMPOSITION, PERCENT								CALCULATED HARDENABILITY
		C	Mn	P	S	Si	Ni	Cr	Mo	D_I-50 M
2.75	6 *	0.17	0.37	0.016	0.024	0.26	3.36	1.44	0.41	11.03



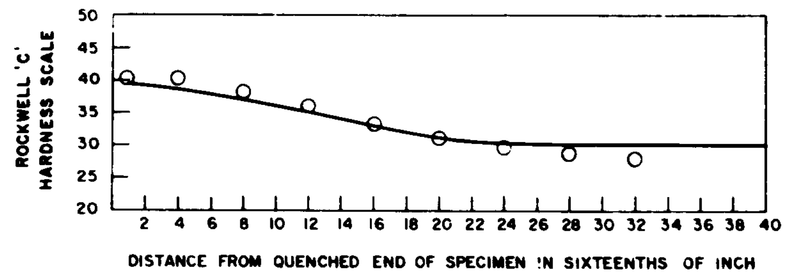
LEGEND:

——— MEASURED

O CALCULATED

* ESTIMATED GRAIN SIZE

PLATE THICKNESS	ASTM GRAIN SIZE	CHEMICAL COMPOSITION, PERCENT								CALCULATED HARDENABILITY
		C	Mn	P	S	Si	Ni	Cr	Mo	D_I-50 M
1.5	6 *	0.13	0.18	0.012	0.016	0.21	2.74	1.50	0.43	5.35



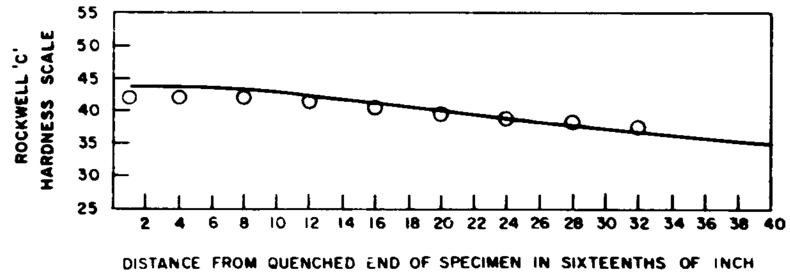
LEGEND:

——— MEASURED

O CALCULATED

* ESTIMATED GRAIN SIZE

PLATE THICKNESS	ASTM GRAIN SIZE	CHEMICAL COMPOSITION, PERCENT								CALCULATED HARDENABILITY
		C	Mn	P	S	Si	Ni	Cr	Mo	D_I-50 M
2.50	6 *	0.16	0.23	0.016	0.02	0.22	2.98	1.42	0.40	6.5



PRODUCER X

PRODUCER Y

Figure 4 - Comparison of Experimental and Calculated Jominy Curves for Commercially Produced HY-80 Steel

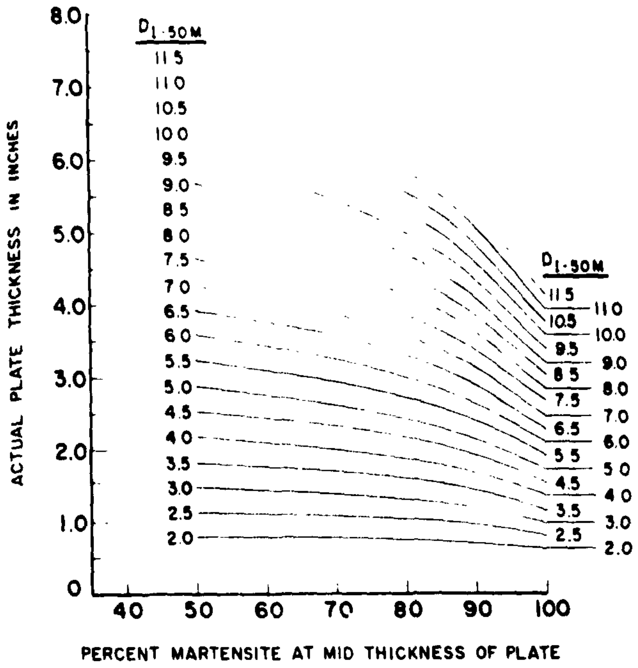


Figure 5 - Relationship between Actual Plate Thickness and Percent Martensite at the Midthickness of a Plate Quenched in Still Water for Any Calculated D_{I-50M}

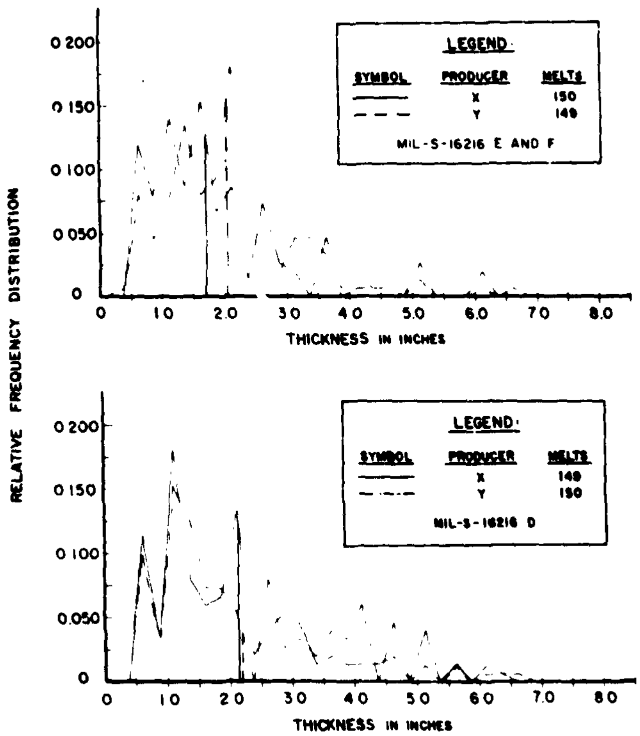
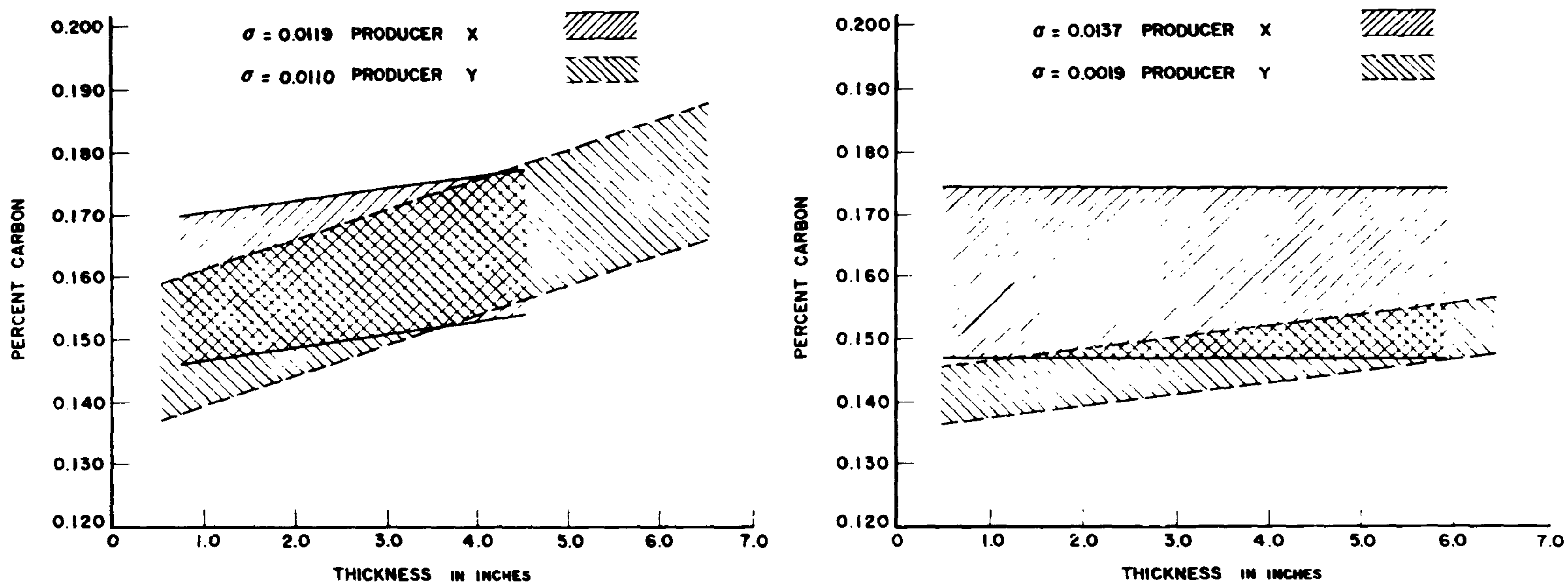


Figure 6 - Relative Frequency Distribution of Plate Thickness of HY-80 Steel Plate Used



MIL-S-16216 D

MIL-S-16216 E AND F

Figure 7 - Correlation of Percent Carbon to Plate Thickness

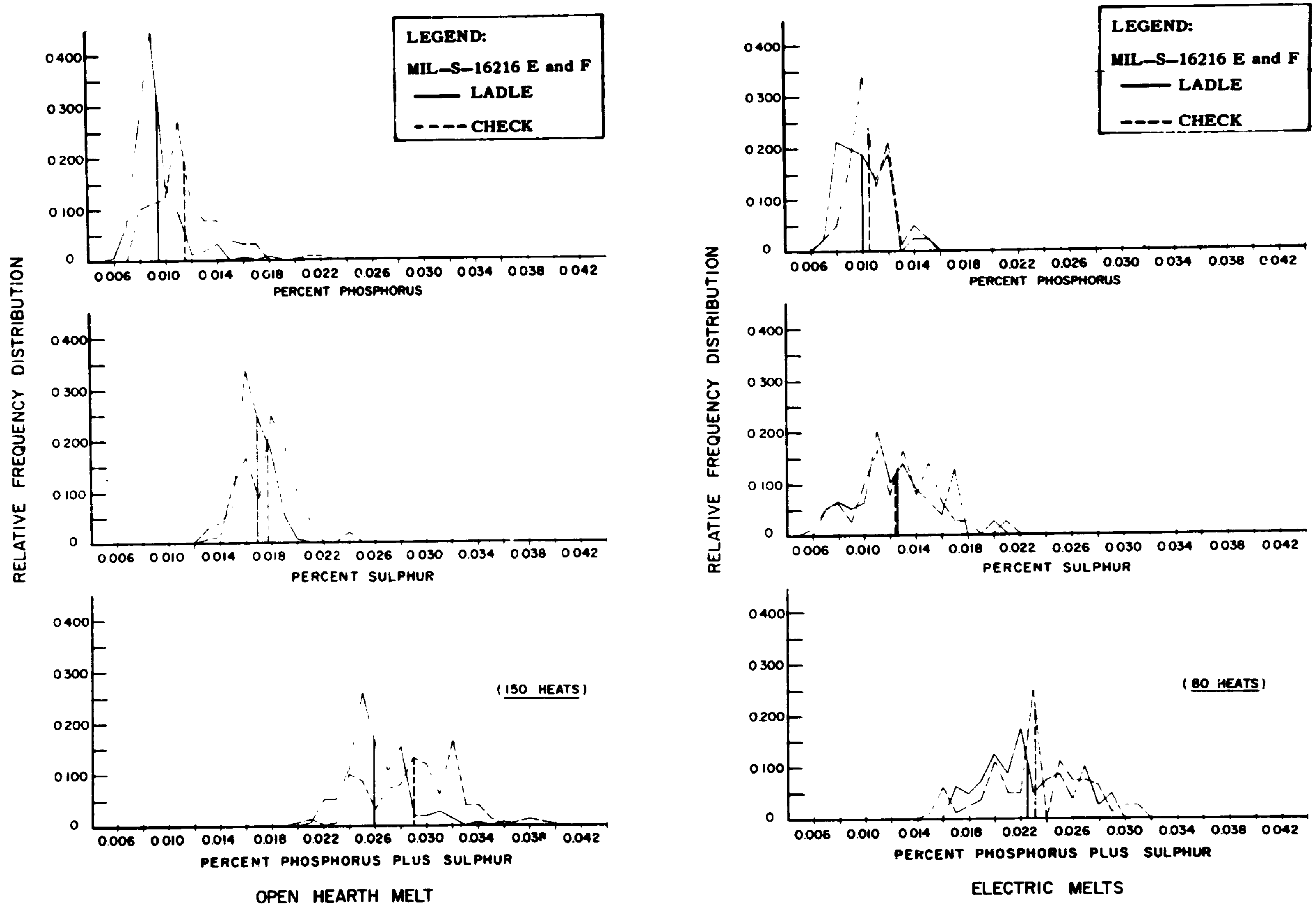


Figure 8 - Comparison of Ladle Melt and Check Analysis for Percent Phosphorous and Sulphur of Open Hearth and Electric Melts of Producer X

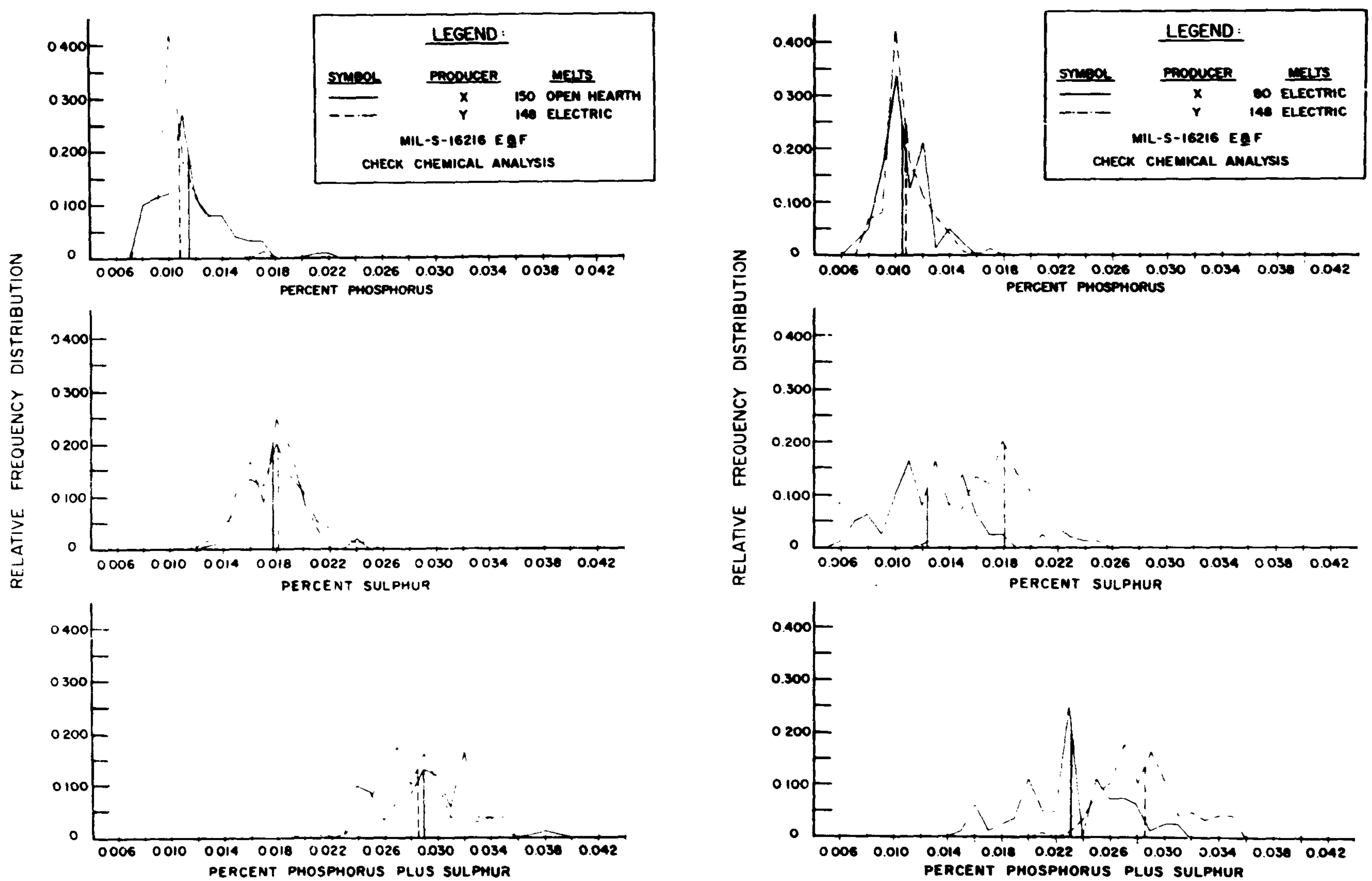


Figure 9 - Comparison of Relative Frequency Distribution of Check Analysis for Phosphorous and Sulphur between Two Producers

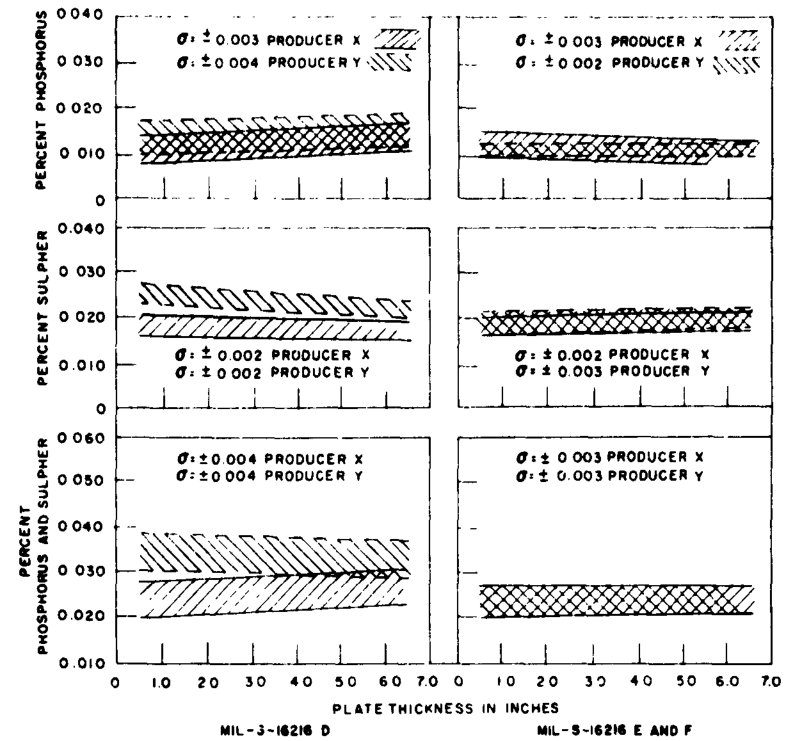


Figure 10 - Correlation of Percent Phosphorcus and Sulphur to Plate Thickness

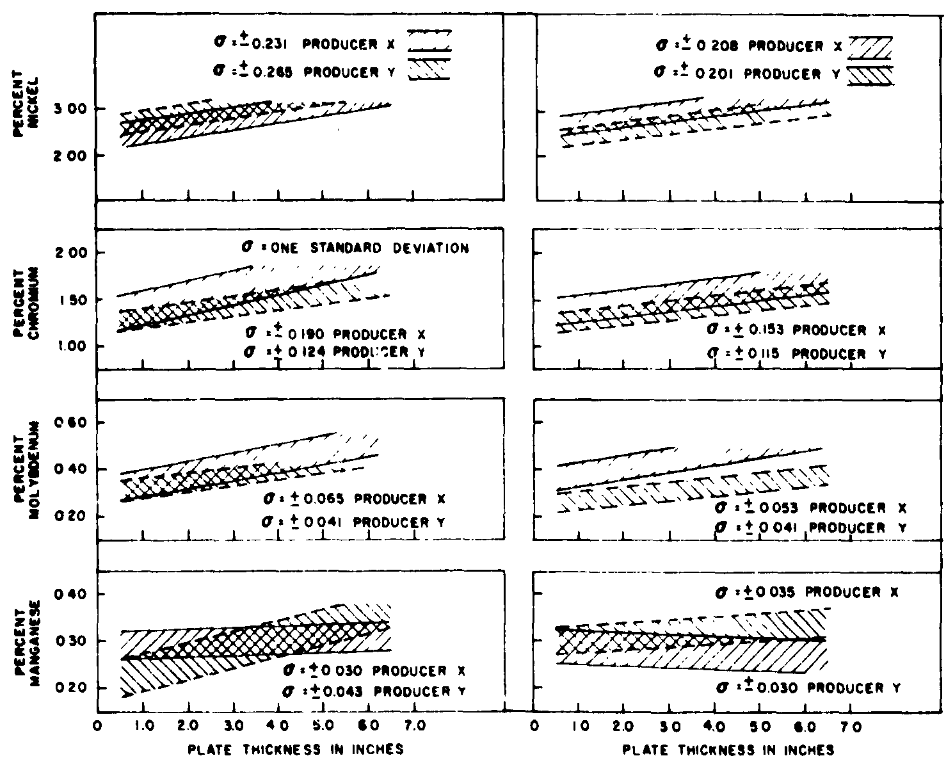


Figure 11 - Correlation of Percent Major Alloying Elements to Plate Thickness

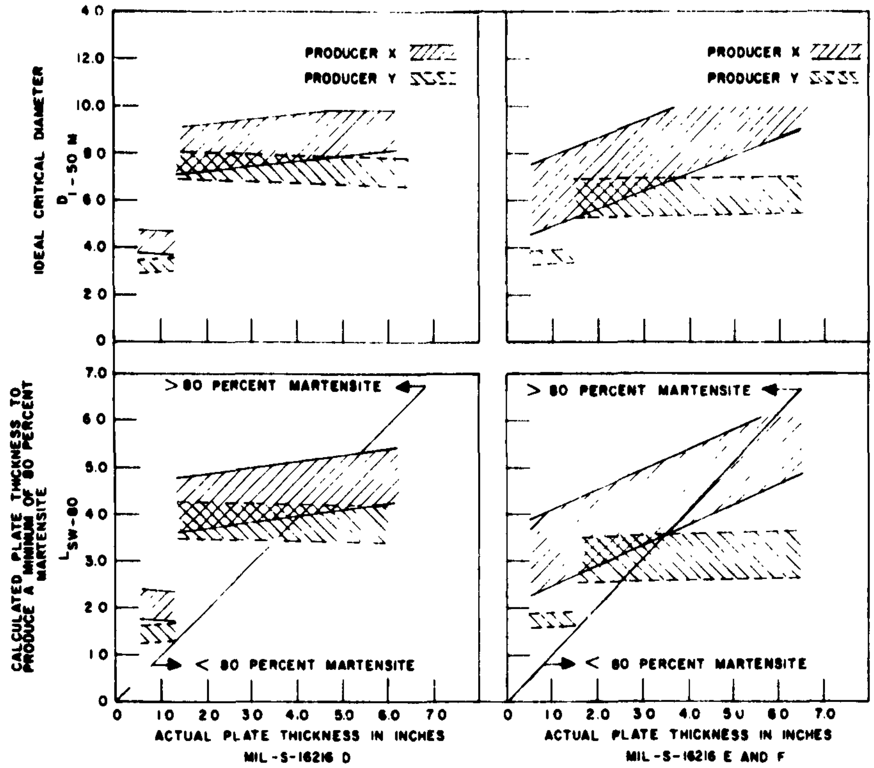


Figure 12 - Correlation of Calculated Hardenability to Actual Plate Thickness

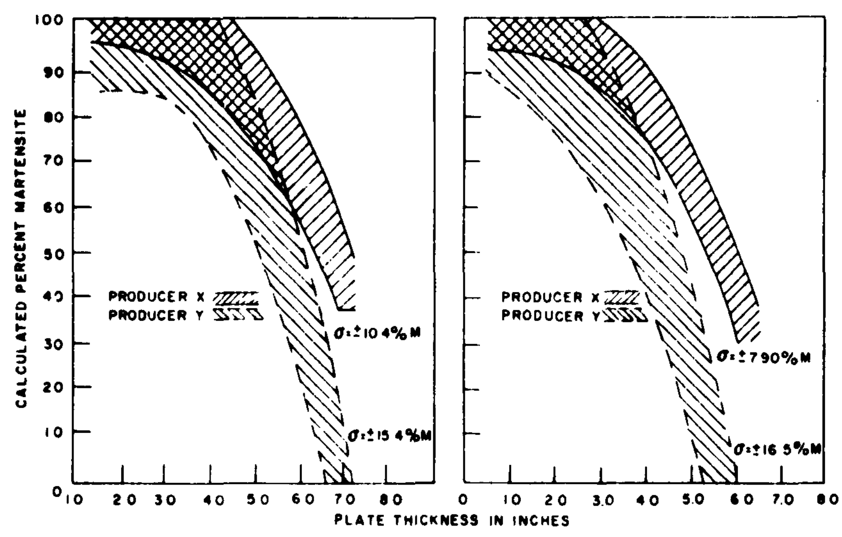


Figure 13 - Correlation of Calculated Percent Martensite to Actual Thickness of Commercially Produced HY-80 Steel Plates

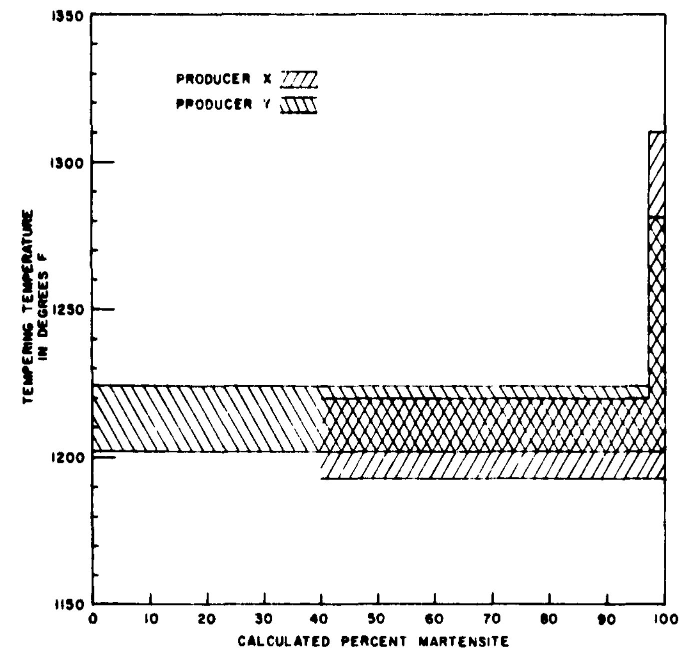


Figure 14 - Correlation of Tempering Temperature to Calculated Percent Martensite for Commercially Produced HY-80 Steel (MIL-S-16216D)

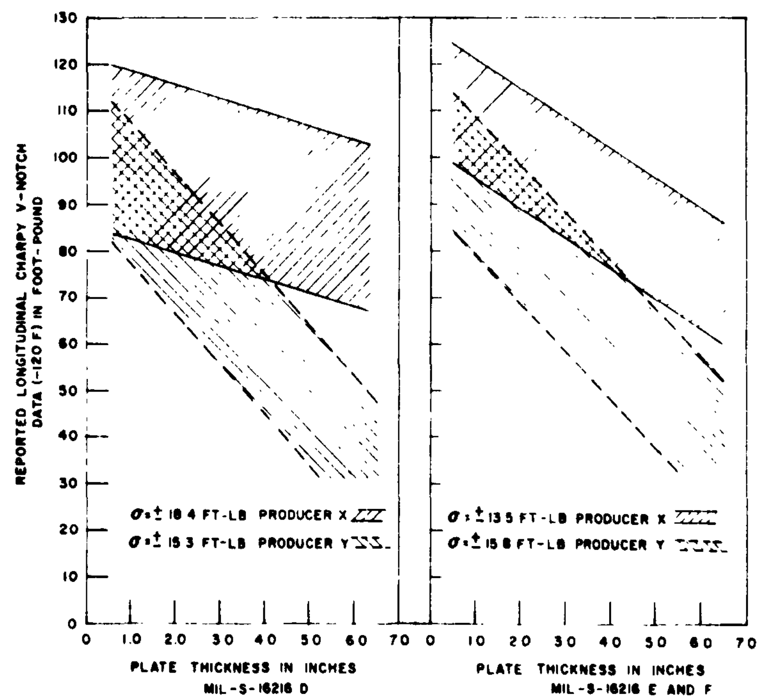
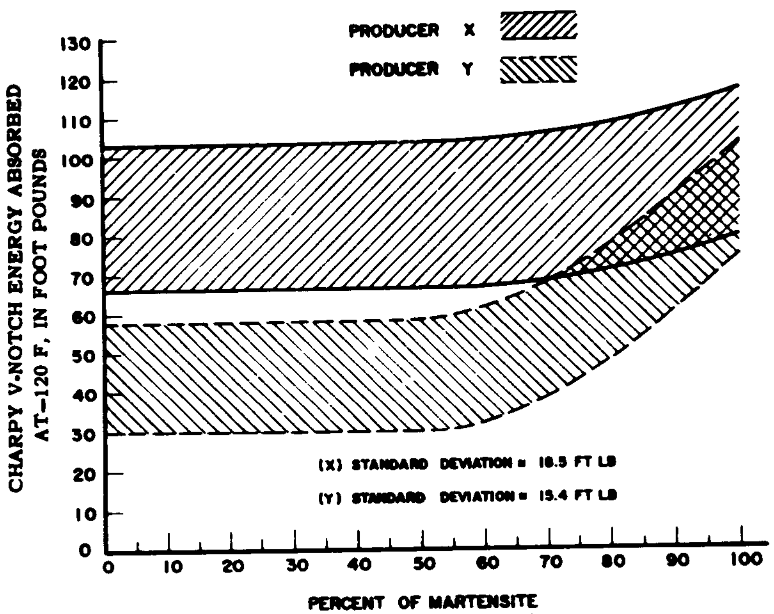
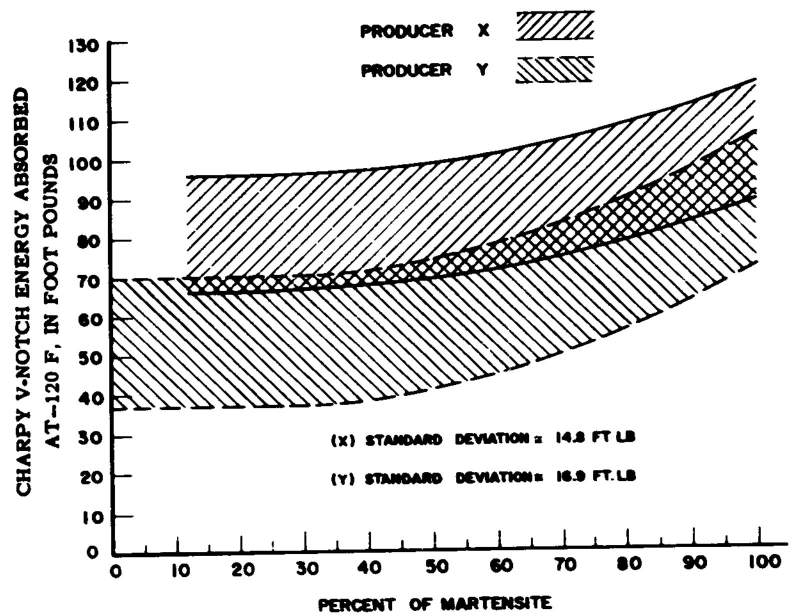


Figure 15 - Correlation of Reported Charpy V-Notch Impact Values to Actual Thickness of Commercially Produced HY-80 Steel Plates



MIL-S-16216 D



MIL-S-16216 E AND F

Figure 16 - Relationship between Reported Charpy V-Notch Values and Calculated Percent Martensite for Commercially Produced HY-80 Steels

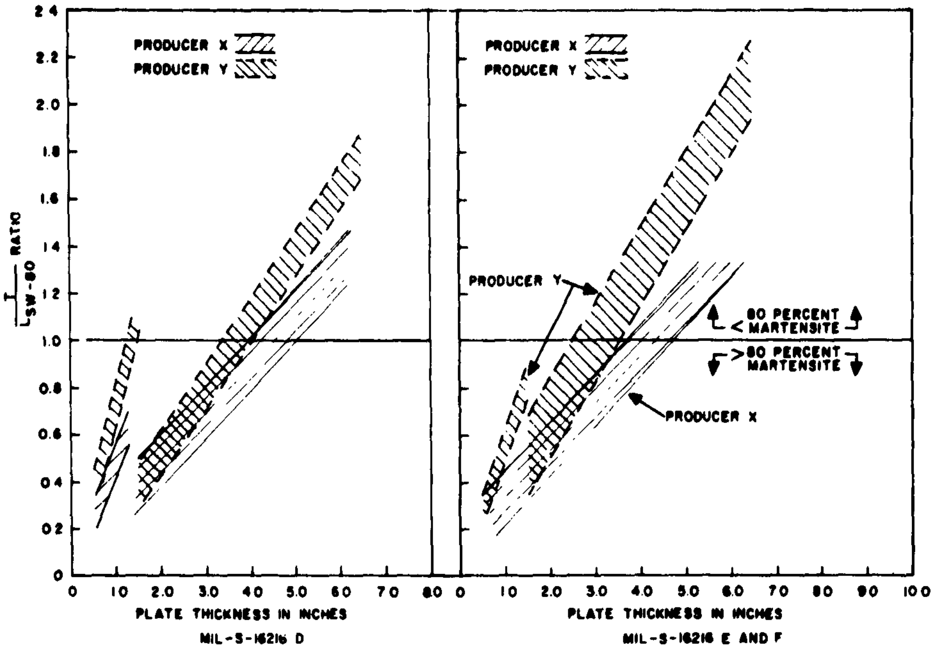


Figure 17 - Correlation of Ratio of Actual Plate Thickness to Calculated Hardenability for Various Plate Thicknesses

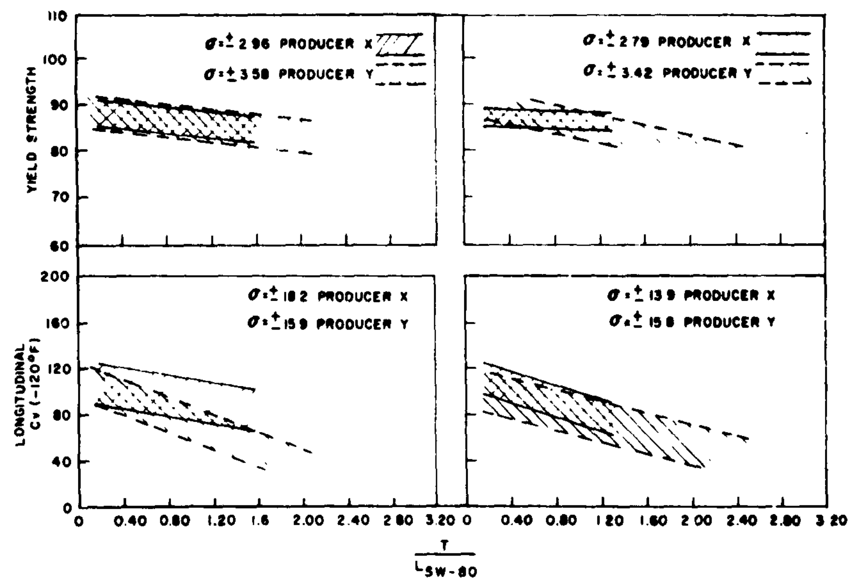


Figure 18 - Correlation of Mechanical Properties to the Ratio of Actual Plate Thickness to Calculated Hardenability

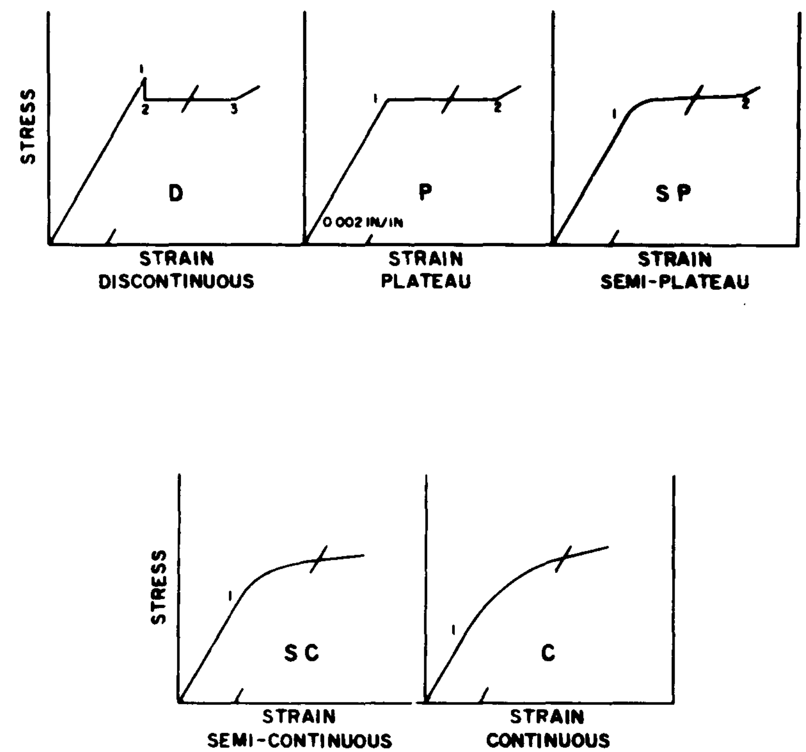


Figure 19 - Types of Stress-Strain Curves for HY-80 Steel

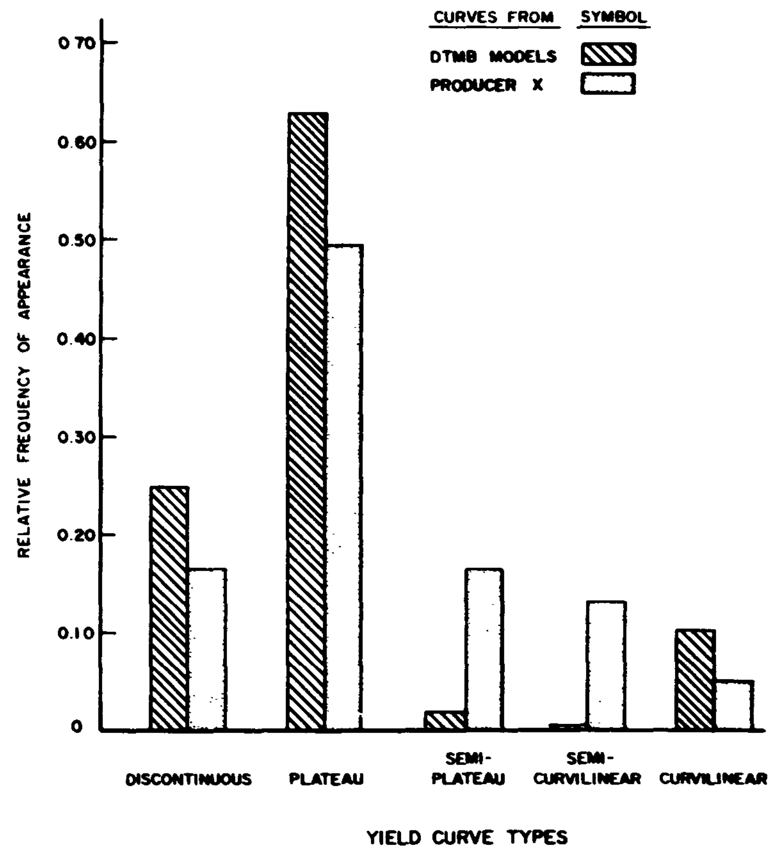


Figure 20 - Relative Frequency Distribution of Yield Curve Types

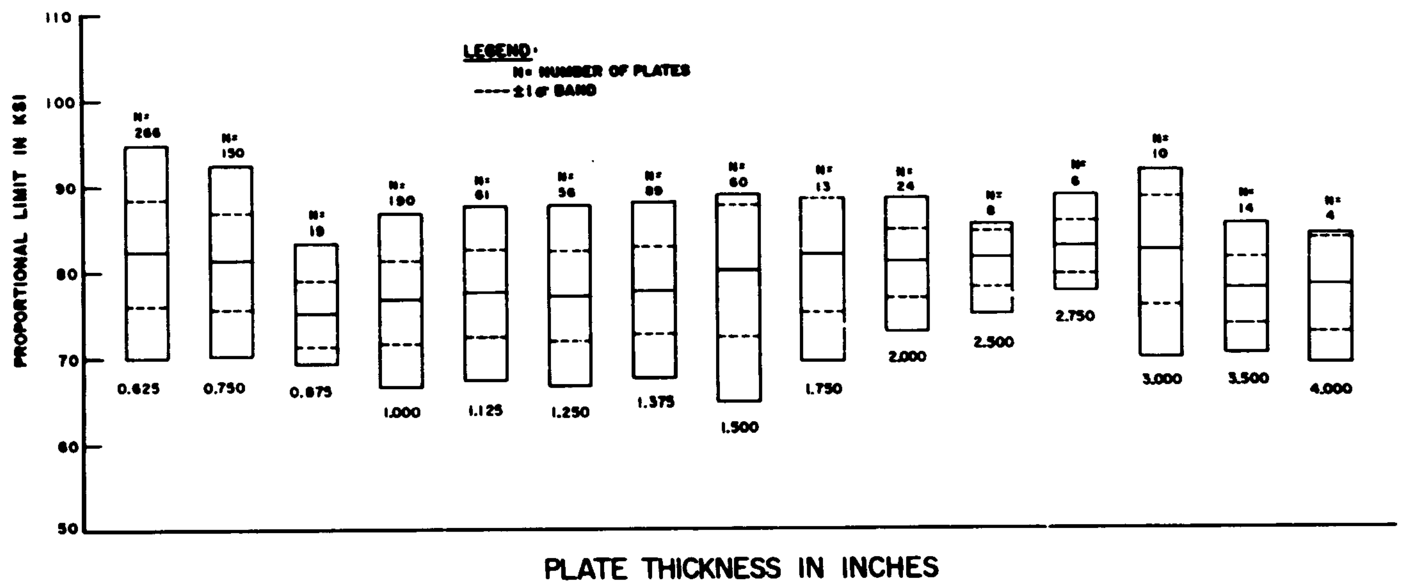


Figure 21 - Relationship between Plate Thickness and Proportional Limit for Commercially Produced HY-80 Steel Plate (MIL-S-16216B)

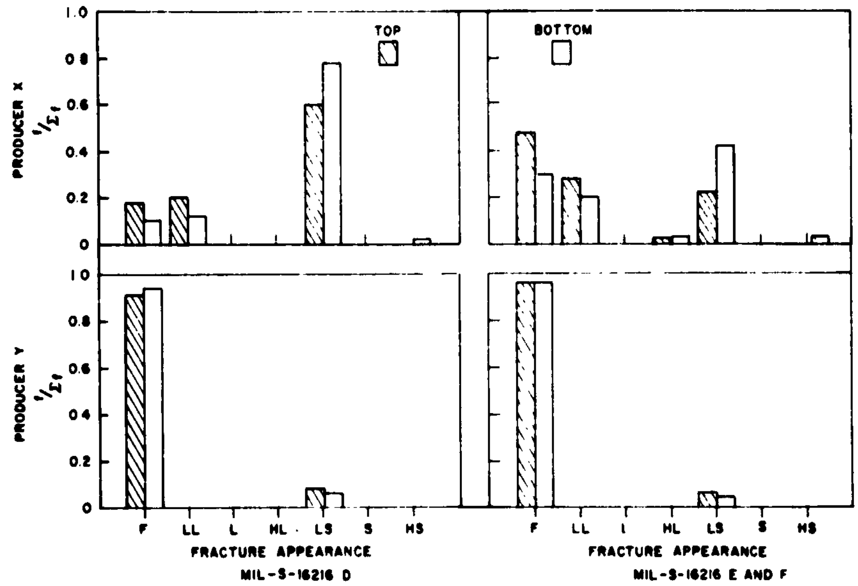


Figure 22 - Relative Frequency Distribution of Fracture Appearances Reported for Commercially Produced HY-80 Steels

REFERENCES

1. Willner, A. R. and Salive, M. L., "The Effects of Austenitizing and Tempering on the Mechanical Properties of Fully Quenched HY-80 Steels," David Taylor Model Basin Report 1523 (Nov 1961).

2. Salive, M. L. and Willner, A. R., "Comparison of Standard and Subsize HY-80 Drop-Weight Specimens for Various Conditions of Heat Treatment," David Taylor Model Basin Report 1583 (Jun 1962).

3. Willner, A. R. and Salive, M. L., "Factors Influencing the Fatigue Life of an HY-80 Composition Steel, Fully Quenched and Tempered to Various Levels," David Taylor Model Basin Report 1807 (May 1964).

4. Steel Plate, Alloy, Structural, High Yield Strength; Military Specification MIL-S-16216D (Navy) of 12 Feb 1959.

5. Bureau of Ships letter A11/NS-011-083(343) Serial 343-211 of 26 May 1959 to David Taylor Model Basin.

6. Bureau of Ships letter R007-01-01 Serial 634B-430 of 26 Jul 1960 to David Taylor Model Basin.

7. Model Basin Fundamental Research Project No. S-R011 0101, Subtask 0401, Problem No. 735-184 of 1 Jul 1962.

8. Simpson, F. W., "Isothermal-Transformation Diagrams for HY-80 Steel," U.S. Steel Corporation, Applied Research Laboratory, Project No. 40.02-100(5), Final Report (a-AS-EA-4) (29 Aug 1957).

9. Steel Plate, Alloy, Structural, High Yield Strength; Military Specification MIL-S-16216E (Ships) of 26 Jun 1959, amended 3 Aug 1961.

10. Steel Plate, Alloy, Structural, High Yield Strength (HY-80 and HY-100); Military Specification MIL-S-16216F (Ships) of 29 Jun 1962.

11. Steel Plate, Alloy, Structural, High Yield Strength (HY-80 and HY-100); Military Specification MIL-S-16216G (Ships) of 27 Feb 1963.

12. "Selection of Alternate Steels for Evaluation in Naval Armor," Minerals and Metals Advisory Board Report MMAB-32-M, Ad Hoc Committee on Naval Armor (31 Dec 1952).

13. Hall, W. H., Naval Proving Grounds Report 1616 (18 Aug 1958) CONFIDENTIAL.

14. Hall, W. H., Naval Proving Grounds Report 1639 (21 Jan 1959) CONFIDENTIAL.

15. Bureau of Ships letter SF 013 0302 Serial 442-48 of 26 Mar 1964 to David Taylor Model Basin.

16. Willner, A. R. and Salive, M. L., "The Effects of Tempered Non-martensite Products on the Notch Toughness and Mechanical Properties of an HY-80 Steel," David Taylor Model Basin Report 1605 (in preparation).

INITIAL DISTRIBUTION

Copies	
21	CHBUSHIPS 2 Sci & Res Sec (Code 442) 3 Tech Lib (Code 210L) 1 Lab Mgt (Code 320) 1 Struc Mech, Hull Mat & Fab (Code 341A) 1 Prelim Des Br (Code 420) 1 Prelim Des Sec (Code 421) 1 Ship Protec (Code 423) 1 Hull Des Br (Code 440) 1 Hull Struc Sec (Code 443) 2 Sub Br (Code 525) 1 Matls Adv (Code 626C-2) 1 Boat Issues (Code 529C) 1 Hull Arrgt, Damage Control (Code 632A) 3 Metals Sec (Code 634B) 1 Matls & Chem Br (Code 634)
20	DDC
2	CHONR 1 Head Struc Mech Br (Code 439) 1 Dir Undersea Programs (Code 466)
4	CNO 1 Tech Anal & Adv Gr (Op 07T) 1 Plans, Programs & Req Br (Op 311) 1 Sub Program Br (Op 713) 1 Tech Support Br (Op 725)
3	CHBUWEPS 2 Chief Scientist (SP-001) 1 Metal Br (RRMA-2)
1	CO & DIR, USNMEL (Code 860)
1	CO & DIR, USNASL (Code 9320)
1	CDR, USNAVWPNLAB (TEGM)
2	NAVSHIPYD PTSMH
2	NAVSHIPYD MARE
1	NAVSHIPYD CHASN
1	NAVSHIPYD NYK

Copies	
1	CNO (ONI) (STIC) (OP-92)
2	DIR, USNRL 1 Code 635 1 Tech Lib
1	CG, Frankford Arsenal, Phila (1324)
1	U.S. Navy Postgraduate School, Metallurgy Department Monterey, California

David Taylor Model Basin. Report 1850.
EVALUATION OF COMERCIALLY PRODUCED HY-80 STEEL, by A. R. Willner and M. L. Salive. July 1964. iv, 39p. illus., graphs, chart, refs. UNCLASSIFIED

The purpose of this investigation was to obtain a better understanding of some of the variables which may affect the properties of HY-80 steel. The data indicate that hardenability is increased with plate thickness. Generally, plates above 3-in. thick contain less than 80 percent martensite. As the percent martensite decreases, so do the Charpy V-notch impact values at -120 F. HY-80 steel made under military specifications MIL-S-16216E and F had lower phosphorous and sulphur content than the HY-80 produced under MIL-S-16216D. The data presented herein will be used by the Model Basin for determining the

1. HY-80 steel—Production—Evaluation
2. HY-80 steel—Metallurgical properties
3. HY-80 steel—Hardenability
4. HY-80 steel—Mechanical properties
5. HY-80 steel—Chemical analysis
I. Willner, Abner R
II. Salive, Marcel L
III. S-R011 01 01

David Taylor Model Basin. Report 1850.
EVALUATION OF COMERCIALLY PRODUCED HY-80 STEEL, by A. R. Willner and M. L. Salive. July 1964. iv, 39p. illus., graphs, chart, refs. UNCLASSIFIED

The purpose of this investigation was to obtain a better understanding of some of the variables which may affect the properties of HY-80 steel. The data indicate that hardenability is increased with plate thickness. Generally, plates above 3-in. thick contain less than 80 percent martensite. As the percent martensite decreases, so do the Charpy V-notch impact values at -120 F. HY-80 steel made under military specifications MIL-S-16216E and F had lower phosphorous and sulphur content than the HY-80 produced under MIL-S-16216D. The data presented herein will be used by the Model Basin for determining the

1. HY-80 steel—Production—Evaluation
2. HY-80 steel—Metallurgical properties
3. HY-80 steel—Hardenability
4. HY-80 steel—Mechanical properties
5. HY-80 steel—Chemical analysis
I. Willner, Abner R
II. Salive, Marcel L
III. S-R011 01 01

David Taylor Model Basin. Report 1850.
EVALUATION OF COMERCIALLY PRODUCED HY-80 STEEL, by A. R. Willner and M. L. Salive. July 1964. iv, 39p. illus., graphs, chart, refs. UNCLASSIFIED

The purpose of this investigation was to obtain a better understanding of some of the variables which may affect the properties of HY-80 steel. The data indicate that hardenability is increased with plate thickness. Generally, plates above 3-in. thick contain less than 80 percent martensite. As the percent martensite decreases, so do the Charpy V-notch impact values at -120 F. HY-80 steel made under military specifications MIL-S-16216E and F had lower phosphorous and sulphur content than the HY-80 produced under MIL-S-16216D. The data presented herein will be used by the Model Basin for determining the

1. HY-80 steel—Production—Evaluation
2. HY-80 steel—Metallurgical properties
3. HY-80 steel—Hardenability
4. HY-80 steel—Mechanical properties
5. HY-80 steel—Chemical analysis
I. Willner, Abner R
II. Salive, Marcel L
III. S-R011 01 01

David Taylor Model Basin. Report 1850.
EVALUATION OF COMERCIALLY PRODUCED HY-80 STEEL, by A. R. Willner and M. L. Salive. July 1964. iv, 39p. illus., graphs, chart, refs. UNCLASSIFIED

The purpose of this investigation was to obtain a better understanding of some of the variables which may affect the properties of HY-80 steel. The data indicate that hardenability is increased with plate thickness. Generally, plates above 3-in. thick contain less than 80 percent martensite. As the percent martensite decreases, so do the Charpy V-notch impact values at -120 F. HY-80 steel made under military specifications MIL-S-16216E and F had lower phosphorous and sulphur content than the HY-80 produced under MIL-S-16216D. The data presented herein will be used by the Model Basin for determining the

1. HY-80 steel—Production—Evaluation
2. HY-80 steel—Metallurgical properties
3. HY-80 steel—Hardenability
4. HY-80 steel—Mechanical properties
5. HY-80 steel—Chemical analysis
I. Willner, Abner R
II. Salive, Marcel L
III. S-R011 01 01

individual or combined metallurgical variables which may have an effect on the mechanical properties of HY-80 steel used in model and prototype construction.

individual or combined metallurgical variables which may have an effect on the mechanical properties of HY-80 steel used in model and prototype construction.

individual or combined metallurgical variables which may have an effect on the mechanical properties of HY-80 steel used in model and prototype construction.

individual or combined metallurgical variables which may have an effect on the mechanical properties of HY-80 steel used in model and prototype construction.

David Taylor Model Basin. Report 1850.
EVALUATION OF COMERCIALLY PRODUCED HY-80 STEEL, by A. R. Willner and M. L. Salive. July 1964. iv, 39p. illus., graphs, chart, refs. UNCLASSIFIED

The purpose of this investigation was to obtain a better understanding of some of the variables which may affect the properties of HY-80 steel. The data indicate that hardenability is increased with plate thickness. Generally, plates above 3-in. thick contain less than 80 percent martensite. As the percent martensite decreases, so do the Charpy V-notch impact values at -120 F. HY-80 steel made under military specifications MIL-S-16216E and F had lower phosphorous and sulphur content than the HY-80 produced under MIL-S-16216D. The data presented herein will be used by the Model Basin for determining the

1. HY-80 steel--Production--Evaluation
2. HY-80 steel--Metallurgical properties
3. HY-80 steel--Hardenability
4. HY-80 steel--Mechanical properties
5. HY-80 steel--Chemical analysis

I. Willner, Abner R
II. Salive, Marcel L
III. S-R011 01 01

David Taylor Model Basin. Report 1850.
EVALUATION OF COMERCIALLY PRODUCED HY-80 STEEL, by A. R. Willner and M. L. Salive. July 1964. iv, 39p. illus., graphs, chart, refs. UNCLASSIFIED

The purpose of this investigation was to obtain a better understanding of some of the variables which may affect the properties of HY-80 steel. The data indicate that hardenability is increased with plate thickness. Generally, plates above 3-in. thick contain less than 80 percent martensite. As the percent martensite decreases, so do the Charpy V-notch impact values at -120 F. HY-80 steel made under military specifications MIL-S-16216E and F had lower phosphorous and sulphur content than the HY-80 produced under MIL-S-16216D. The data presented herein will be used by the Model Basin for determining the

1. HY-80 steel--Production--Evaluation
2. HY-80 steel--Metallurgical properties
3. HY-80 steel--Hardenability
4. HY-80 steel--Mechanical properties
5. HY-80 steel--Chemical analysis

I. Willner, Abner R
II. Salive, Marcel L
III. S-R011 01 01

David Taylor Model Basin. Report 1850.
EVALUATION OF COMERCIALLY PRODUCED HY-80 STEEL, by A. R. Willner and M. L. Salive. July 1964. iv, 39p. illus., graphs, chart, refs. UNCLASSIFIED

The purpose of this investigation was to obtain a better understanding of some of the variables which may affect the properties of HY-80 steel. The data indicate that hardenability is increased with plate thickness. Generally, plates above 3-in. thick contain less than 80 percent martensite. As the percent martensite decreases, so do the Charpy V-notch impact values at -120 F. HY-80 steel made under military specifications MIL-S-16216E and F had lower phosphorous and sulphur content than the HY-80 produced under MIL-S-16216D. The data presented herein will be used by the Model Basin for determining the

1. HY-80 steel--Production--Evaluation
2. HY-80 steel--Metallurgical properties
3. HY-80 steel--Hardenability
4. HY-80 steel--Mechanical properties
5. HY-80 steel--Chemical analysis

I. Willner, Abner R
II. Salive, Marcel L
III. S-R011 01 01

David Taylor Model Basin. Report 1850.
EVALUATION OF COMERCIALLY PRODUCED HY-80 STEEL, by A. R. Willner and M. L. Salive. July 1964. iv, 39p. illus., graphs, chart, refs. UNCLASSIFIED

The purpose of this investigation was to obtain a better understanding of some of the variables which may affect the properties of HY-80 steel. The data indicate that hardenability is increased with plate thickness. Generally, plates above 3-in. thick contain less than 80 percent martensite. As the percent martensite decreases, so do the Charpy V-notch impact values at -120 F. HY-80 steel made under military specifications MIL-S-16216E and F had lower phosphorous and sulphur content than the HY-80 produced under MIL-S-16216D. The data presented herein will be used by the Model Basin for determining the

1. HY-80 steel--Production--Evaluation
2. HY-80 steel--Metallurgical properties
3. HY-80 steel--Hardenability
4. HY-80 steel--Mechanical properties
5. HY-80 steel--Chemical analysis

I. Willner, Abner R
II. Salive, Marcel L
III. S-R011 01 01

individual or combined metallurgical variables which may have an effect on the mechanical properties of HY-80 steel used in model and prototype construction.

individual or combined metallurgical variables which may have an effect on the mechanical properties of HY-80 steel used in model and prototype construction.

individual or combined metallurgical variables which may have an effect on the mechanical properties of HY-80 steel used in model and prototype construction.

individual or combined metallurgical variables which may have an effect on the mechanical properties of HY-80 steel used in model and prototype construction.