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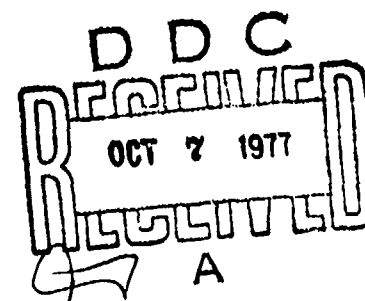
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THE EFFECT OF HEAT TREATMENT ON THE STRUCTURE AND PROPERTIES OF STANDARD AND MODIFIED VASCO X-2 STEEL

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March 1977



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ABSTRACT

Vasco X-2 CVM is a patented high hot hardness carburizing grade gear steel. It is currently being considered for application in the next generation of Army helicopters because of its higher resistance to scuffing. Very limited metallurgical data exist for this alloy in the open literature. This paper compares the heat treatment responses of a 0.24 (standard) and 0.15 (modified) carbon Vasco X-2 steel. The effect of a wide range of austenitizing and tempering temperatures on the structure and mechanical properties is presented. The major result of the investigation indicates that by judicious choice of austenitizing and tempering heat treatments, optimum microstructure and mechanical properties can be developed for the modified Vasco X-2 steel. Rolling contact fatigue, four-square gear testing, and single tooth bending tests have been initiated to evaluate its suitability as a high performance gear material.

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INTRODUCTION

Vasco X-2 was developed by Teledyne-Vasco of Latrobe, Pennsylvania, as a carburizing grade steel with good hot hardness for gear and shaft applications. It is fundamentally a modified H-12 hot work die steel with a carbon level reduced to 0.20 to 0.25 weight percent. The alloy designated Vasco X-2 CVM has been patented by Vasco (U.S. Patent 3,036,912). It is said "to provide an excellent combination of high strength, maximum toughness, and high fatigue strength." Wear resistance is developed by carburization which produces surface hardness values in excess of Rockwell C 60. Very limited metallurgical data exist on this alloy in the open literature. A good summary of the available data has been published on a Ready Reference Data Sheet by the Teledyne-Vasco Corporation.

Since the alloy undergoes secondary hardening during tempering, control of the hardness cannot readily be achieved by control of tempering temperature. For the 0.20 to 0.25 weight percent carbon X-2 steel, the hardness is approximately HRC 50, which is higher than that desired in the core structure of carburized gears. The carbon level was lowered, therefore, to a carbon level that would produce heat-treated hardness values more acceptable to gear manufacturers. This new alloy is commonly referred to as modified Vasco X-2. Most data thus far available on this alloy have been developed by Boeing-Vertol and are contained in their report D301-10036-2 entitled "Vasco X-2, 0.15% carbon (BMS 7-223) Steel Transmission Gear Material Evaluation, Test Results, and Final Report." The main thrust of that report is to present the engineering metallurgical properties of modified Vasco X-2 necessary to procure production material of optimum quality and heat treatment. The Boeing-Vertol procurement specification BMS 7-223 corresponds to Vasco specification MB-X2.

The aim of this investigation is to evaluate the metallurgical properties for a wider range of heat treatment conditions of both standard and modified Vasco X-2. Our report is concerned only with the core material properties; a later report will be concerned with the effect of case hardening. It includes a study of the properties of two carbon levels of Vasco X-2 steel, 0.15 and 0.24 weight percent. The effects of a wide range of austenitizing and tempering temperatures on structure and mechanical properties are included.

EXPERIMENTAL PROCEDURES

The compositions of the alloys investigated in this program are listed in Table 1. Vasco X-2 and Vasco X-2(M) are the standard and modified alloys. As can be seen from the table the compositions are very close, with the major difference being the carbon content. This relatively small difference in carbon content will be seen to have a major effect on the heat treatment responses of these alloys.

The alloys were received as plate stock either 3/8- or 5/8-inch thick by approximately one-foot square in all cases. Tensile and Charpy bars were made from the 5/8-inch plate, whereas all other work was carried out on the 3/8-inch stock. Both the Charpy and tensile bars were oriented with their long directions parallel to the rolling direction.

Table 1. COMPOSITION OF ALLOYS

Element	Composition (Weight Percent)	
	Vasco X-2	Vasco X-2(M)
C	0.24	0.15
Cu		0.08
Mn	0.32	0.23
P	0.010	0.013
S	0.007	0.009
Si	0.88	0.96
Ni		0.07
Mo	1.43	1.34
Cr	4.92	4.92
W	1.38	1.28
V	0.45	0.42
Co		0.03

Specimens were austenitized in the temperature range 1650 to 2150 F and were tempered in the range from room temperature to 1100 F. The tensile and Charpy bars were austenitized and tempered in rough machined condition with a Ceramcoating to protect the surface. All other austenitizing treatments were carried out in an argon atmosphere or in sealed Vycor tubing. Specimens were either oil quenched (tensile and Charpy bars) or fast cooled on a cool steel plate (small specimens about 3/4" x 3/4" x 3/8" thick) from the austenitizing temperature and air cooled from the tempering temperature. All specimens were austenitized for at least 30 minutes at temperature and were double tempered for two plus two hours.

The experimental techniques employed in this study were standard. Rockwell C hardness values were employed; retained austenite was determined by X-ray diffraction techniques using filtered CrK (alpha) radiation. Metallography was carried out on specimens mechanically polished followed by a picral etch; primary ferrite was determined by quantitative metallography. Tensile properties were determined with 0.252-inch tension specimens; and K_Q fracture toughness values were determined on precracked Charpy bars which were tested in slow bend where precracking and testing were carried out on ManLabs equipment.

RESULTS

Effect of Austenitizing Temperature

Hardness

Figure 1 shows the effect of austenitizing temperature on hardness of 0.24 and 0.15 carbon Vascc X-2. Also included is the hardening response of H-12 steel (0.35 weight percent carbon), from which Vasco X-2 was derived. In each case the hardness initially rises rapidly, and then reaches a plateau. The lower the carbon content, the higher the temperature at which this plateau is reached. Of particular interest is the large difference in hardness for only a 0.09 weight

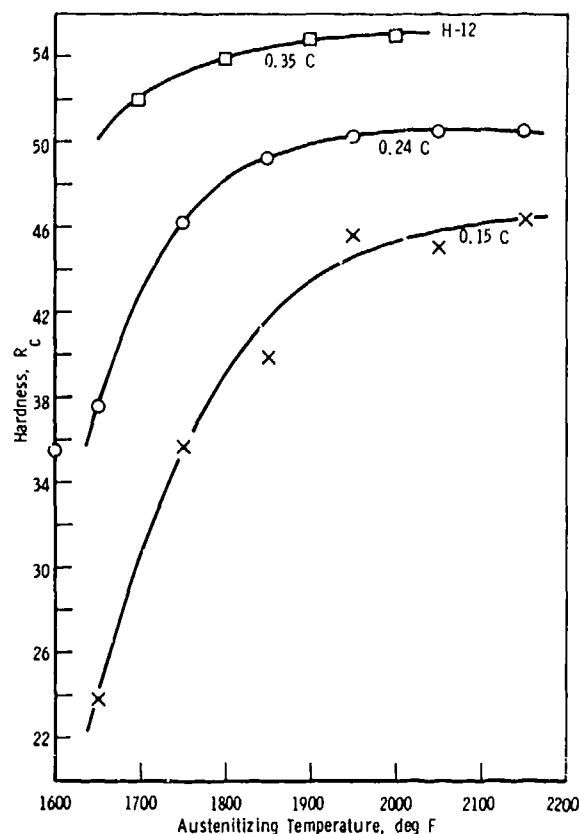


Figure 1. Effect of austenitizing temperature on hardness for 0.15 C and 0.24 C Vasco X-2 and H-12 steels.

percent change in carbon content. Figures 2 and 3 show the effect of refrigeration in liquid nitrogen on the hardness. The hardness values taken on the same specimen (Figure 2a) indicate a small but consistent increase in hardness on all specimens as a result of the refrigeration. If the same specimen was not used (Figure 2b), the experimental scatter tended to mask the effect.

Phase Analysis

Metallography

The effect of austenitizing temperature on the microstructure of the 0.24 C and 0.15 C Vasco X-2 alloys is shown in Figures 3 and 4. The structures consist predominantly of primary ferrite and martensite. The retained austenite is too finely divided and is present in too small a quantity to be readily observed by light microscopy. At low austenitizing temperatures the structures of both alloys consist predominantly of ferrite and martensite with a small amount of undissolved carbides, indicating that the alloys were probably quenched from the three-phase ferrite plus austenite, plus carbide field. The amount of primary ferrite decreases with increasing austenitizing temperature for both steels, reaching a low value (less than 5 volume percent) for an austenitizing temperature of 1850 F for the 0.24 C alloy and 1950 F for the 0.15 C alloy. The amount of ferrite is significantly higher for the lower carbon alloy at the lowest austenitizing temperature (1650 F).

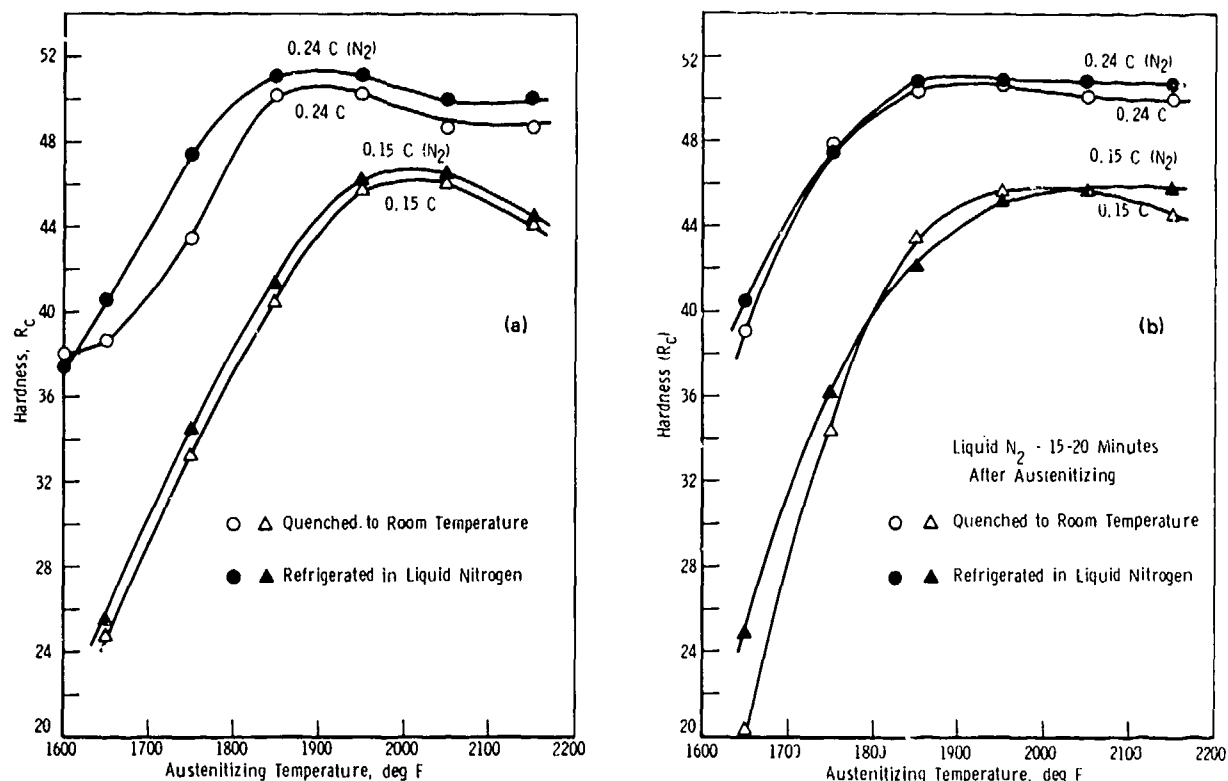


Figure 2. Effect of refrigeration in liquid nitrogen on the hardness versus austenitizing temperature of 0.15 C and 0.24 C Vasco X-2 steels: (a) on same specimen and (b) refrigerated within 20 min. after quench.

Primary Ferrite

Figure 5 is a quantitative metallographic evaluation of the amount of primary ferrite for the 0.24 C and 0.15 C alloys of Vasco X-2 as a function of austenitizing temperature. For the lower austenitizing temperatures, the amount of primary ferrite is much higher for the 0.15 C than for the 0.24 C alloy. The amount of primary ferrite decreases rapidly with increasing austenitizing temperature for both alloys. At an austenitizing temperature of 1850 F, the amount of primary ferrite in the 0.24 C alloy has decreased to about 1 volume percent, whereas an austenitizing temperature of 2050 F is required to produce the same low amount of primary ferrite in the 0.15 C alloy. Figure 6 shows a composite of as-quenched hardness and percent primary ferrite for the 0.24 C and 0.15 C alloys. For a given carbon content, the hardness is inversely proportional to the amount of primary ferrite.

Retained Austenite

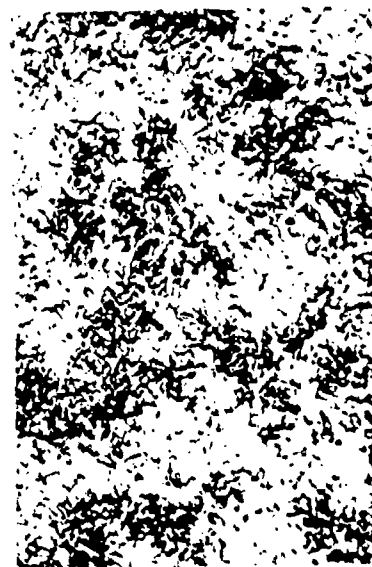
The effect of austenitizing temperature on the amount of retained austenite for the 0.24 C steel cooled to room temperature and for the 0.15 C alloy cooled in liquid nitrogen is shown in Figure 7. The amount of retained austenite increases with increased austenitizing temperature up to about 1900 to 2000 F followed by a drop-off for higher austenitizing temperatures. The data, however, do not permit definitive conclusions at this time. No significant texture was observed in these specimens but the large grain size for specimens austenitized



1550 F



1650 F



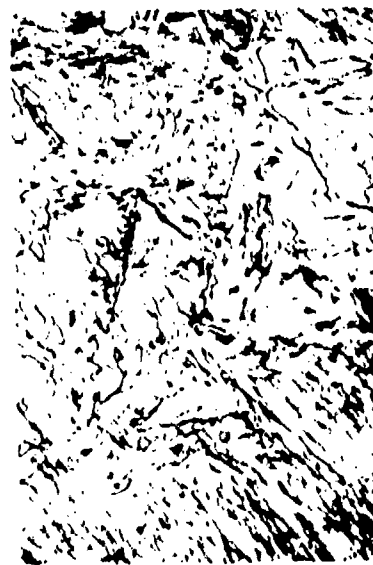
1750 F



1850 F



1950 F



2050 F

Figure 3. Microstructures of 0.24 C Vasco X-2 steel austenitized between 1550 and 2050 F. Mag. 500X.



1650 F



1750 F



1850 F



1950 F



2050 F



2150 F

Figure 4. Microstructures of 0.15C Vasco X-2 steel austenitized between 1650 and 2150 F. Mag. 500X.

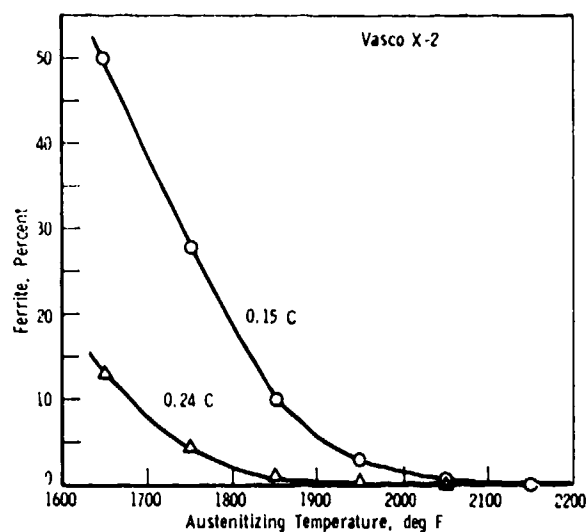


Figure 5. Effect of austenitizing temperature on the amount of primary ferrite for 0.15 C and 0.24 C Vasco X-2 steels.

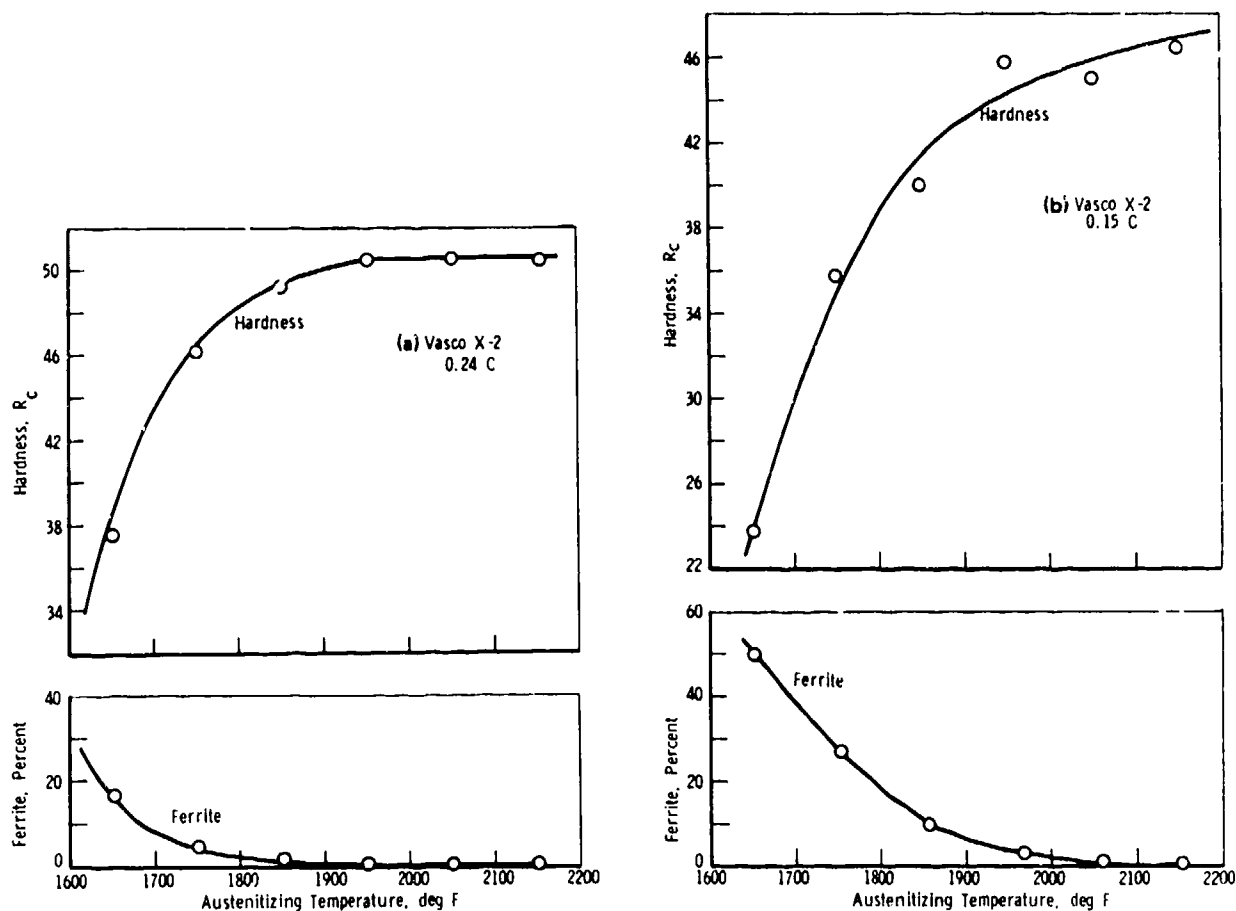


Figure 6. Effect of austenitizing temperature on the amount of primary ferrite and hardness for: (a) 0.24 C Vasco X-2 steel and (b) 0.15 C Vasco X-2 steel.

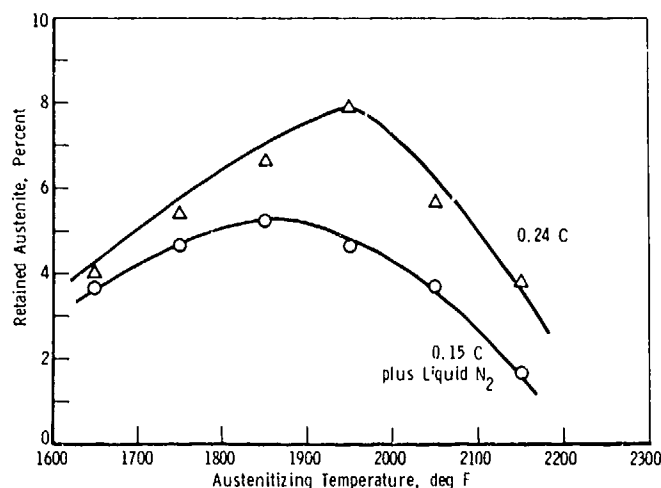


Figure 7. Effect of austenitizing temperature on the amount of retained austenite for 0.15 C and 0.24 C Vasco X-2 steels.

above about 2000 F could account for the apparent drop-off in the amount of retained austenite above this temperature. In addition to the low amount of retained austenite, it is felt that the major contributions to suspected low precision in these retained austenite determinations are:

- (1) the high X-ray background intensity;
- (2) the partial overlap of the CrK (beta) ferrite diffraction line with the relevant austenite line; and
- (3) the high breadth (coupled with the low intensity) of the relevant austenite diffraction line.

It is felt that the first two of these problems will be improved or eliminated with the acquisition of a diffracted beam monochromator and that this will significantly improve the accuracy of the determination of retained austenite by X-ray diffraction techniques.

The initial increase in the amount of retained austenite with an increase in the austenitizing temperature is probably due to the enhanced solution of the carbides which raises both the alloy content and the carbon content in the matrix. The increase in matrix alloy content lowers the M_s and M_f temperatures, which in turn tends to increase the amount of austenite retained at room temperature.

Fracture Toughness (K_Q)

The effect of increased austenitizing temperature on the K_Q fracture toughness is shown in Figure 8 for the 0.24 C and 0.15 C alloys. For tempering temperatures of 600 F and below, the K_Q fracture toughness increases a great deal for the highest austenitizing temperature investigated. For the 0.24 C alloy (Figure 8a), the K_Q for an austenitizing temperature of 1850 F exceeds $70 \text{ ksi}\sqrt{\text{in.}}$ while for the 0.15 C alloy (Figure 8b), the K_Q is approximately $45 \text{ ksi}\sqrt{\text{in.}}$ for a similar austenitizing temperature. The K_Q fracture toughness for the 0.15 C alloy, however, increases with increased austenitizing temperature and approaches

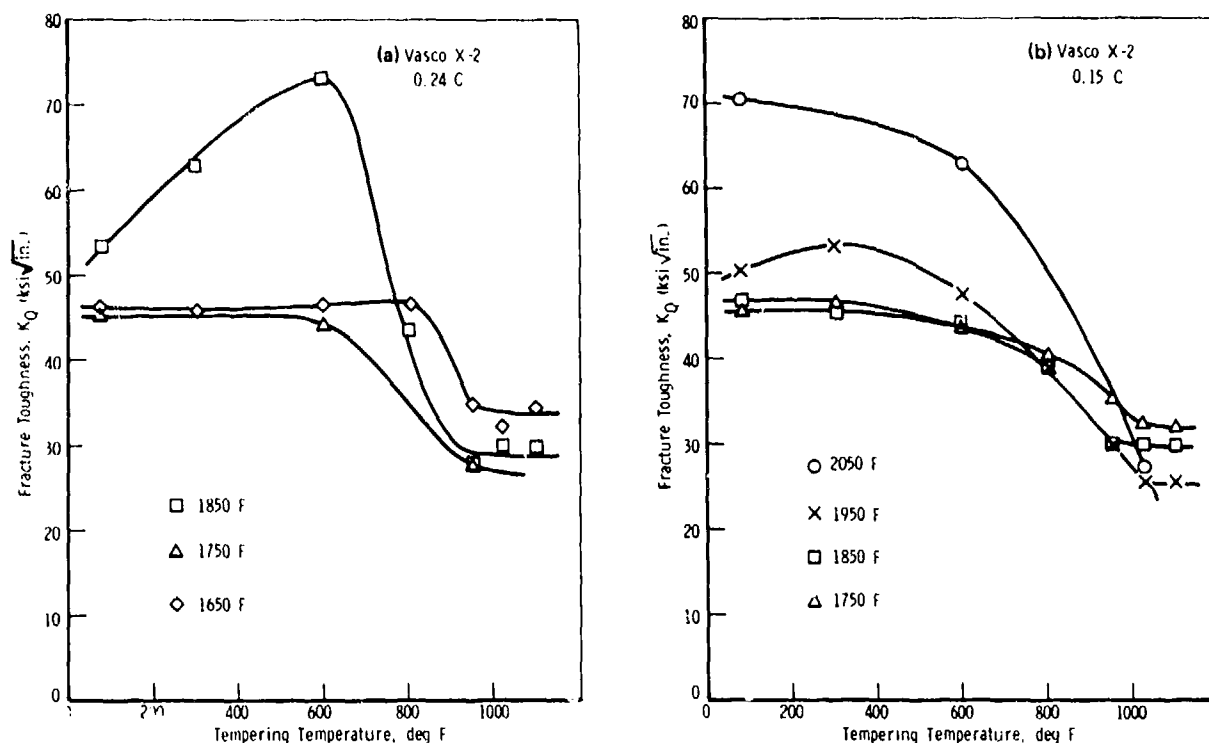


Figure 8. Effect of tempering temperature on the fracture toughness:
(a) 0.24 C Vasco X-2 steel and (b) 0.15 C Vasco X-2 steel.

70 $\text{ksi}\sqrt{\text{in.}}$ for an austenitizing temperature of 2050 F. The standard austenitizing temperature for the H-12 hot work die steel is 1850 F. We see that this austenitizing temperature is satisfactory for the 0.24 C Vasco X-2 modification but would appear to be low for the 0.15 C modification. This will be discussed in more detail later.

Tensile Properties

A very limited amount of tension testing was carried out on both the 0.24 C and 0.15 C alloys of Vasco X-2. Figure 9 shows the effect of austenitizing temperature on the 0.2% yield and tensile strengths of both alloys tempered at 600 F. In general, both the yield and tensile strengths increase with increased austenitizing temperature with no unexpected changes in yield/tensile ratio over the range of temperatures investigated.

Effect of Tempering Temperature

Hardness

Figure 10 shows the effect of tempering temperature on the hardness of the 0.24 C and 0.15 C Vasco X-2 alloys. For all austenitizing temperatures, there is a definite secondary hardening peak which occurs at approximately 1000 F. A slight minimum in hardness occurs for lower tempering temperatures while a rapid

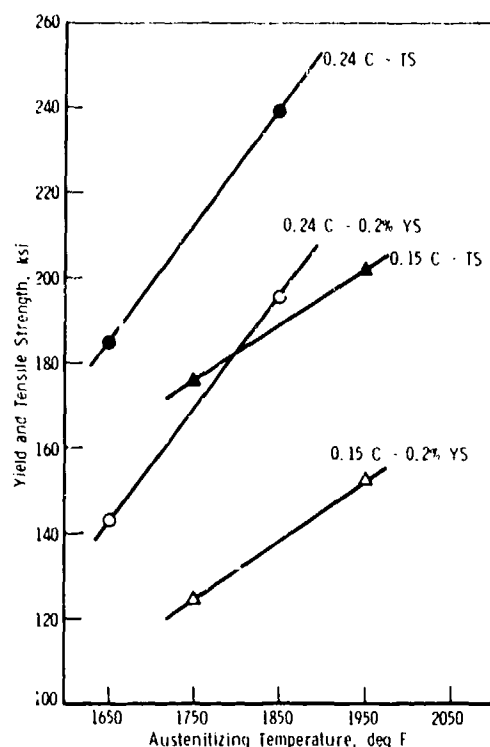


Figure 9. Effect of austenitizing temperature on the yield and tensile strengths of 0.15 C and 0.24 C Vasco X-2 steels.

drop in hardness occurs for tempering temperatures above about 1025 F. A grouping of the tempering curves occurs for austenitizing temperatures at and above 1850 F for the 0.24 C alloy while a similar grouping at and above 1950 F for the 0.15 C alloy.

Retained Austenite

The effect of tempering temperature on the amount of retained austenite is shown in Figure 11 for a single austenitizing temperature for each alloy. The apparent increase in retained austenite for intermediate tempering temperatures is not real, and is felt to be related to a possible annealing effect at these temperatures. The sharp drop in the amount of retained austenite for tempering temperatures above about 900 F, however, is felt to be real. In earlier work on a similar alloy (H-11) but employing a more sensitive X-ray technique,* the amount of retained austenite for tempering temperatures above 900 F dropped to a few tenths of one percent. This conditioning process observed during the tempering of steels is caused by carbide precipitation in the austenite, which raises the transformation temperature for martensite formation and, therefore, "conditions" the austenite to transform to martensite during subsequent cooling to room temperature.

Fracture Toughness (K_Q)

The effect of tempering temperature for several austenitizing temperatures on fracture toughness (K_Q) is shown in Figure 8 for the 0.24 C and 0.15 C alloys of Vasco X-2.

*FOPIANO, P. J., and Das GUPTA, S. C. *Effect of Prestraining and Aging on the Mechanical Properties of Vacuum-Melted H-11 Steel*. Journal of Iron and Steel Institute, February 1969, p. 220-224.

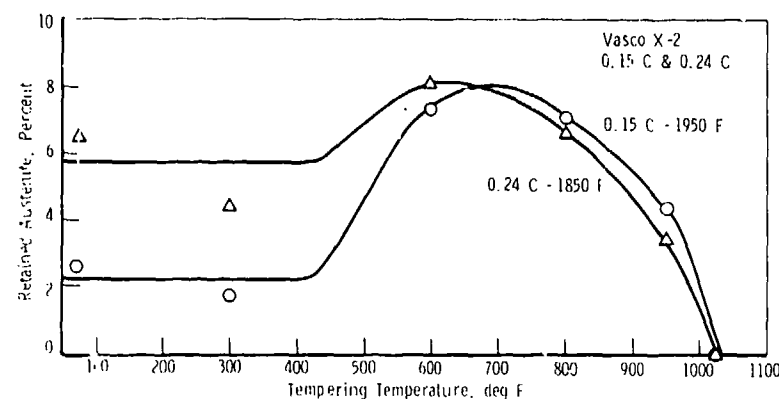
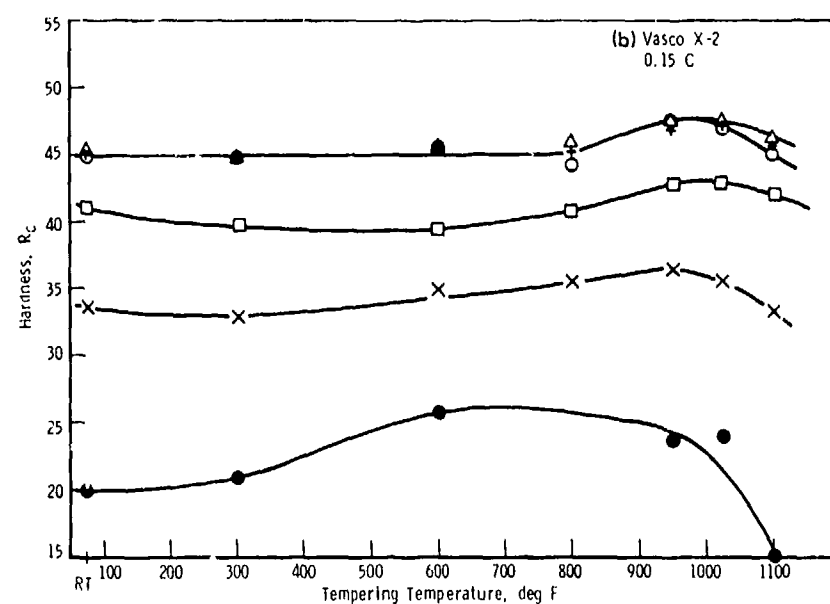
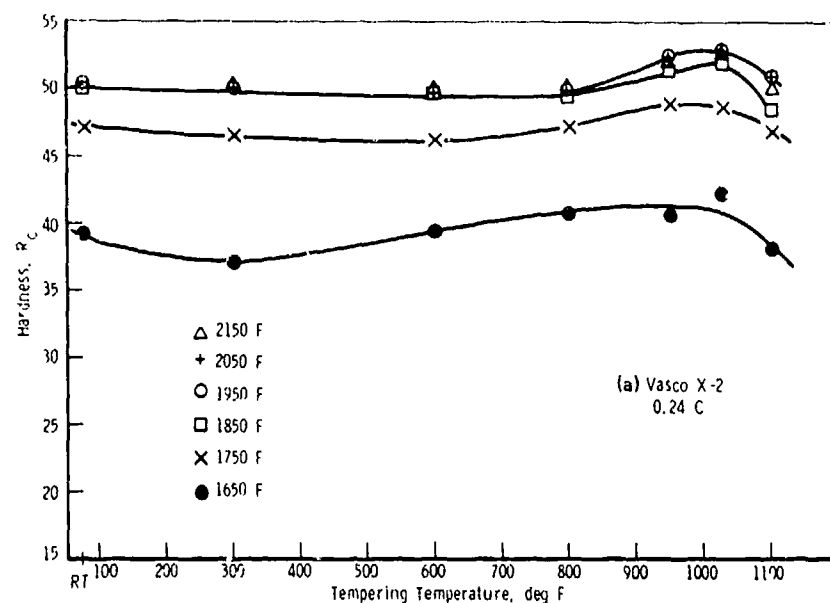


Figure 10. Effect of tempering temperature on hardness of (a) 0.24 C and (b) 0.15 C Vasco X-2 steels austenitized between 1650 and 2150 F.

Figure 11. Effect of tempering temperature on retained austenite for 0.15 C and 0.24 C Vasco X-2 steels.

Figures 12a-g show the effect of tempering temperature on K_Q fracture toughness and Rockwell C hardness for selected austenitizing temperatures. Hardness values were taken on the same specimens. In general, the fracture toughness decreased with increasing tempering temperature above about 600 F. This trend corresponded to an increase in hardness up to a tempering temperature of about 1025 F. Above 1025 F the hardness decreases continuously with increasing tempering temperature but no corresponding increase in fracture toughness was observed. The major effect of increasing the tempering temperature above 600 F is to lower the amount of retained austenite. This effect is essentially completed above 900 F.

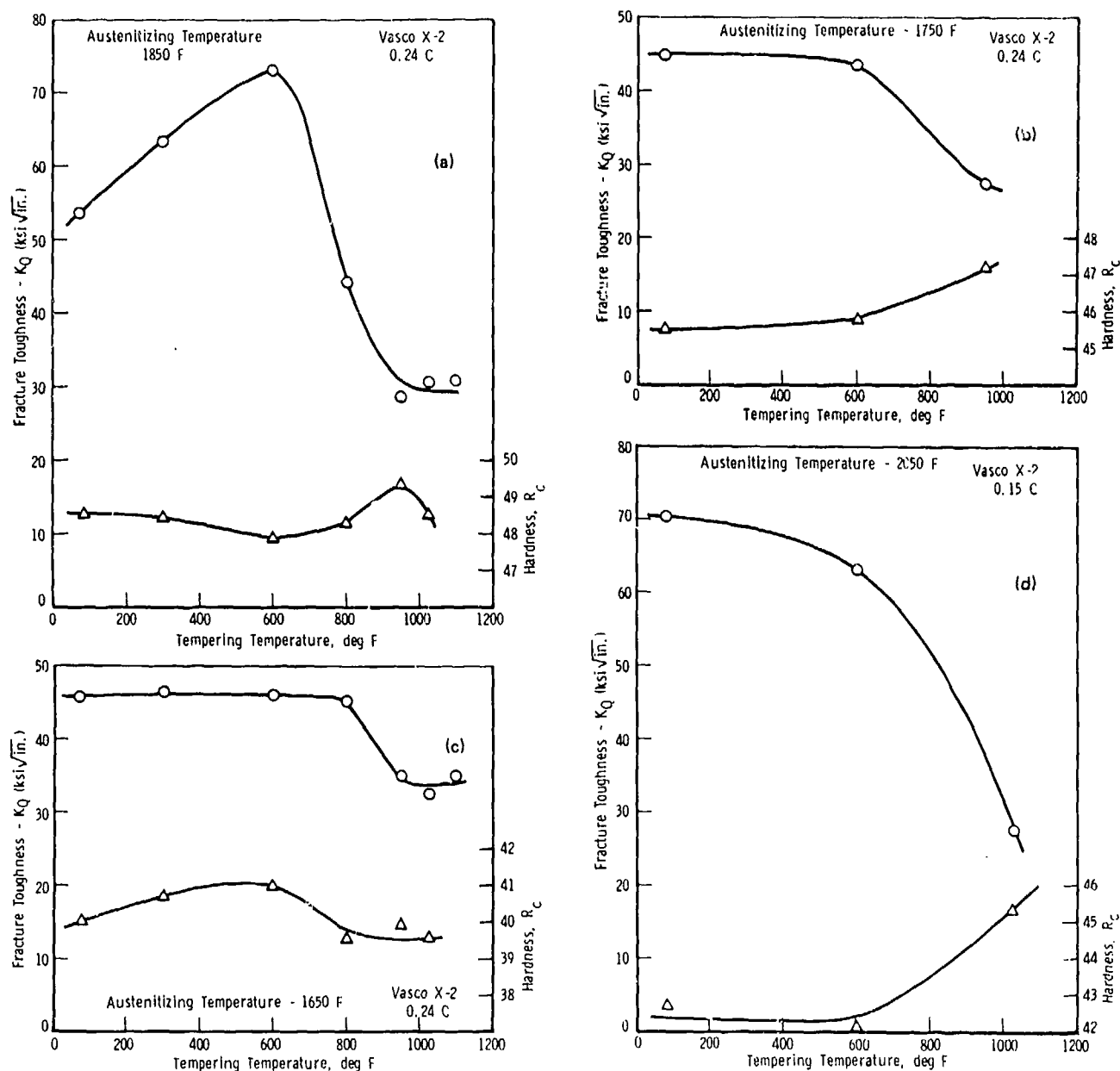


Figure 12 a-d. Effect of tempering temperature on fracture toughness and hardness for 0.24 C and 0.15 C Vasco X-2 steels austenitized between 1650 and 2050 F.

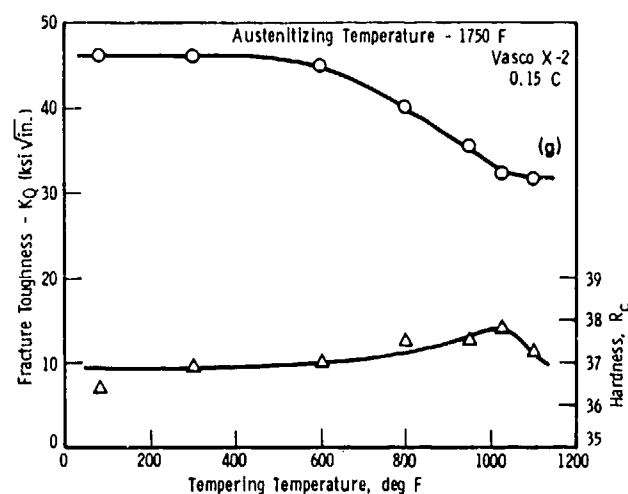
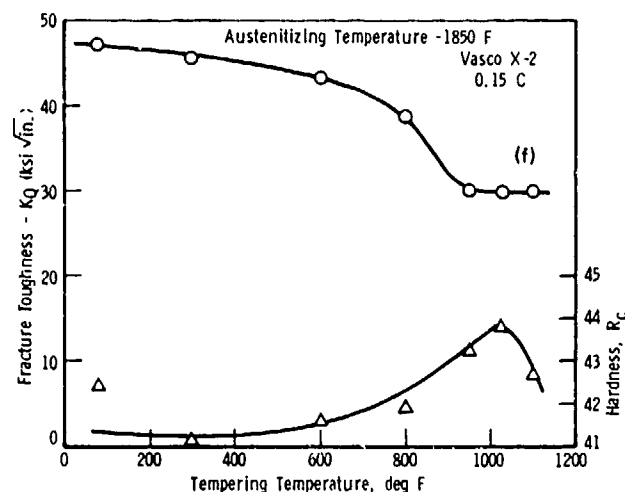
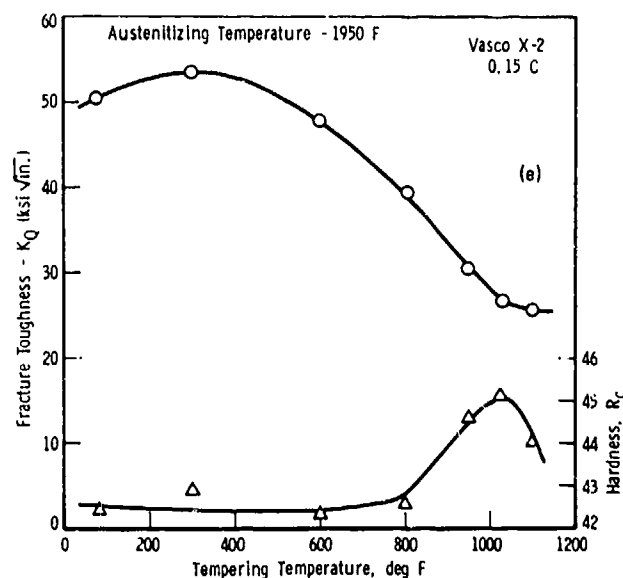
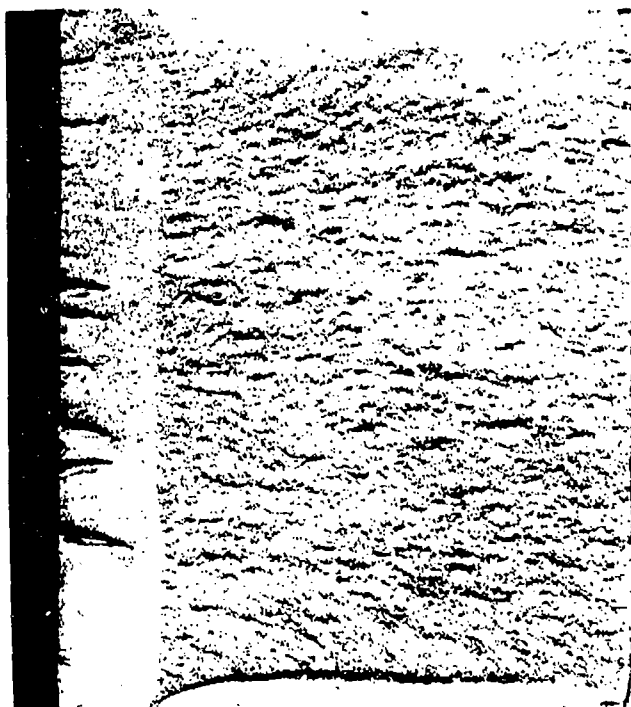
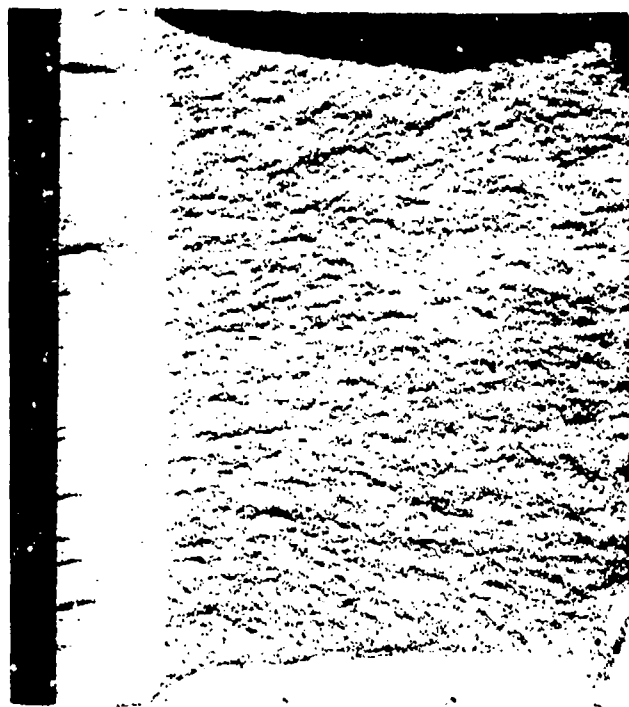


Figure 12e-g. Effect of tempering temperature on fracture toughness and hardness for 0.15 C Vasco X-2 steel austenitized between 1750 and 1950 F.

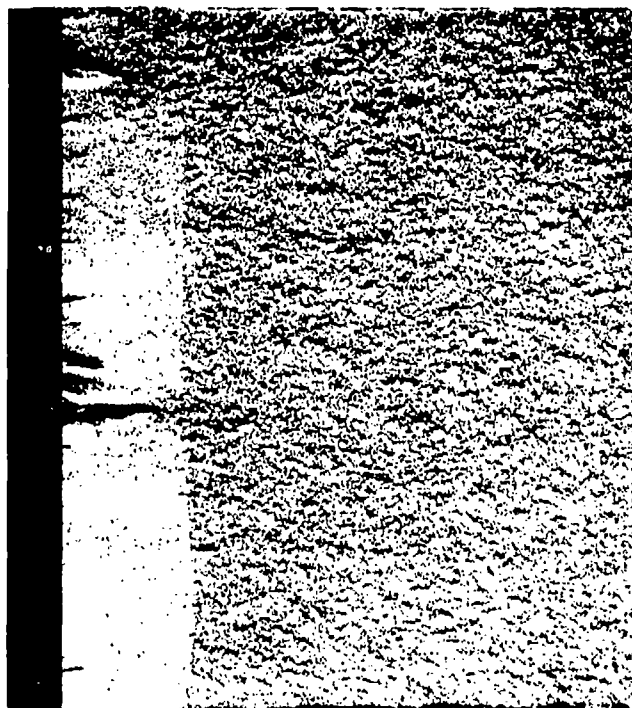
Figure 13 shows the effect of tempering temperature on the fracture surface appearance of specimens of the 0.24 C Vasco X-2 alloy which had been austenitized at 1850 F. For specimens tempered at RT and 600 F a shear lip is observed while for specimens tempered at 950 F no shear lip was observed. This is consistent with Figure 12a which shows a sharp drop in fracture toughness for tempering temperatures above 600 F. Similarly, Figure 14 shows the effect of tempering temperature on the fracture surface of specimens of the 0.15 C Vasco X-2 alloy which had been austenitized at 2050 F. Again, for specimens tempered at RT and 600 F a shear lip is observed while for specimens tempered at 1025 F no shear lip is observed. This is consistent with the observation in Figure 12d which shows a sharp drop in fracture toughness for tempering temperatures above 600 F. The presence of a shear lip is indicative of a ductile fracture.



RT

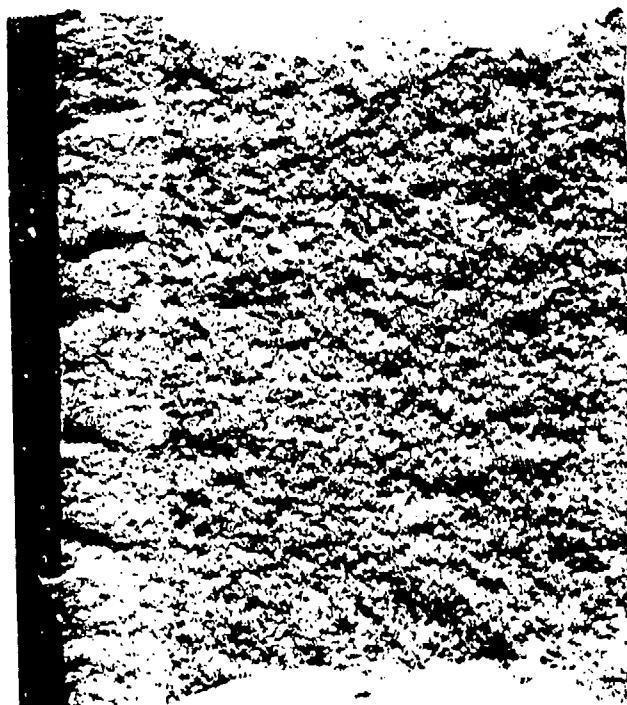


600 F

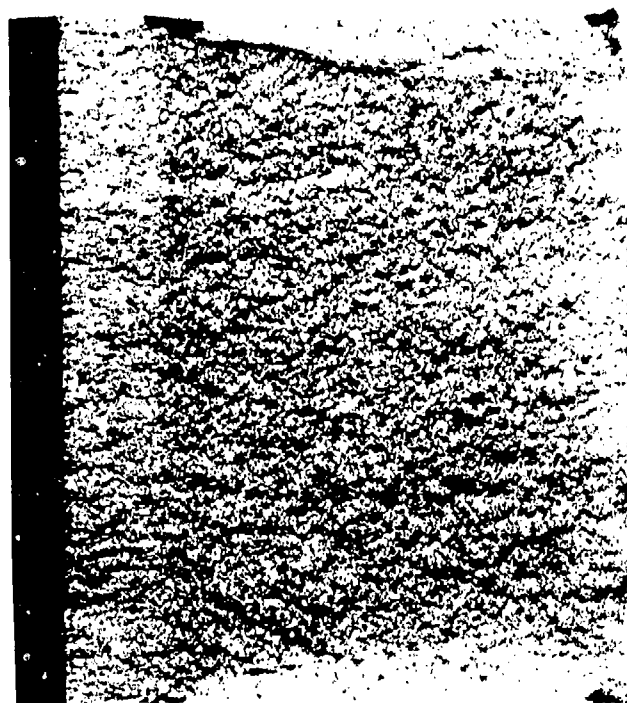


950 F

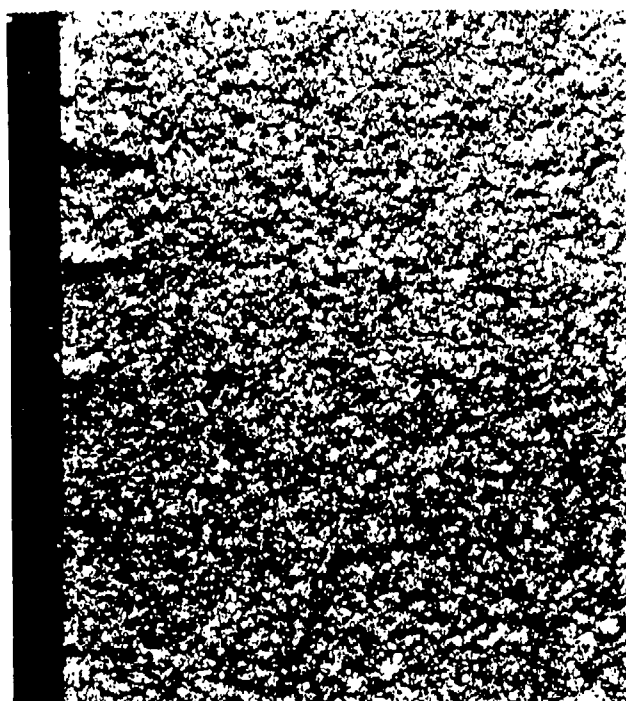
Figure 13. Effect of tempering temperature on the fracture surface of 0.15 C Vasco X-2 steel. Mag. 10X.



RT



600 F



1025 F

Figure 14. Effect of tempering temperature on the fracture surface of 0.24 C Vasco X-2 steel. Mag. 10X.

Tensile Properties

Figure 15 shows the effect of tempering temperature on the tensile properties of specimens austenitized at 1850 F for 0.24 C alloy and at 1950 F for the 0.15 C alloy. Hardness values are also included in these figures for the same heat-treat conditions. There is only a very slight increase in the yield and tensile strengths at the secondary hardening peak. The hardness data show a very characteristic secondary hardening peak but these data are plotted on a much expanded scale. The main characteristic of secondary hardening steels, of course, is not so much the secondary hardening peak but the resistance to softening at higher tempering temperatures.

DISCUSSION OF RESULTS

While the standard and modified compositions of Vasco X-2 differ mainly by the modified alloy containing some 0.09 weight percent less carbon, the effect of this change on the heat treatment response is considerable.

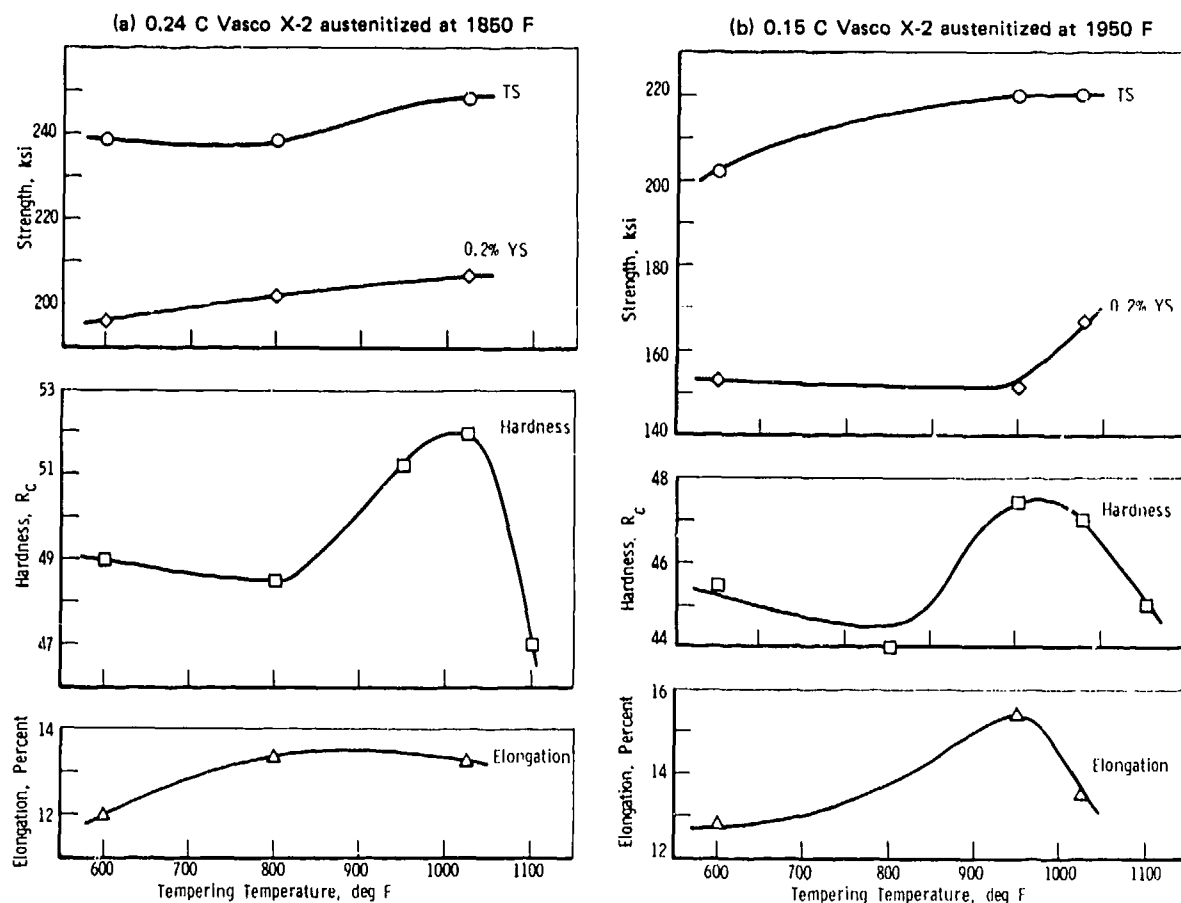


Figure 15. Effect of tempering temperature on tensile properties and hardness.

Effect of Austenitizing Temperature

The major effect of carbon content is to change the temperature range over which the equilibrium phases ferrite and austenite are stable. As the photomicrographs in Figure 3 and 4 show, supported by the quantitative measurements of primary ferrite content in Figure 5, the 0.15 C alloy is in the two-phase ferrite plus austenite field at austenitizing temperatures up to at least 2000 F, while the 0.24 C alloy becomes fully austenitic only at a temperature of at least 1900 F. This effect of carbon content on the phase stability is reflected in the hardness and other mechanical properties, since the martensite produced from the austenite during quenching provides a structure which combines high hardness and strength, together with toughness. On the other hand, the presence of primary ferrite in the structure leads to reduced hardness and strength, and also to reduced toughness.

Thus the decrease in carbon lowers not only the hardness over a wide range of austenitizing temperatures but effectively shifts the hardness versus austenitizing temperature curve to higher temperatures (Figure 1). If we locate the recommended austenitizing temperature of 1850 F for H-12 as some 50 F inside the plateau region, a similar plateau location for 0.15 C Vasco X-2 would be in the 1950 to 2000 F range. It is suggested, therefore, that the austenitizing temperature for 0.15 C Vasco X-2 be increased initially to 1950 F.

The 1850 F austenitizing temperature that has been normally employed for the 0.15 C Vasco X-2 alloy produces a great deal of primary ferrite. Since large amounts of primary ferrite are considered detrimental to the mechanical properties of steels and are usually avoided, the hardness (Figure 1 and 6b), tensile properties (Figure 9), and even the K_Q fracture toughness (Figure 8b) would in each case be higher for an austenitizing temperature of 1950 F than for 1850 F.

The effect of austenitizing temperature on the amount of retained austenite is not very strong but there appears to be a slight increasing trend up to 1900 to 2000 F. This is consistent with the X-ray diffraction observation that the carbide lines gradually disappear with increasing austenitizing temperature. It is expected that as the carbides dissolve with increasing austenitizing temperature the amount of retained austenite should increase somewhat. Once the carbides have dissolved, however, it is expected that the amount of retained austenite should remain constant with further increase in austenitizing temperature. This has not been observed. Since the grain size also begins to increase significantly in this same temperature range (1900 to 2000 F), the apparent decrease in the amount of retained austenite determined by X-ray diffraction analysis, for austenitizing temperatures above 1900 to 2000 F, may be due to grain size effects.

The amount of retained austenite decreases and the hardness increases as the result of subcooling treatments in liquid nitrogen for the whole range of austenitizing temperatures. The effects are small and, therefore, the normal scatter band can produce some inconsistencies unless the change in hardness (or retained austenite) are determined on the same specimen. This was done for hardness in both the 0.24 C and 0.15 C Vasco X-2 alloy (Figure 2a).

Metallographically (Figures 3 and 4), the predominant phases for specimens quenched from 1650 F are primary ferrite and martensite. As shown earlier, the amount of ferrite decreases with increased austenitizing temperature for both the 0.24 C and 0.15 C alloys. The grain size is also observed to increase in the 1900 F to 2000 F temperature range (Figures 3 and 4) for both the 0.24 C and 0.15 C alloys. For specimens austenitized above 1900 F the carbides are mostly dissolved.

Effect of Tempering Temperature

Both the 0.24 C and 0.15 C Vasco X-2 alloys indicate a secondary hardening peak as the result of tempering at about 1000 F for all austenitizing temperatures investigated (Figure 10). This secondary hardening peak is due to the formation of alloy carbides. These carbides develop more readily at the higher tempering temperatures because they require substitutional diffusion of the alloying elements (in this case principally chromium) for their formation, whereas iron carbides can develop at lower temperatures by the interstitial diffusion of carbon.

While tempering has relatively minor effects on the ferrite, it has a significant effect on the amount of retained austenite. As indicated in Figure 11, the amount of retained austenite drops to a very low value in both the 0.24 C and 0.15 C Vasco X-2 alloys for tempering temperatures above 900 F. This process of conditioning the austenite is due to a depletion of the austenite (principally of carbon) by carbide formation which has the effect of raising the M_S (and M_f) temperature, therefore decreasing the amount of retained austenite. In a more sensitive X-ray evaluation of retained austenite in H-11, it was observed that the retained austenite did not in fact drop to zero but only to a few tenths of a percent.

The recommended tempering temperature for Vasco X-2 is 600 F. This is much lower than is ordinarily employed for this type of secondary hardening steel which is usually tempered in the secondary hardening region. Figure 8 indicates a good reason for the selection of 600 F since for a wide range of austenitizing temperatures of the 0.24 C and 0.15 C alloys, the fracture toughness decreases continuously (sometimes very sharply) for tempering temperatures above 600 F. Not only is the amount of austenite relatively high at 600 F but it is also relatively stable. Another reason to use a tempering temperature of 600 F in carburized steels is to restrict the formation of carbide networks at prior austenite grain boundaries. This steel, of course, is used principally in the carburized condition.

CONCLUSIONS

1. The amount of ferrite in the 0.24 C and 0.15 C Vasco X-2 alloys decreases rapidly with increased austenitizing temperature up to 1850 and 1950 F, respectively.
2. The hardness of the 0.24 C and 0.15 C Vasco X-2 alloys increases rapidly with increasing austenitizing temperature up to 1850 and 1950 F, respectively, as

the amount of primary ferrite decreases. Above these temperatures no further increase in hardness is obtained with further increase in austenitizing temperature (plateau region).

3. Lowering the carbon level of Vasco X-2 from 0.24 C to 0.15 C has the effect of not only lowering the hardness for all heat treatment conditions but of shifting the hardness plateau to higher austenitizing temperatures.

4. The amount of retained austenite in these two alloys does not appear to be a strong function of austenitizing temperature.

5. For tempering temperatures at and below 600 F, the K_Q fracture toughness is higher with increased austenitizing temperature above 1750 and 1950 F for the 0.24 C and 0.15 C Vasco X-2 alloys, respectively, consistent with the decrease in the amount of primary ferrite.

6. The tensile and yield strengths of both Vasco X-2 alloys appear to parallel the hardness properties.

7. For the 0.15 C Vasco X-2 alloy it is recommended that the austenitizing temperature be raised to at least 1950 F. This has the effect of lowering the amount of primary ferrite to a value below 5 volume percent and of bringing the material into the plateau region of the hardness versus austenitizing temperature curve.

8. The effects of increasing the tempering temperature for the 0.24 C and 0.15 C Vasco X-2 alloys can be summarized as follows.

(a) The strength and ductility parameters vary only slightly up to the secondary hardening peak.

(b) The K_Q fracture toughness decreases rapidly above about 600 F for all austenitized conditions.

(c) The amount of retained austenite drops to a very low value above about 900 F.

9. For the 0.15 C Vasco X-2 alloy, it is recommended that the tempering temperature be held at 600 F which is consistent with current industrial practice.

10. For the 0.24 C Vasco X-2 alloy, the 1850 F austenitizing temperature is acceptable metallurgically but its hardness (approximately HRC 50) value is unacceptably high for current carburized gear technology. Based on the present work it can be seen that if the austenitizing temperature of this alloy were lowered to achieve the necessary hardness, two undesirable conditions would result:

(a) the amount of primary ferrite would increase well above 5 volume percent leading to inferior toughness, and

(b) the austenitizing temperature would lie on the rapidly changing portion of the hardness versus austenitizing temperature curve making temperature control impractical on a commercial basis.

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THE EFFECT OF HEAT TREATMENT ON THE
STRUCTURE AND PROPERTIES OF STANDARD
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Eric B. Kulja

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