DIRECTION OF R&D AND CURRENT STATUS OF UNDERSTANDING OF ADVANCED GEAR STEELS

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ABSTRACT

High performance gears in the modern helicopter must operate at ever increasing torque and RPM. A major consequence of this increased torque and RPM is a significant increase in the surface temperature and increased scuffing of the gears. In response to this problem, Boeing-Vertol introduced a new class of steel (hot work tool steel) as a high performance aircraft gear steel and started a trend which all subsequent work has confirmed to be a correct decision. This report focuses on the three most prominent candidate critical high temperature aircraft gear steels including Vasco X-2M, CARTECH X-53 (PYROWEAR 53), and CBS600. The heat treatment responses of these alloys will be compared. Three additional alloys (M50NiL, CBS1000M, and AMAX B) will be discussed in less detail. Most of the information contained in this report is metallurgical in nature with the appreciation that considerable engineering and manufacturing information is available for most of the alloys, but with the realization that much work still needs to be done.

INTRODUCTION

The modern helicopter is continually being required to lift ever heavier loads and to do this at ever increasing speed. The net effect of this is that the gears which carry this power from the turbine to the rotor are subjected to higher torques at higher RPM. An important consequence of this increased torque and RPM is that a significant increase in temperature at the contact surface of the gear can be expected which can only be partially alleviated by more robust lubrication cooling systems. Estimates as to the expected surface temperature range from 200 to 300C. This surface temperature should be distinguished from the oil-out temperature which has a maximum of about 120C. This oil-out temperature does not fluctuate widely during flight from the 'standard' operating temperatures and is continuously maintained by control of the oil-in temperature by a lubrication cooling system.

The workhorse of the major American helicopter producers for critical high performance gearing is the carburizing grade steel AISI 9310 (Table 1). This steel is only recommended for continuous use at temperatures up to about 150C, above which it will experience serious losses in strength with long exposure times. Because of this loss in elevated temperature strength, the scuffing resistence of AISI 9310 becomes increasingly suspect in the new environment of increased torque and RPM (and estimated surface temperatures of 200-300C). The evidence for this deteriorating scuffing resistance is difficult to document since the rejection of the great majority of gears at Army rework facilities are based on very subjective rejection criteria. The vast majority of gears are rejected because of pitting but no effort is made to determine if the pitting is from scuffing or from fatigue effects. The differentiation between these is difficult for in-service failures and should be carried out in a laboratory rather than shop environment.

In the late 60's, Boeing-Vertol (B-V) decided that a replacement for AISI 9310 was highly desireable for advanced drive systems. They no doubt arrived at this conclusion based on observations of gears taken out of service, good engineering, and at least some leap in faith. In an engineering study comparing several steels including VASCO X-2, Bower 315 etc., Vasco X-2 was selected as having the best combination of properties necessary to produce good aircraft quality high performance gears. The one area where Vasco X-2 was clearly at a disadvantage (compared to AISI 9310) was in the values of fracture toughness. This of course was not too surprizing since it has long been appreciated that alloy steels (such as AISI 9310) have higher fracture toughness values than tool steels (Vasco X-2 of course is a low carbon variation of H-12 which is a hot work tool steel). The fracture toughness of AISI 9310 in fact is so high (above 100 M Pa$\sqrt{m}$) that it is not considered a critical design parameter. With the use of Vasco X-2 the situation changed and fracture toughness became a very important consideration if not a design parameter. In fact, the fracture toughness has perhaps assumed more importance than is justified, since the required fracture toughness for high performance gear applications is not known. A general concept has generally been accepted, however, that fracture toughness shall be as high as possible consistent with meeting other property requirements such as strength, fatigue resistance, and ductility. It should be emphasized that while the gear surface must be hard and wear resistant, the webbing of the gear (the low carbon core material) must be resistant to crack initiation and propogation. In fact Boeing-Vertol employs the threshold (as determined from crack progagation studies) of the core material as an important parameter in the design of the web of the gear. While the fracture of the carburized tooth is certainly not desireable, it does not present the possibility of instant disaster of a fracture which has initiated in the web of the gear.

The introduction, therefore, of Vasco X-2 as a high performance aircraft gear steel by Boeing-Vertol started a trend which all subsequent work has confirmed to be a correct decision. The following report will focus on the three most prominent candidate steels including Vasco X-2M (a lower carbon version of the original Vasco X-2), CARTECH X-53 (PYROWEAR 53), and CBS600. The heat treatment responses of these alloys including hardness, tensile properties, fracture toughness, microstructure, and Charpy energy will be presented. Three additional alloys will be discussed in less detail but with specific advantages not present in the other alloys such as ease of carburizing, conservation of alloying elements, or reduced susceptibility to embrittlement during aging. Vasco X-2M (VIMVAR) is the only advanced high temperature carburizing grade steel currently in use today in critical gear applications in aircraft. This does not mean that it is the only steel that could be used for this application but it does mean that considerable engineering and manufacturing effort has gone into making this a successful high temperature (high hot hardness) high performance gear steel. Any successor to VASCO X-2M should not merely be marginally better but should have some property or processing characteristics which are clearly superior or should eliminate a weakness in VASCO X-2M that could be critical to the long range surviveability of the gear.

The present report compares the properties of alternative steels to those for VASCO X-2M. The three (3) initial candidate steels have been evaluated in considerable engineering detail by BOEING-VERTOL (VASCO X-2M), Bell (CARTECH X-53) and Sikorsky (CBS600). Most of the information, however, contained in this report will be of a metallurgical nature. The report will present data on VASCO X-2M in considerable detail while the data on the other alloys will be presented to illustrate the essential differences. As will be realized all the facts are not in and we will attempt to point out where we feel more work is needed.

RESULTS AND DISCUSSION

Figure 1 shows the effect of tempering temperature on the R_c hardness values for the initial three (3) candidate high temperature carburizing grade steels in comparison to AISI 9310. Table 1 shows the compositions of these alloys. The essential differences between these alloys which reflects the compositions will be discussed. The AISI 9310 curve is typical of high strength alloy steels which show continuous softening for tempering temperatures above about 150C. The hardness values of CBS600 also drop off continuously with increasing tempering temperature but the rate of softening is retarded. Vasco X-2M and CARTECH X-53 are typical of the so-called secondary hardening steels where a secondary hardening peak occurs at about 500C. These steels are much more resistant to softening. It is estimated that VASCO X-2M, CARTECH X-53, and CBS600 can operate continuously at 315, 275, and 230C respectively. Also shown in Fig. 1 are the maximum temperature ranges for present and future helicopter transmissions.

VASCO X-2M

Fig. 2 shows the effect of austenitizing temperature on the R_c hardness of 0.15, 0.24 and 0.35 w/o carbon VASCO X-2 where 0.35 carbon is the hot work tool steel H-12. The increase in hardness is principally due to the decrease in the amount of primary ferrite with increased austenitizing temperature as is shown in Fig. 3 (0.15C and 0.24C) and metallographically for Vasco X-2M in Fig. 4. While the amount of retained austenite varies between 3 and 5% with increased austenitizing temperature, the effect of these small changes on the hardness is small.

Fig. 5 shows the effect of tempering temperature on the hardness for various austenitizing temperatures. A secondary hardening peak is observed at about 500C. A slight increase in hardness is observed for austenitizing temperatures above 1010C which is the commercially used hardening temperature. This increase is no doubt due to the increased resolution of the alloy carbides at the higher temperature.

Fig. 6 shows the effect of tempering temperatures on the K_Q fracture toughness for various austenitizing temperatures. For the commercial heat treatment of 1010C followed by a 315C temper, the K_Q is about 45 MPa$\sqrt{m}$. By increasing the austenitizing temperature to about 1125C, the fracture toughness can be significantly increased to over 60 MPa$\sqrt{m}$) but the grain size becomes very large for austenitizing temperature above 1100C. At a tempering temperature of about 500C, there is a complete disappearance of a shear lip on the fracture surface. This observation is consistant with the drop in fracture toughness for tempering temperatures above 315C. The values of fracture toughness reported here are for vacuum arc remelted (VAR) material. This value has been increased to about 70 MPa$\sqrt{m}$ in vacuum induction melted vacuum arc remelted (VIM-VAR) material which is in current usage by Boeing-Vertol in the CH 47-D. The carburizing of VASCO X-2M is difficult because of the high chromium content. Uniform carburizing, however, can be obtained by a pre-oxidizing treatment before the standard endothermic gas carburizing or by vacuum carburizing. (Vacuum carburizing is a process which uses no carrier gas, can be carried out at high temperature, and eliminates surface oxidation.) A program is currently underway to qualify the vacuum carburizing process for critical aircraft gear applications.

The effect of tempering temperature on the Charpy energy of Vasco X-2M is shown in Fig. 7. Also shown in this figure is the effect of 1000 hours aging at 260°C. The decrease in Charpy energy for long term aging at 230C has considerable practical significance 260C has same metallurgical significance. In the short term, the major helicopter producers agree that the effect of long term aging at 230C is related to the expected increased surface temperature of main drive transmission gears under high torque and RPM conditions. In the long term, of course, it is expected that transmissions will operate at temperatures (oil-out temperature) exceeding 200C. The effect of long time exposure at temperatures of 260 and 230C on the Charpy energy has been investigated in considerable detail for CARTECH X-53 and will be discussed below:

Another important requirement for high temperature gears is that the hardness shall be unaffected by long term exposure at elevated temperature. Table 2 shows the effect of aging 1000 hours at 315C on the hardness (Ref 4). AISI 9310 softens considerably with long term aging while Vasco X-2M retains its hardness even after extended aging.

The fracture toughness in carburized cases for many of the same steels is shown in Table 3 (Ref 4). Again the fracture toughness was determined before and after exposure for 1000 hours at 315C. It can be seen that the toughness decreased about 50% after exposure for Vasco X-2M. It must be emphasized here that Vasco X-2M is not currently used above about 125C and that the method employed for measuring the fracture toughness of a carburized case is not an ASTM standard test procedure. The change in the fracture toughness, however is felt to be significant and the effect of long time aging at 230C of the core (low carbon) Vasco X-2M is currently being investigated in much more detail.

CARTECH X-53 (X-53)

The effect of austenitizing temperature on the properties and microstructure of X-53 closely parallels those of VASCO X-2M. A major difference is the absence of even the small amount of retained austenite observed in Vasco X-2M. The commercial austenitizing (hardening) temperature for X-53 is 910C vs 1010C for Vasco X-2. With tempering, X-53 has a secondary hardening peak at about 500C. The Charpy energy decreases sharply and continuously for tempering temperatures above 260C (Fig. 8). This decrease is independent of austenitizing temperature between 850 and 950°C. Included on the same figure is the effect of 1000 hour aging at 260F on the Charpy energy. The large drop in Charpy energy with long time aging at 260C is of considerable practical significance. First of all, X-53 is a strong candidate as a high temperature high performance carburizing grade gear steel because of its high fracture toughness. Because of the critical nature of the observation and the feeling by representatives from the four (4) major U.S. helicopter producers that 230C (450F) would be a more appropriate aging temperature, the data in Fig. 9 was collected. The samples used in the production of the data in Fig. 9 were heat treated at Bell Helicopter according to their standard specifications including a pseudo-carburizing treatment. Aging treatments at 230C as a function of time and the Charpy impact testing were carried out at AMMRC. Each point on the curve represents the average of three (3) readings. The material employed to collect the data in Fig. 9 is double vacuum melted (VIM-VAR) while the material employed to collect the data in Fig. 8 was air melted plus VAR. There is more scatter in the data than would normally be expected for Charpy energy determinations. This scatter appears to decrease for longer aging times. The mechanism for embrittlement has been shown (Ref 5) to be the precipitation of alloy carbides (M_6C) at prior austenite grain boundaries. The scatter in the Charpy energy data for aging times up to 1000 hrs at 230C is not understood and there is no reason to suspect either the Bell or the AMMRC heat treatments.

The loss in Charpy energy appears to be fully recovered for aging times of 2000 hrs at 230C and the scatter in the data is much reduced. Since the hardness is not effected by this long aging treatment, it suggests measures that can be taken to eliminate both the scatter and more importantly the drop off in Charpy energy (as yet subject to considerable scatter) for long time low temperature aging.

One obvious solution to the drop in toughness would be to duplicate the 2000 hrs. at 230C aging treatment by a significantly shorter aging (tempering) treatment at 315C. Since the activation energy for the diffusion of molybdenum in iron is 57.7 kcal, the time to attain equivalent diffusion at 315C is only about 0.67 hours (see Table 4). But this calculation is based on substitutional diffusion and we know that grain boundary and dislocation diffusion will predominate at the low aging temperatures being considered. If we assume an activation energy of 30 kcal for the low aging temperatures, we calculate a time of about 30 hrs. at 315C to be equivalent to 2000 hrs. at 230C. Since the region near the prior austenite grain boundaries are observed to be devoid of carbides, a combination of diffusion mechanisms is felt to be operative. In summary, if specimens are tempered at 315C for 30 hours, embrittlement of our structure should be avoided with no loss in strength and subsequent in service aging at and below 315C should have no effect on the toughness. An experiment testing this idea is currently in progress at our laboratory.

CBS600

CBS600 was developed by Timken as a carburizing grade bearing steel for service above 150C. The philosophy used in designing the alloy was to retard the decomposition of the martensite by additions of silicon, chromium, and molybdenum. This was quite different from the philosophy used in the development of secondary hardening steels (Vasco X-2M and CARTECH X-53) which achieve their high temperature properties by the development of stable alloy carbides of molybdenum, vanadium, and tungsten. CBS600 carburizes much more readily than for example VASCO X-2M, presumeably because of the lower chromium content (1.5 W/O vs 5.0 W/O for Vascos X-2M). Jatczak (Timken) feels that CBS600 should be capable of operating at a maximum service temperature of 450F (230C).

The effect of austenitizing temperature on the mechanical properties and microstructures of CBS600 closely parallels those for Vasco X-2M and X-53. The commercial austenitizing (hardening) temperature for CBS600 is about 910°C which is just about at the beginning of the plateau region of the hardness vs austenitizing temperature curve. The effect of temering temperature on the hardness for several austenitizing temperatures is shown in Fig. 10. No secondary hardening peak is observed for any austenitizing temperature but the hardness retention with increased tempering temperature is considerably better than for AISI 9310 steel (Fig. 1). Fig. 11 shows a composite of the effect of tempering temperature for specimens austenitized at 900C on the tensile, Charpy energy, and K_Q fracture toughness. The ultimate tensile strength, and Charpy energy all decrease continuously if not sharply with increased tempering temperature while the yield strength and the K_Q fracture toughness do not change significantly over the same range of tempering temperature. The sharp drop in Charpy energy with increased tempering temperature of X-53 is not observed for CBS600. The values of Charpy energy and K_Q fracture toughness are representative of single vacuum melted steel and would be higher for double vacuum melted (VIM-VAR) steels. The effect of long time aging at 230C on the Charpy energy for CBS600 is currently underway at AMMRC.

M50 NiL

General Electric, in cooperation with Massachusetts Institute of Technology and Fafnir Bearing Company under contract to the Air Force and Navy is performing a program designed to identify a material suitable for ultra-high-speed rolling element bearing operation (up to 3 million DN). In addition to having rolling contact fatigue life and hot hardness as high as for M50 (the high hot hardness bearing steel widely used in aircraft gas turbine engines in the USA) the new material must have a high fracture toughness. M50 NiL was the material developed on this program as a carburizing grade rolling element bearing.

The evolution of M50 NiL began as a low carbon modification of M50. The reduced carbon level (0.15% versus 0.80%) provided the potential for surface hardening by carburizing thus creating a bi-hardness structure. The addition of 3% nickel was to provide ferrite control and stability, added toughness, and improved fabricability. M50NiL's success as a bearing steel, comparable to homogeneous M50 steel with much improved fracture toughness, suggests that it should be applicable as a carburizing grade high temperature gear steel. A major drawback may be its high alloy content which may increase the cost of materials to unacceptable levels. Preliminary vacuum carburizing tests at AMMRC indicate that it readily carburizes at about 1050C in spite of the 4.5% chromium and that there appears to be no tendency to form continuous grain boundary carbides. This very important processing consideration may more than compensate for the low core K_{Ic} (about 40 MPa$\sqrt{m}$) and high alloy content.

CBS1000M

This alloy is based on a composition developed by Timken as a carburizing grade bearing steel (CBS1000). Unlike CBS600, it is a secondary hardening carburizing grade steel with a temperature capability comparable to Vasco X-2M. The commercial austenitizing temperature is about 1100C (same as for M50 NiL). The K_{Ic} for VAR material is about 40 MPa$\sqrt{m}$. This value is expected to be significantly higher for VIM-VAR material. The fracture toughness as well as the hardness is retained after exposure for 1000 hours at 315°C. Early consideration of this alloy was rejected because of its low Charpy energy at 40C but here again this low value is expected to increase for VIM-VAR material. A major incentive to use this steel as a carburizing grade gear steel are manifold and include considerable experience in its use as a carburized bearing steel, the stability of both hardness and fracture toughness after 1000 hours aging at 315C, and the ease of carburizing. The modification of this alloy by AMAX suggests that the composition of CBS1000M can be optimized with advantage. This work will be discussed below.

AMAX B

This alloy was developed at amax metals Research Laboratories in Ann Arbor, Michigan under contract to AMMRC. The program grew out of contacts at National Materials Advisory Board meetings which focussed on the shortcomings of several candidate steels for use as carburized gears for high temperature service in helicopters (Ref 3). The initial program concentrated on a comparison of carburized candidate high temperature steels (shown in Table I), and the investigation of six experimental steels. This program concluded that an experimental composition similar to CBS1000 had the highest impact fracture strength, even higher than AISI 9310 A follow-on program had as its major goal to optimize this experimental composition by variations in the concentrations of silicon, molybdenum, and nickel. The objectives were to produce by composition and heat treatment, fracture characteristics similar to AISI 9310 and a minimum surface (carburized) hardness of 58 R_c both before and after 1000 hour exposure at 315C. AMAX B satisfies these criteria with a composition almost 2% less molybdenum and almost 1% less nickel than CBS1000. This program, now completed, should be complemented by tests of long time stability at 230C (as for X-53). Successful completion of these tests suggest that this alloy, with every indication of stability up to 315C, may well become the prime candidate for the replacement of Vasco X-2M. Considerable processing studies and gear tests (including rolling contact fatigue, single tooth bending, and 4 square gear testing), however, must be carried out before the final decision can be made on this alloy.

SUMMARY

The use of high temperature high performance gears in helicopters has wide acceptance within the helicopter industry in the USA. With the exception of CBS600, the efforts have for the most part focussed on low carbon modifications of secondary hardening tool steels. Vasco X-2M is the only high temperature gear steel currently flying in the main drive train of helicopters in the USA. Because of the extensive engineering data base associated with VASCO X-2M, the long history of manufacturing development, and the significant improvements in metallurgical parameters over the past 15 years, Vasco X-2M would be the obvious choice for a high temperature gear steel requirement for critical aircraft applications. This does not mean that other steels should not be considered. In fact, the two additional major candidate steels were chosen principally because they had a higher fracture toughness than Vasco X-2M. In the past several years considerable metallurgical, engineering, and manufacturing information has been developed for CBS600 and X-53 by Sikorsky and Bell respectively.

CBS600 is a carburizing bearing steel developed by Timken and has had considerable use in roller bearings for applications up to 230C. It is the only candidate high temperature gear steel which is not a secondary hardening tool steel. Except in special applications, it is not expected to find wide application in helicopter drive trains because (1) its marginal temperature capability and (2) its high fracture toughness is being approached by secondary hardening tool steels. For example, the fracture toughness of Vasco X-2M was gradually increased from about 45 MPa$\sqrt{m}$ to 70-80 MPa$\sqrt{m}$ by improved melting practice (VAR, VAR-VAR, and VIM-VAR).

X-53, had initially a higher fracture toughness than Vasco X-2M in the vacuum arc remelted (VAR) condition. With the improvement in fracture toughness of both alloys with increased cleanliness (VIM-VAR), the difference in fracture toughness is less but still significant. A temper embrittlement transformation was first identified in X-53. This embrittlement appears to be dependent on the austenitizing temperature and the lowest value of toughness (as determined by room temperature Charpy energy values) with increased time or temperature of aging is higher for the VIMVAR than the VAR material. Long aging times (2000 hours) at 230C result in improved toughness and less scatter in the data. Experiments are currently underway at AMMRC to determine the practicality of duplicating the toughness values for specimens aged for 2000 hrs. at 230C with those obtained on specimens aged for much shorter times at 315C. It appears that X-53 could become a competitor to Vasco X-2M as the next aircraft quality high temperature gear steels but it is not clear if the possible benefits are worth the added costs to carry out the necessary engineering and manufacturing studies.

M50NiL is being developed as a high fracture toughness bearing steel. As a gear steel, the 40 MPa$\sqrt{m}$ fracture toughness, makes it a poor last of the materials being considered. M50NiL, however, can be readily vacuum carburized and in the integral gear/bearing configurations being currently designed into advanced transmission systems may well be considered as a high temperature gear material especially in applications where operating temperatures in excess of 300C are expected. It should be reiterated that the value of fracture toughness necessary for gear steels is not known.

CBS1000M was also developed by Timken as a higher temperature carburizing bearing steel than CBS600. It has comparable fracture toughness to M50NiL and can be carburized as readily as AISI 9310. At this time, it would not appear to be a strong candidate for use as an aircraft quality high temperature gear steel despite its ability to retain both its hardness and toughness after 1000 hours aging at 315C. Although it has been widely used as a high temperature carburizing grade bearing steel by Timken, considerable engineering and manufacturing effort must be expended before it can be seriously considered for use as a gear steel. The hoped for payoff vis a vis Vasco X-2M does not appear to be sufficiently great to justify the added costs.

AMAX B was developed as a compositional modification of CBS1000 at the AMAX Metal Research Center in Ann Arbor, Michigan. The major requirements for the development of this alloy were the retention of both the carburized surface hardness and fracture toughness after an aging cycle of 1000 hrs. at 315C. The approximate 2w/o less molybdenum and 1w/o less nickel in AMAX B would suggest a higher fracture toughness value than for CBS1000. Although no ASTME399 valid K_{Ic} test has been performed, the K_{Ic} for AMAX B appears to be considerably higher than for CBS1000. A great deal of metallurgical, engineering, and manufacturing effort must be carried out on AMAX B before it can be even considered for an aircraft quality high temperature gear application. It is felt, however, that its ease of carburizing, low alloy content, and high fracture toughness in addition to retention of both hardness and toughness after exposure for

1000 hrs. at 315C make it a very good candidate to replace Vasco X-2M. In fact, it may well be an excellent candidate steel for the integral gear/bearing/spline configurations found in advanced drive systems and be worth the cost of development. Before a more definitive projection of this alloy can be made, however, metallurgical studies (relatively low cost) must be carried out. The use of high temperature high performance carburized gears in advanced helicopter drive systems is expected to dominate the next decade. With the addition of elevated temperature transmissions, this domination is expected to accelerate. While Vasco X-2M, for technical as well as economic reasons, is the logical selection (at this time) for critical aircraft high temperature gear applications, it is expected that, within the next decade, at least one of the candidate gear alloys will compete successfully with Vasco X-2M. These successful candidate steels will no doubt be secondary hardening tool steels because of their greater scuffing resistance than AISI 9310 and their improved fracture toughness vis a vis VASCO X-2M.

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TABLE 1 - CHEMICAL COMPOSITIONS
OF GEAR STEELS

Steel	C	Si	Cr	Ni	Mo	W	V	Cu
AISI 9310	.1	.25	1.25	3.5	-	-	-	-
VASCO X-2M	.15	1.00	5.0	-	1.5	1.5	.5	-
CBS 600	.20	1.00	1.48	-	1.0	-	-	-
CARTECH X-53	.10	1.00	1.00	2.0	3.0	-	2.0	2.0
CBS 1000	.15	.5	1.00	3.0	4.0	-	.5	-
AMAX B	.12	1.00	1.00	2.25	2.25	-	0.5	-
M50NiL	.12	.25	4.5	3.0	4.0	-	1.2	-

TABLE 2 - SURFACE HARDNESS OF
CARBURIZED STEELS BEFORE
AND AFTER EXPOSURE FOR
1000 HOURS AT 315C. (REF. #4)

Surface Hardness of Carburized and Hardened Steels Hardness, R_C

Steel	Before[a]	After[a]
AISI 9310	61.2	52.3
CBS 600	65.4	58.8
VASCO X-2M	58.7	61.0
CARTECH X-53	58.4	59.5
CBS 1000	58.6	58.4
AMAX B	60.0	60.0
M50NiL	61.0	61.0

a - before and after exposure for 1000 hours at 315C.

TABLE 3 - FRACTURE TOUGHNESS OF CARBURIZED STEELS BEFORE AND AFTER EXPOSURE FOR 1000 HOURS AT 315C (REF. #4)

Fracture Toughness in Carburized Cases
(Corrected for Residual Stress Effects)

Steel	Carbon Content, %	Fracture Toughness, K_{I_c}[a] MPa$\sqrt{m}$ (ksi$\sqrt{in.}$) Before Exposure[b]	After Exposure	Change,[c] %
CBS600	0.50	53 (48)	47 (43)[d]	(10)
	0.75	45 (41)	36 (33)[d]	(8)
CBS1000	0.50	44 (40)	33 (30)	(10)
	0.75	21 (19)	26 (24)	(25)
X2(M)	0.50	45 (41)	21 (19)	(53)
	0.75	25 (23)	13 (12)	(48)
X-53	0.50	48 (44)	22 (20)	(54)
	0.75	36 (33)	23 (21)	(36)
SAE 9310	0.50	42 (38)	Too Soft	--
	0.75	27 (25)	Too Soft	--

[a] K_{I_c} determined using specimens with short crack lengths.

[b] Exposure to 315 C (600 F) for 1000 hours.

[c] Parentheses indicate the change was a decrease (negative).

[d] Some softening occurred but remained above HRC 58 (see Table 2).

TABLE 4 - DIFFUSION CALCULATIONS

$$D = D_o \exp(-Q/RT)$$

$$D_1 t_1 = D_2 t_2$$

$$t_2 = \exp(Q/RT_2 - Q/RT_1)\, t_1$$

D = DIFFUSION CONSTANT

Q = ACTIVATION ENERGY

R = GAS CONSTANT

T_1 = 230C + 273 = 505K

T_2 = 315C + 273 = 588K

t_1 = 2000 hrs. (at 230C)

t_2 = X hrs. (at 315C)

FOR Q = 57,700 Cal.; t_2 = 0.67 hrs.

Q = 30,000 Cal.; t_2 = 30 hrs.

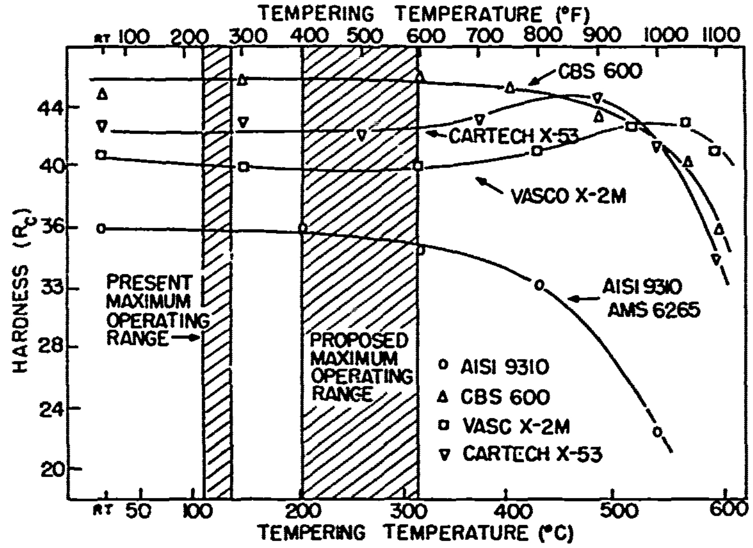


FIGURE 1 - EFFECT OF TEMPERING TEMPERATURE (2 + 2 HOURS) ON HARDNESS FOR SEVERAL GEAR STEELS

VASCO X-2

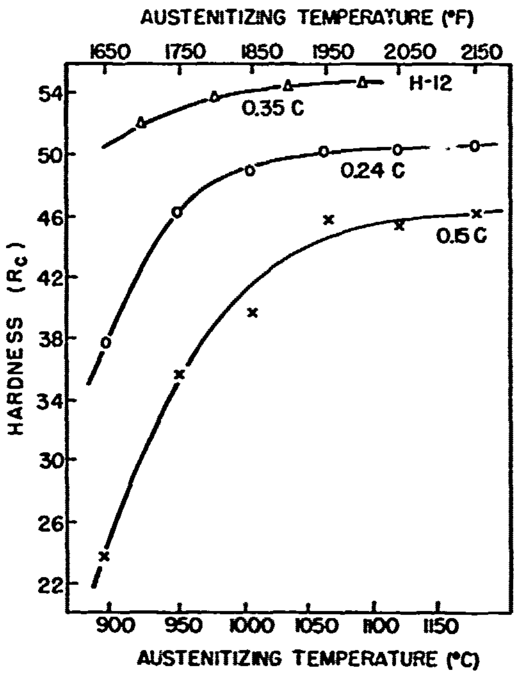


FIGURE 2 - EFFECT OF AUSTENITIZING TEMPERATURE ON HARDNESS FOR VASCO X-2

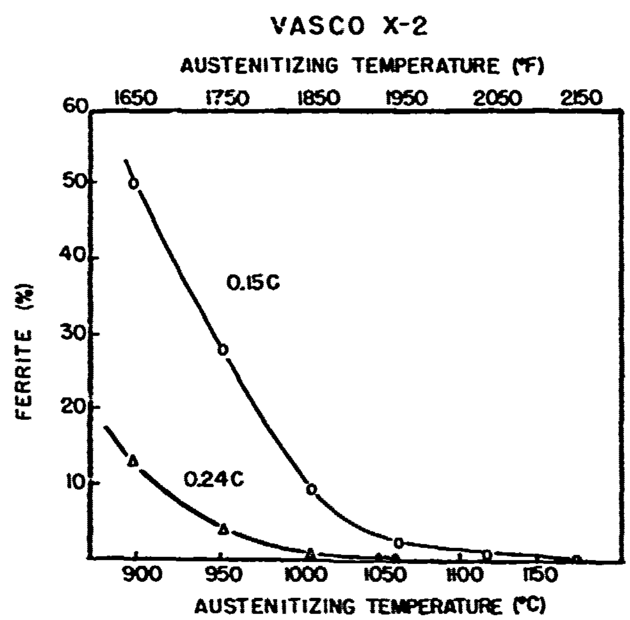
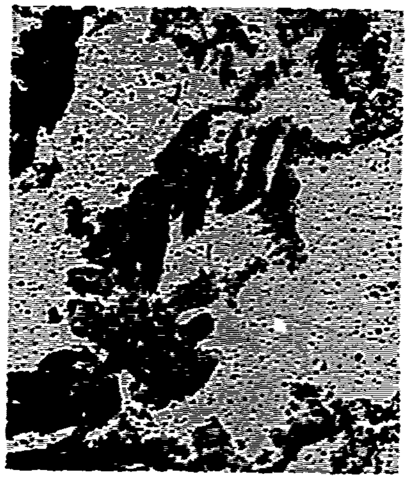
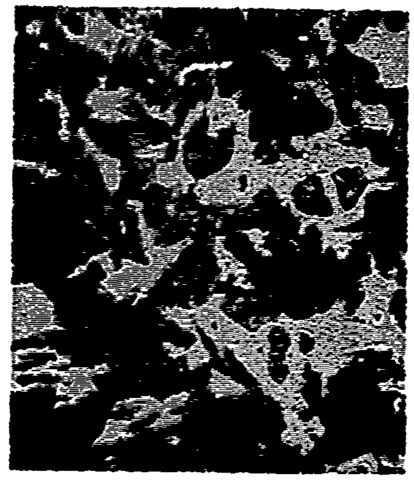


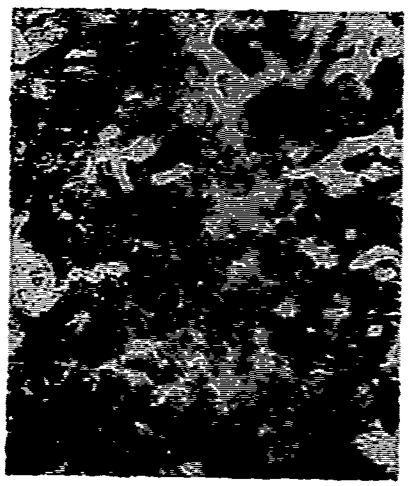
FIGURE 3 - EFFECT OF AUSTENITIZING TEMPERATURE ON AMOUNT OF PRIMARY FERRITE FOR VASCO X-2



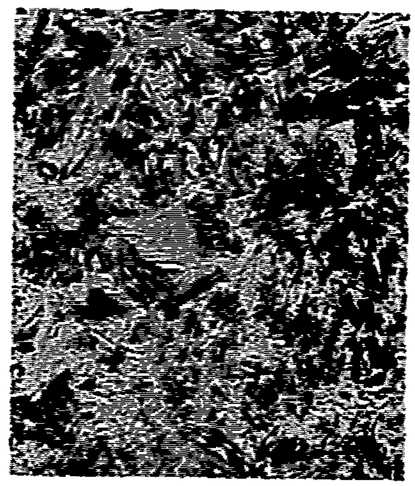
900C 500X



950C 500X



1000C 500X



1050C 500X

FIGURE 4 - EFFECT OF AUSTENITIZING TEMPERATURE ON THE MICROSTRUCTURE OF VASCO X-2M

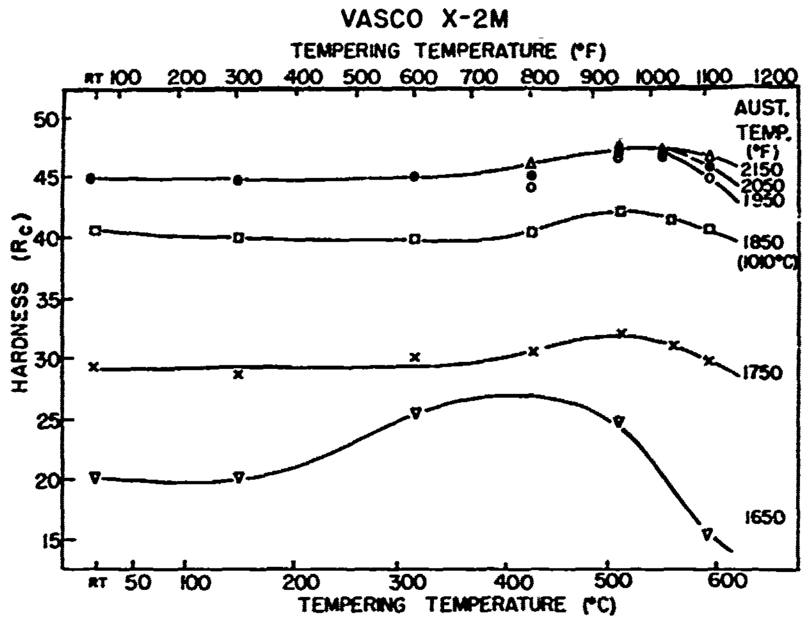


FIGURE 5 - EFFECT OF TEMPERING TEMPERATURE ON HARDNESS OF VASCO X-2M FOR SEVERAL AUSTENITIZING TEMPERATURES

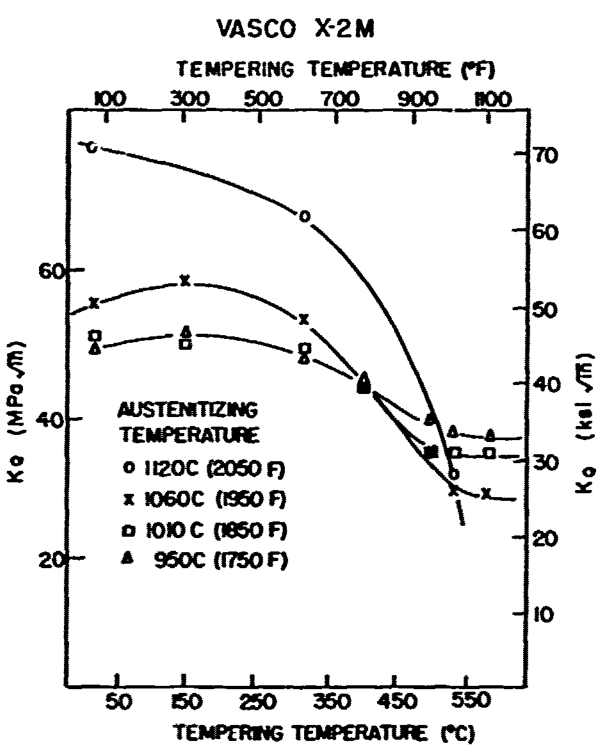


FIGURE 6 - EFFECT OF TEMPERING TEMPERATURE ON K_Q FRACTURE TOUGHNESS OF VASCO X-2M

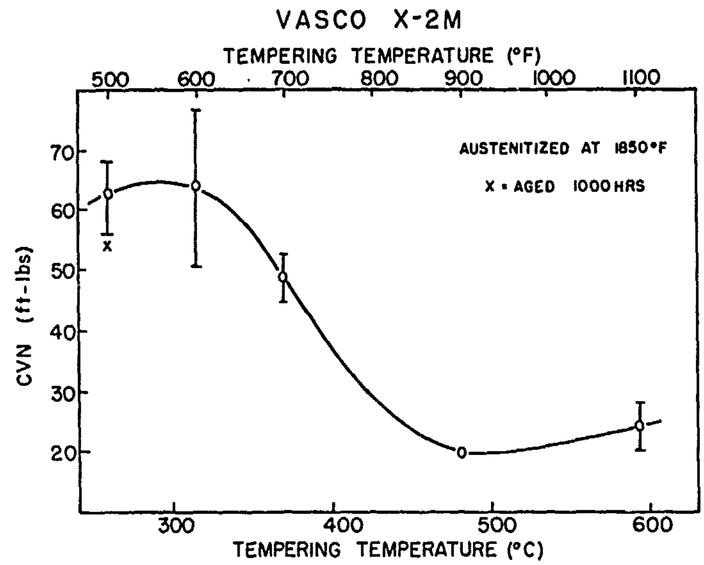


FIGURE 7 - EFFECT OF TEMPERING TEMPERATURE ON THE CHARPY ENERGY OF VASCO X-2M

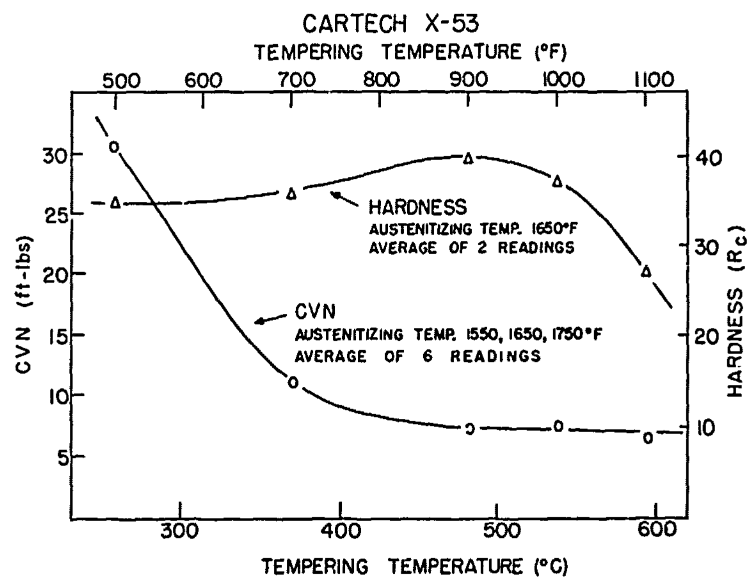


FIGURE 8 - EFFECT OF TEMPERING TEMPERATURE ON THE HARDNESS AND CHARPY ENERGY OF X-53

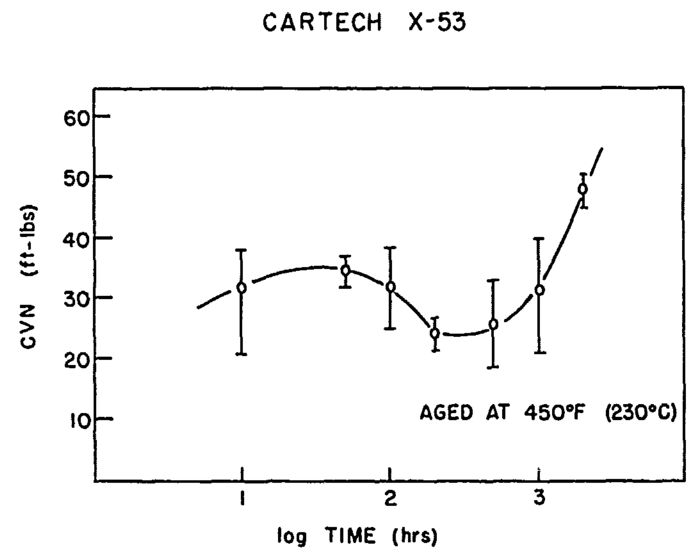


FIGURE 9 - EFFECT OF AGING TIME AT 230C ON CHARPY ENERGY OF X-53

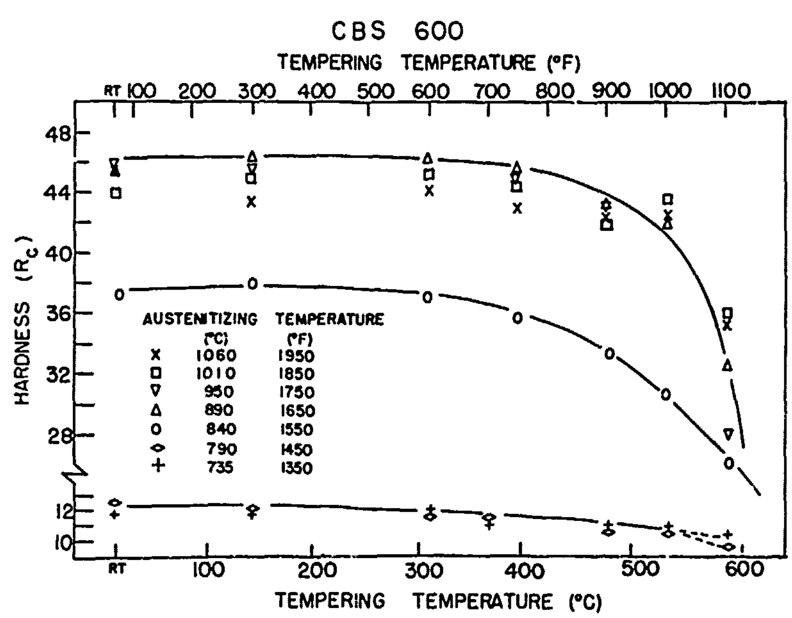


FIGURE 10 - EFFECT OF TEMPERING TEMPERATUPE ON HARDNESS OF CBS600 FOR SEVERAL AUSTENITIZING TEMPERATURES

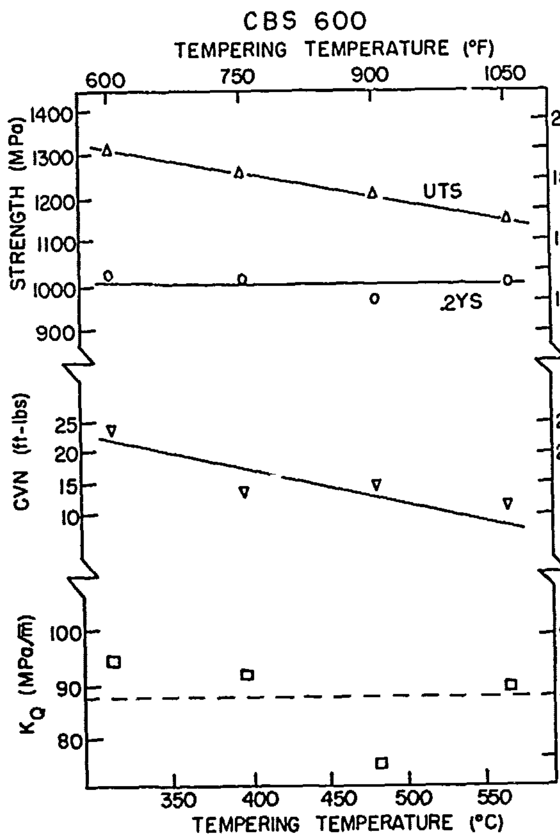


FIGURE 11 - EFFECT OF TEMPERING TEMPERATURE OF STRENGTH AND TOUGHNESS OF CBS600