



# Property and microstructure evaluation as a function of processing parameters: Large HY-80 steel casting for a US Navy submarine

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Received 26 August 2005; accepted 8 October 2005  
Available online 7 February 2006

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## Abstract

Processing techniques can significantly alter the properties of a material and can ultimately determine whether a component will perform its function safely. This effort involves the investigation of the processing parameters of HY-80 steel castings; specifically a large HY-80 submarine casting that failed while in service due to improper processing. Samples taken from the failed casting were evaluated in the as-received condition and after exposures to various improper quench and temper scenarios that were possible during casting production. Microstructural examination and hardness measurements were used to evaluate the condition of the high strength steel and these results were correlated to Charpy impact toughness. One important result of this work indicates that hardness alone is not a good indication of material condition: the same measured hardness values yielded very different fracture behavior. The window of favorable processing parameters as defined by heat treatment temperature was clarified based on the specification requirements set by the US Navy for HY-80 castings.

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*Keywords:* Fracture toughness; Microstructures; Structural steels

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## 1. Introduction

After World War II, significant effort was made to develop a steel that would better serve the needs of the US Navy and allow for the development of higher performance platforms. The development and subsequent qualification of HY-80 steel for use in naval applications took over a decade, but resulted in a steel with approximately twice the yield strength of high tensile steel (HTS), the previous steel employed by the US Navy in primary ship structures [1]. HY-80 also has improved toughness and increased weldability. The low carbon content (0.18%) was similar to that of HTS, but other detrimental elements such as phosphorus and sulfur (Table 1) were more strictly limited in HY-80 [1].

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Table 1  
Comparison of the compositions of HTS and of HY-80 steels (by wt%)

Element	HTS	HY-80
H		
C	0.200 max	0.200 max
Mn	1.30 max	0.52–0.78
P	0.04 max	0.02 max
S	0.05 max	0.02 max
Si	0.15–0.35	0.53 max
Cr		1.29–1.71
Ni		2.68–3.32
Mo		0.27–0.63
Cu		0.20 max
V		0.030 max
Ti		0.020 max

Steels are formed in many different methods, including machining from solid metal, fabrication using welding, pressing, hot forging and casting. Casting is often used to form large, irregularly shaped, welded HY-80 submarine components. This process is carefully performed and monitored to assure a quality product.

HY-80 castings receive most of their favorable properties from heat treatments that follow the initial pouring of the casting. Castings are initially austenitized and quenched to form a nearly 100% martensitic microstructure. This microstructure is extremely hard and strong, but also extremely brittle. To obtain acceptable ductility and toughness, the part is tempered. MIL-S-23008C requires the isothermal hold at the tempering temperature to be no less than 1190 °F (643 °C), which is below the intercritical, two phase (ferrite + austenite) region for the Fe–C system [2].

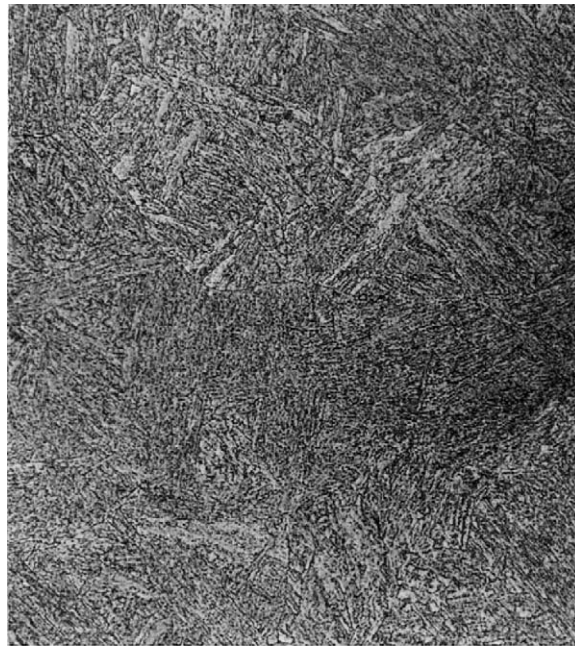
Holding at the tempering temperature causes the carbon in the supersaturated martensite to react with the iron to form very fine, numerous, and evenly distributed carbide particles within the martensite phase. These particles result in a largely improved toughness with an acceptable loss in strength. This quench and temper process creates a tempered martensitic structure as seen in Fig. 1. This microstructure gives HY-80 a high yield strength (80 ksi, 552 MPa) while maintaining good toughness and ductility.

The desired ductile to brittle transition temperature for HY-80 is 0 °F (−18 °C). This is well below the transition temperature for HTS and represents added fracture safety in that the brittle transition of properly processed HY-80 occurs far below operating temperatures. From [3], the target upper shelf Charpy impact energy for HY-80 was expected to be on the order of 120 ft-lbs (162.7 J).

The US Navy uses HY-80 extensively on its submarines and this study focuses exclusively on the cracking failure of a large HY-80 submarine casting. A through thickness crack in the casting resulting in a leak was detected and evaluated in a previous study [4]. The casting was shown to have the required chemical composition from Table 1. On-site hardness measurements were taken and showed hardness values that were slightly elevated compared to expected values. A previous study showed that the region surrounding the crack had higher than normal Vickers hardness (HV) values of 318 and 418 on either side of the crack [5]. Samples from the failed casting showed that the toughness as measured by Charpy impact energy was lower than allowed by MIL-S-23008C (50 ft-lbs at −100 °F) (67.8 J at −73 °C) in particular isolated locations.

Microstructural examination of these specimens showed a low toughness, intercritical (IC) microstructure of ferrite and undertempered martensite (Fig. 2), which indicates heat treatment temperature deviations from those specified in MIL-S-23008C [5,6]. Specifically, temperature excursions above approximately 1300 °F can result in the formation of austenite from the tempered martensite. Upon quick cooling the austenite transforms to untempered martensite, a very brittle phase. The failed casting was eventually replaced. However, the exact heat treatment times and temperatures that result in this undesirable intercritical microstructure have yet to be clearly defined.

In order to isolate the undesirable processing parameters, this effort focuses on several different possible heat treatment scenarios. The macrohardness, microhardness, microstructures, and impact toughness are evaluated for the as-received and laboratory heat-treated specimens. The determination for acceptable toughness values for each specimen is based on the criteria set forth by MIL-S-23008C [7]. A comparison of the labora-



**40 microns**

Fig. 1. Tempered martensitic microstructure found in a properly heat-treated HY-80 casting [4].

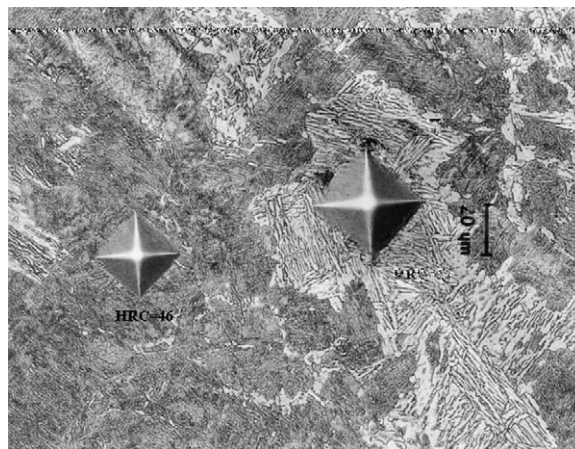


Fig. 2. Untempered martensite (dark phase, high hardness) and layered ferrite (light phase, lower hardness) and martensite microstructure found in failed HY-80 material [5].

tory heat-treated microstructures that failed to meet the required specification to the failed casting condition will help to clarify the range of undesirable heat treatment temperatures.

## 2. Experimental methodology

Sections of HY-80 removed from the failed submarine casting were provided by Naval Sea Systems Command, SEA92T. The removal locations within the casting is unknown, however, the thickness of the casting is on the order of 4.0-in. (10-cm) at these locations. Earlier chemical composition tests carried out on the failed HY-80 casting indicated that the composition was consistent with MIL-S-23008C [5]. It is assumed that the results of the chemical composition were valid for the entire casting.

Table 2  
Average macrohardness of HY-80 sections following laboratory heat treatments

Specimen ID	Heat treatment	Average Rockwell C hardness converted to Vickers scale	Expected microstructure
As-quenched	$A + Q$	367.8	Untempered martensite
Quench + temper	$A + Q + T$	278.8	Tempered martensite
Temper + low IC	$A + Q + T + 721\text{ }^\circ\text{C}/1\text{ h}$	264.8	Intercritical structure
Low IC + temper	$A + Q + 721\text{ }^\circ\text{C}/1\text{ h} + T$	215.5	Tempered intercritical structure
Temper + high IC	$A + Q + T + 799\text{ }^\circ\text{C}/1\text{ h}$	263.4	Intercritical structure
High IC + temper	$A + Q + 799\text{ }^\circ\text{C}/1\text{ h} + T$	127.0	Tempered intercritical structure
Med IC + temper	$A + Q + 760\text{ }^\circ\text{C}/1.5\text{ h} + T$	337.9	Tempered intercritical structure

$A$ , austenitized at  $900\text{ }^\circ\text{C}/1\text{ h}$ ;  $Q$ , water quench;  $T$ , tempered at  $643\text{ }^\circ\text{C}/1\text{ h}$ .

Smaller sections of the as-received material were machined into Charpy impact specimens and macrohardness measurements were taken using the Rockwell C hardness scale. Larger sections were selected for heat treatment because of their size and because they had no visible indications of welding. These sections were austenitized and quenched to “reset” the material to a nearly 100% martensitic structure and then subjected to different heat treatment sequences (Table 2). The temperature dependency of microstructural development in the IC range was explored by examining three temperatures within the IC range: “low” ( $1330\text{ }^\circ\text{F}$ ,  $721\text{ }^\circ\text{C}$ ), “medium” ( $1400\text{ }^\circ\text{F}$ ,  $760\text{ }^\circ\text{C}$ ) and “high” ( $1470\text{ }^\circ\text{F}$ ,  $799\text{ }^\circ\text{C}$ ). The chosen heat treatments were designed to mimic scenarios that could occur in the commercial furnace due to improper temperature control. For instance, if the target temperature was exceeded during the temper process and then recovered to the desired temperature to finish out the temper, this would be an example of an IC + tempered condition. These controlled laboratory heat treatments were conducted to obtain specimens for which microstructure and impact properties could be examined and compared with the as-received specimens in the failed casting.

Conventional hardness measurements were obtained for the as-received samples and samples from each heat treatment. Sections from each condition were mounted, polished and etched with 2% Nital solution for examination with optical microscopy. Each specimen was viewed at a low magnification to locate regions of interest. Once a region was identified, the microhardness measurements were taken; the location of each indentation was digitally recorded. Microhardness in conjunction with optical microscopy was used for phase identification.

Macrohardness readings of the Charpy impact specimens were taken prior to impact testing. The as-received Charpy impact specimens were tested at  $30\text{ }^\circ\text{F}$  ( $-1\text{ }^\circ\text{C}$ ),  $0\text{ }^\circ\text{F}$  ( $-18\text{ }^\circ\text{C}$ ), and  $-100\text{ }^\circ\text{F}$  ( $-73\text{ }^\circ\text{C}$ ) so that they could be compared to a ductile to brittle transition curve from a previous study of HY-80, as well as for comparison to specification requirements. The heat-treated specimens were tested at  $0\text{ }^\circ\text{F}$  ( $-18\text{ }^\circ\text{C}$ ) and  $-100\text{ }^\circ\text{F}$  ( $-73\text{ }^\circ\text{C}$ ) only. Minimum absorbed energy requirements for HY-80 castings are set forth in MIL-S-23008C as 70 ft-lbs (95 J) and 50 ft-lbs (67.8 J) at test temperatures of  $0\text{ }^\circ\text{F}$  ( $-18\text{ }^\circ\text{C}$ ) and  $-100\text{ }^\circ\text{F}$  ( $-73\text{ }^\circ\text{C}$ ), respectively.

All samples that failed to meet the specification were sectioned parallel to the fracture surface just below the machined notch and prepared for microstructural examination and microhardness measurement. Several specimens that met specification values were also mounted to make microstructural comparisons.

### 3. Results and analysis

#### 3.1. Initial macrohardness results

Immediately following heat treatment, the macrohardnesses of the seven laboratory heat treatment conditions were measured. The results are summarized and shown graphically in Fig. 3.

The “as-quenched” heat treatment was selected to obtain a microstructure with the highest hardness (and lowest toughness) expected, due to the anticipated 100% untempered martensitic structure. Results in Fig. 3 indicate high hardness values typical of this microstructure.

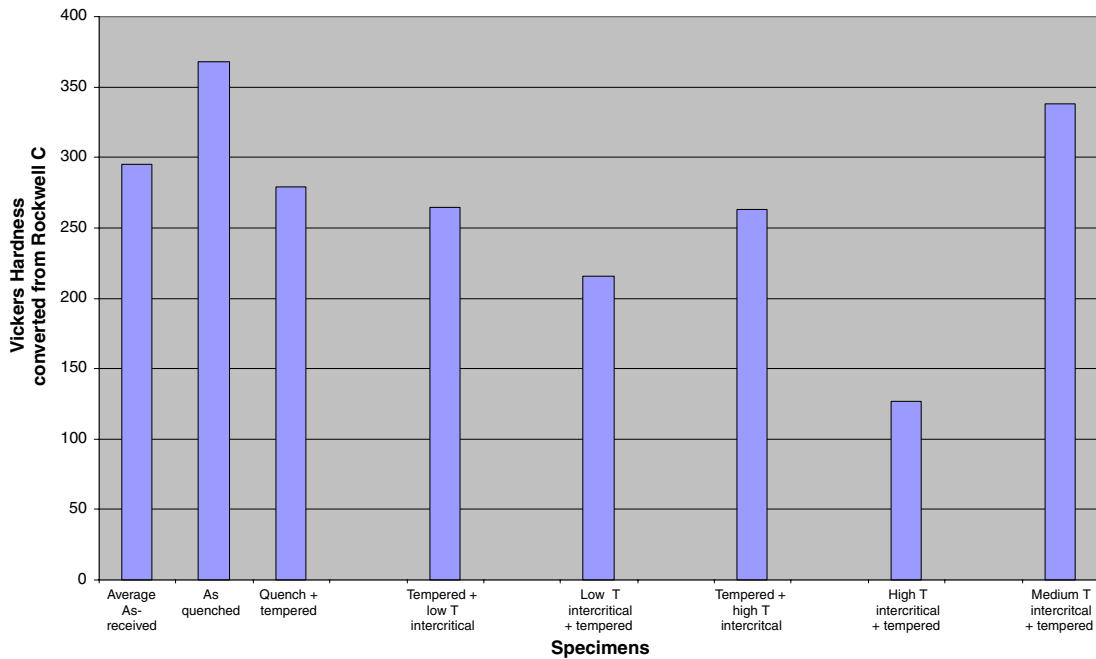


Fig. 3. Macrohardness of heat-treated HY-80 sections compared to average as-received hardness. All specimens were austenitized and quenched prior to the heat treatments listed with the exception of the as-received condition.

The “quench and tempered” heat treatment was expected to yield structure and properties that met the specifications for HY-80. The macrohardness values obtained were consistent with this desirable microstructure.

The remaining heat treatments were chosen to simulate heat treatment temperature excursions that could explain the low-toughness microstructure obtained in the failed HY-80 casting. For the low and high IC cases, the conditions of tempering before and after the IC step were explored to compare the martensite hardness with values measure in the failed HY-80 casting.

Estimations from the iron–carbon phase diagram indicate that higher IC temperatures would have shown a larger volume fraction of the martensite phase compared to the lower IC temperatures if enough time was given for the phase transformations to reach equilibrium. (The IC heat treatment time for the low and high temperatures was an hour in each case.) Therefore, an increased hardness in the high temperature treatment compared to the low temperature treatment was expected due to the high hardness of untempered martensite and the lower hardness of ferrite. This is not observed here. Therefore, it is suspected that the equilibrium volume fractions of these phases were not obtained in a 1-h time. However, the reduced hardness of the specimens that were tempered subsequent to the IC heat treatment is consistent with the typical reduction in hardness obtained when tempering martensite.

It appears that the IC heat treatment for the high and low IC cases did not drastically affect the hardness as compared to the desired quenched and tempered microstructure. In the case where tempering occurred first, it appears that the untempered martensite from the IC structure was not sufficient to elevate the hardness, or that the presence of low hardness ferrite compromised the overall hardness value. In the case where tempering followed the IC structure, the reduced hardness supports the idea that the presence of low hardness ferrite and the absence of untempered martensite (i.e., the martensite that is present is now tempered) reduces the hardness significantly compared to the desired quenched and tempered microstructure. Again, the temperature dependency of the hardness trends indicates that the phase reactions did not go to equilibrium.

An interesting case was obtained for the medium IC + tempered condition. In this case, the IC heat treatment time was extended to 90 min. (The subsequent tempering treatment was identical to those used in the high and low IC cases in that the low, medium and high IC specimens were tempered in the same furnace

run.) Based on temperature alone, one would expect a hardness intermediate to the high and low IC temperatures. Instead, Fig. 3 shows a hardness value that is significantly higher than both the high and low IC specimens and significantly higher than that obtained in the desired quenched and tempered microstructure. The fact that the medium IC heat treatment was conducted for a longer time further supports that the idea that equilibrium volume fractions of these phases were not obtained in the high and low temperature heat treatments. Hence, the time dependency of the IC exposure needs to be further explored.

### 3.2. Microstructural analysis

The macrohardness results obtained in Fig. 3 represent an average hardness of all the phases present. Microhardness enables the measurement of the hardness of much smaller regions of material as compared to macrohardness, and can sometimes measure the hardness of a single phase. In this section, the combined results of microscopy, microhardness and heat treatment temperatures are used to identify the phases present and substantiate the discussion above, and are correlated to impact toughness behavior.

In the as-received material, two distinct microstructural regions are noted as shown in Fig. 4a. The first region consists of untempered martensite with high hardness and a grey, “hazy” appearance. The second region consists of a layered structure of martensite and ferrite. Untempered martensite was confirmed by its high hardness (HV 554) and also from comparison to earlier micrographs of untempered martensite. The layered structure contained various amounts of ferrite (a low hardness phase) and had a lower hardness in regions where this phase was more prevalent (HV 351.7). This microstructure is similar to the microstructure observed in the region of the original crack [5].

The austenitized and quenched specimen had an evenly distributed untempered martensite phase as seen in Fig. 4b. This hardness value (HV 395.2) is consistent with steel of 0.2% carbon content [4].

The quench and tempered martensite specimen in Fig. 4c is the desired heat treatment for HY-80. The hardness is lower than the as-quenched specimen (300 HV), an indication that the tempering process has occurred. The measured hardness is consistent with the desired hardness of HY-80 [5].

All of the remaining specimens were austenitized, quenched and then exposed to various combinations of IC heat treatments. The tempered + low IC specimen showed a fairly uniform ferrite (white) and martensite (dark) microstructure arranged in layers as seen in Fig. 5a. The fineness of the layered structure prohibits the measurement of the hardness of the individual phases. However, it is believed that the low hardness ferrite layers average with the high hardness expected for the untempered martensite layers, resulting in low-to-reasonable microhardness values. Higher magnification focused on the ferrite-dominated region (Fig. 5b), shows the lighter color of the ferrite layered with the martensite. The measured hardness values were lower in this region where there was more ferrite phase (239 HV). Similarly, the higher magnification of the martensite-dominated region (Fig. 5c) shows the characteristic appearance of martensite and a higher measured hardness (324 HV).

The low IC + tempered specimen also shows a layered structure of ferrite and martensite. The lower hardness (HV 272.6, 245.1) is consistent with tempering of the martensite phase.

The tempered + high IC specimen produced martensite with less ferrite compared to the low IC heat treatment, as would be expected from the iron–carbon phase diagram. The absence of a large amount of ferrite in local areas makes the microstructure harder in these areas (HV 350.6). A local region of martensite with more ferrite gives a lower hardness (HV 289.6). It is therefore concluded that the increased hardness expected with increasing IC temperature was not observed in the Rockwell C macrohardness measurements due to the overall averaging effect of the macrohardness technique. The high IC + tempered specimens showed a lower hardness indicative of tempering (HV 278.6), as was observed in the low IC heat treatments.

The medium IC + tempered specimen was held at the IC temperature for a longer time (1.5 h) than the previous specimens. In this case, a microstructure consisting of regions of untempered martensite with high hardness (HV 431.6) was produced. This phase was interspersed with regions of layered martensite and ferrite (HV ~395). It is this structure that most strongly resembles the as-received casting microstructure. This particular heat treatment indicated that hold times greater than one hour in the IC region can produce markedly different microstructures from what is observed in the previous specimens. Importantly, the microstructure obtained closely resembles the poor-toughness structure observed in the failed casting (Fig. 5d).

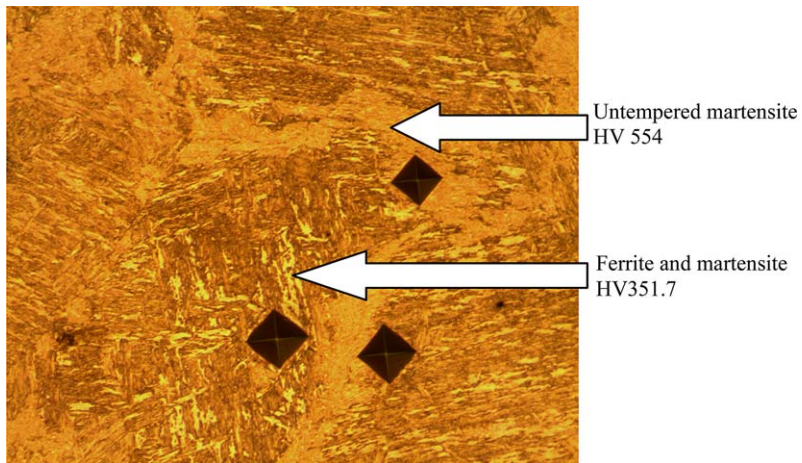


Fig. 4a. Optical micrograph of as-received HY-80 casting material, Nital etch, 200× magnification.

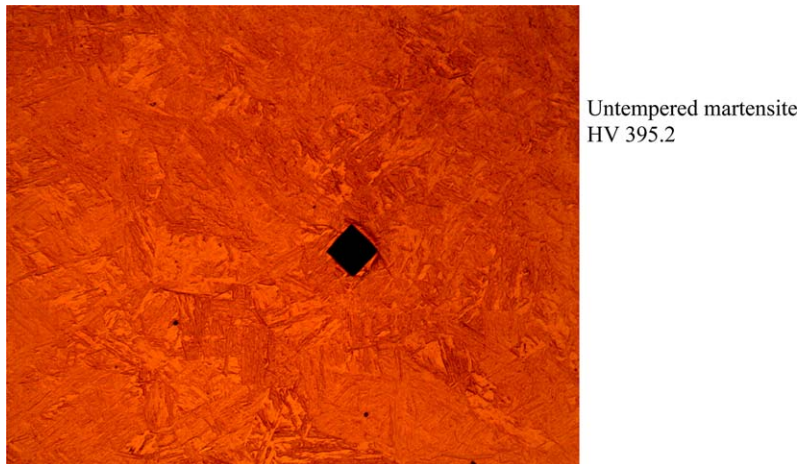


Fig. 4b. Optical micrograph of as-quenched HY-80 casting material, Nital etch, 200× magnification.

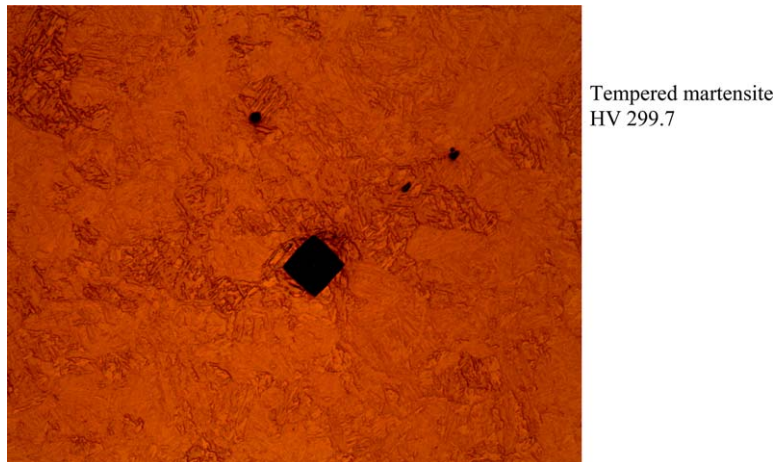


Fig. 4c. Optical micrograph of quenched and tempered HY-80 casting material, Nital etch, 200× magnification.

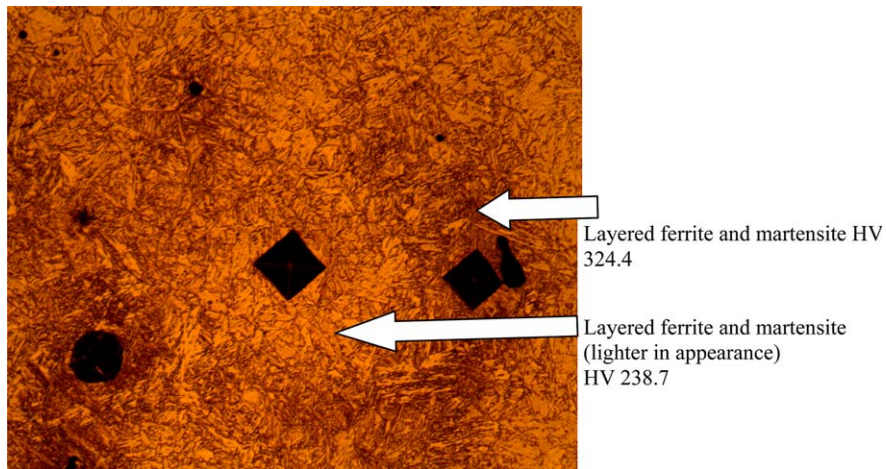


Fig. 5a. Optical micrograph of tempered + low IC HY-80 casting material, Nital etch, 200× magnification. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

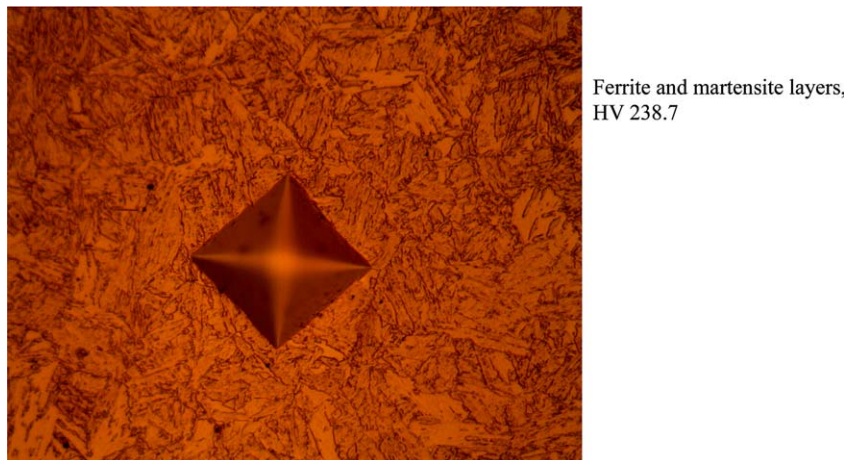


Fig. 5b. Optical micrograph of tempered + low IC HY-80 casting material, Nital etch, 500× magnification.

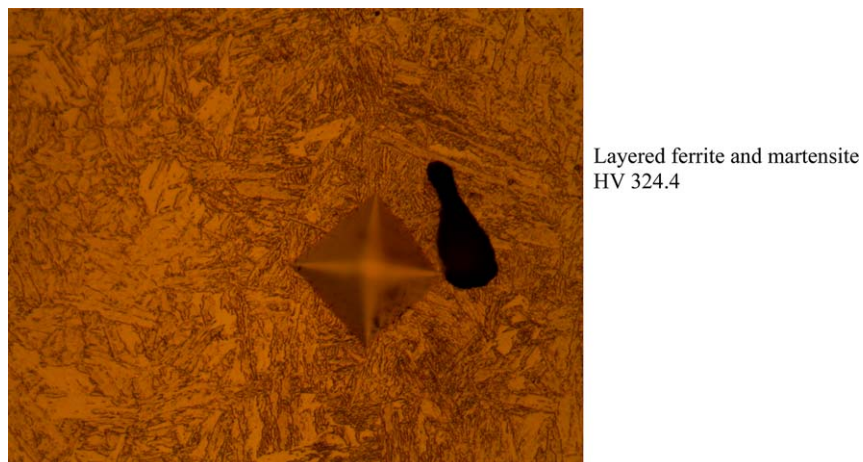


Fig. 5c. Optical micrograph of tempered + low IC HY-80 casting material, Nital etch, 500× magnification.



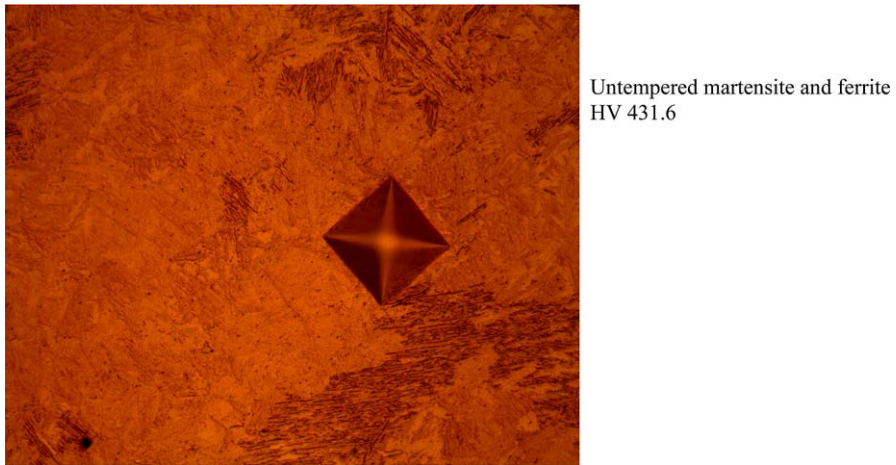


Fig. 5d. Optical micrograph of medium IC + tempered HY-80 casting material, Nital etch, 500x magnification.

### 3.3. Charpy impact testing

Charpy V-notch specimens were machined from the as-received and heat-treated specimens according to ASTM specifications [8]. The as-received material was tested at  $-100\text{ }^{\circ}\text{F}$  ( $-73\text{ }^{\circ}\text{C}$ ),  $0\text{ }^{\circ}\text{F}$  ( $-18\text{ }^{\circ}\text{C}$ ) and  $30\text{ }^{\circ}\text{F}$  ( $-1\text{ }^{\circ}\text{C}$ ). Fig. 6 compares the Charpy impact energies obtained in this study with properly processed HY-80 material [9]. The ductile to brittle transition range for HY-80 is designed to be well below service temperatures, but data indicates that the as-received material from the failed casting had a transition between  $15\text{ }^{\circ}\text{F}$  ( $-9\text{ }^{\circ}\text{C}$ ) and  $-75\text{ }^{\circ}\text{F}$  ( $-59\text{ }^{\circ}\text{C}$ ). Therefore, the material from the failed casting exhibits brittle behavior at higher temperatures than is desired.

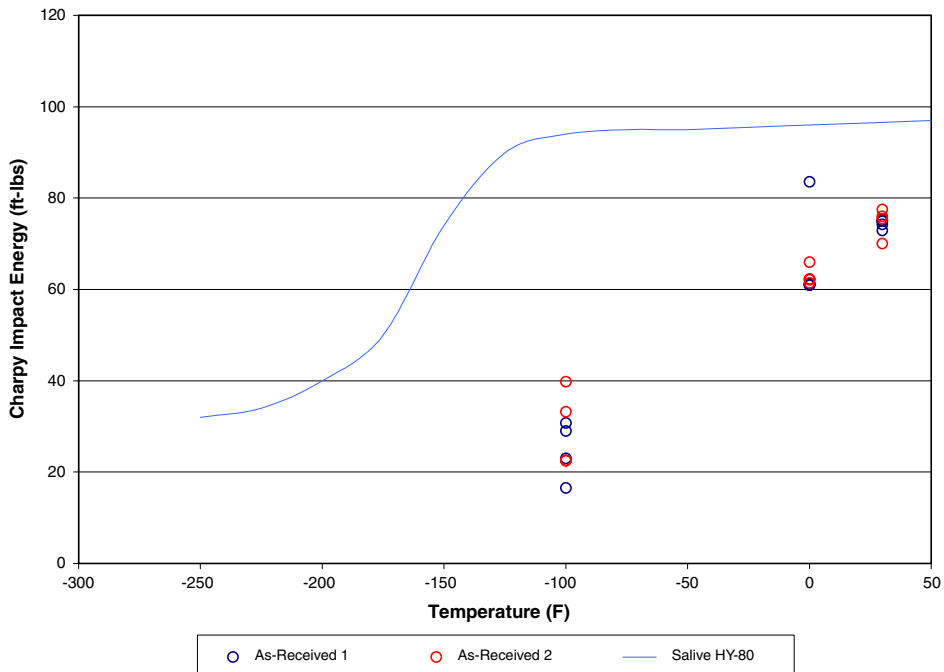


Fig. 6. Charpy impact energy as a function of test temperature for as received HY-80 casting material as compared to properly processed HY-80 [9].

It has been speculated that hardness could be used as an indicator of improperly processed material in that impact toughness typically decreases with increasing hardness. Therefore, the macrohardness of each specimen was compared to the toughness obtained from the Charpy impact testing. The results for all specimens are

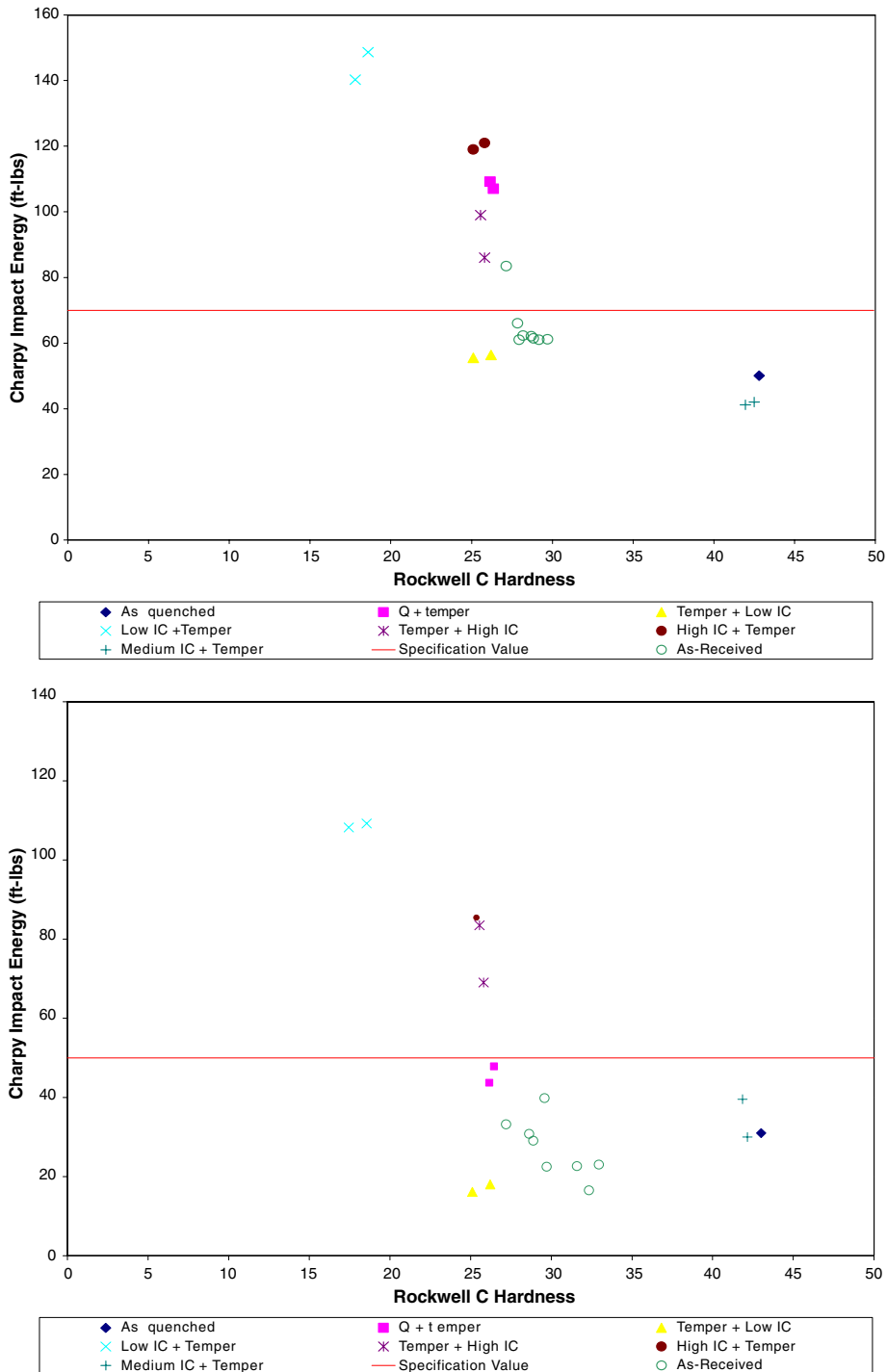


Fig. 7. Charpy impact energy (CVN) as a function of average Rockwell C hardness for a test temperature of (a) 0 °F and (b) -100 °F. Red lines indicate minimum acceptable toughness as given by military specifications. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

shown in Fig. 7a for testing at 0 °F (−18 °C) and in Fig. 7b for testing at −100 °F (−73 °C). As a reference, the minimum acceptable toughness values from MIL-S-23008C for each temperature are also shown: all those specimens below the red lines failed to meet specification values.

The as-quenched and the medium IC + tempered conditions had high hardness values. As expected, they failed to meet the toughness specifications at both temperatures (Fig. 7a and b).

The remaining specimens all had macrohardness values that were in a similar range; consistent with values for properly processed HY-80 material. However, Fig. 8 shows that the as-received and tempered + IC conditions consistently resulted in material that did not meet specifications. These results indicate that although high hardness can be an indicator that there is a problem with HY-80 processing, it is possible to have poor toughness values for material with typical hardness values.

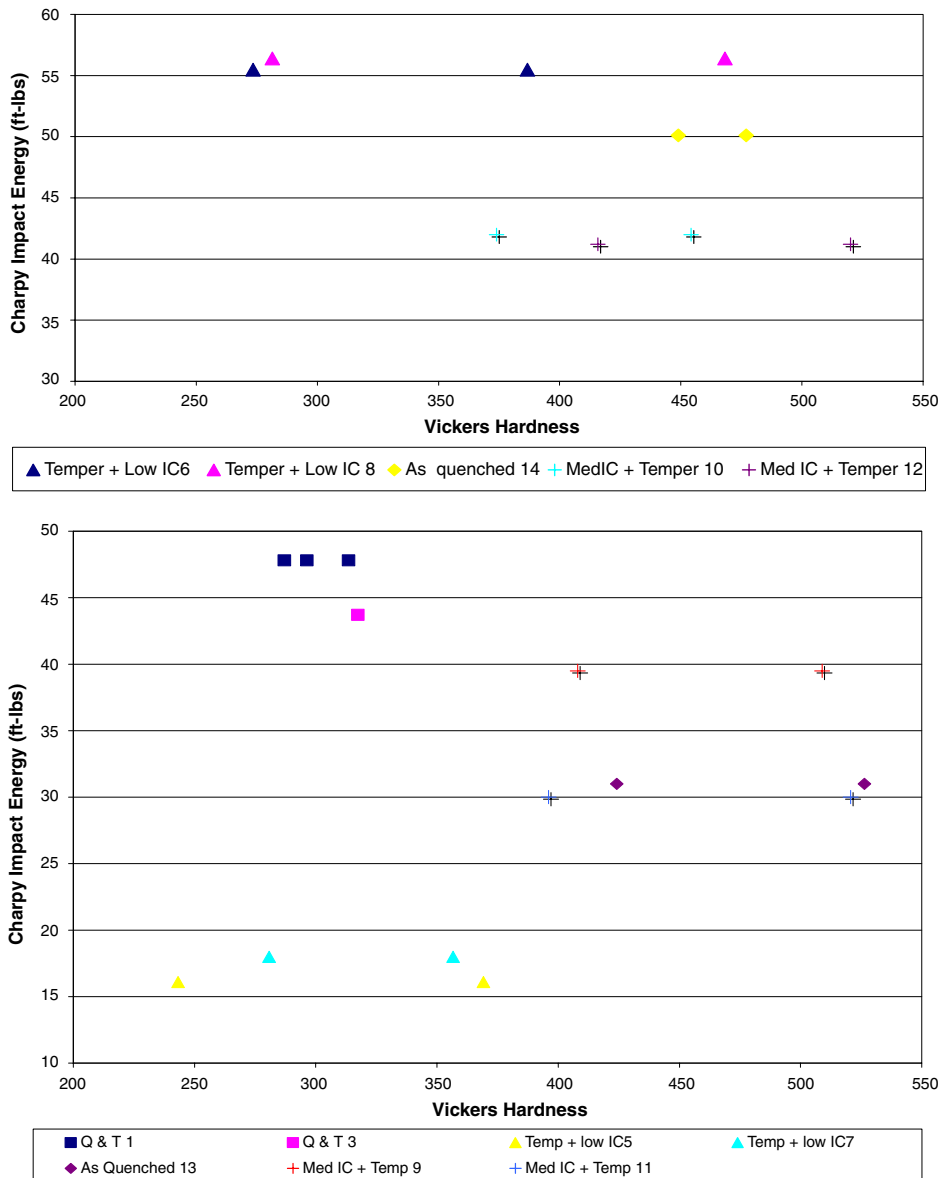


Fig. 8. Charpy impact energy as a function of Vickers microhardness for specimens that failed the specification requirements at (a) 0 °F (b) −100 °F.

Charpy impact specimens that failed to meet specification were sectioned to examine the microstructure directly associated with the deficient impact toughness values and microhardness results are shown in Fig. 8. Results show that each specimen that failed to meet specifications (with the exception of the as-quenched and the quench and tempered) showed two microstructural regions with differing hardness values. In each case, there was a region of high hardness martensite, which likely results in the poor impact properties of the material condition and controls the fracture behavior.

#### 4. Conclusions

1. The as-received HY-80 showed a non-homogenous microstructure. There were two distinct microstructural regions present: untempered martensite and a layered martensite–ferrite structure. The exact location of the as-received HY-80 from the BAT casting is unknown, so it is not possible to tell how close these specimens were from the actual crack location. However, this microstructure does resemble the microstructure in the vicinity of the crack.
2. The as-received material had a transition temperature range between 15 °F (−9 °C) and −75 °F (24 °C). The higher part of the transition range enters into possible operating conditions and is disagreement with acceptable values for properly processed HY-80 material.
3. It is confirmed that heat treatment temperatures from 1330 to 1470 °F (721–799 °C) produce intercritical microstructures that differ from the desired uniform microstructure of tempered martensite. This range of temperatures produces ferrite and martensite in various untempered and tempered conditions.
4. A correlation of Charpy impact toughness with measured macrohardness indicates that hardness alone is not a reliable indicator of impact properties. As expected, high hardness structures that result from the medium IC + tempered and the as-quenched conditions do result in low toughness values. However, a low IC heat treatment with acceptable hardness failed to meet specifications for toughness.
5. Follow-up microstructural examination and hardness measurements of the specimens that failed to meet specification indicate that in each case there was the presence of both high (untempered martensite) and low hardness (ferrite) phases in the structure. It is likely the presence of the hard, more brittle phase results in a low measured toughness values.
6. This work shows that entrance into the intercritical region during the tempering process can produce an affected microstructure that could markedly affect the integrity of an HY-80 casting. The results obtained from the medium IC + tempered condition indicates that the evolution of IC microstructures as a function of time should be more fully explored in order to evaluate the sensitivity of HY-80 material to excursions into the intercritical temperature region.

#### Acknowledgments

The material for this effort was supplied by Franklin Wharton of Naval Sea Systems Command. Special thanks to Geoff Mercier from NSWC Carderock Division for his expertise and the guidance he offered during a summer internship. Technical assistance was provided by Tony Antenucci and Steve Crutchley from the United States Naval Academy.

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