Fatigue Crack Propagation in Carburized X-2M Steel

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The growth rates of fatigue cracks propagating through the case and into the core have been studied for carburized X-2M steel (0.14 C, 4.91 Cr, 1.31 Mo, 1.34 W, 0.42 V). Fatigue cracks were propagated at constant stress intensities, ΔK, and also at a constant cyclic peak load, and the crack growth rates were observed to pass through a minimum value as the crack traversed the carburized case. The reduction in the crack propagation rates is ascribed to the compressive stresses which were developed in the case, and a pinched clothespin model is used to make an approximate calculation of the effects of internal stress on the crack propagation rates. We define an effective stress intensity, $K_e = K_a + K_i$, where K_a is the applied stress intensity, $K_i = \sigma_i d_i^{1/2}$, σ_i is the internal stress, and d_i is a characteristic distance associated with the depth of the internal stress field. In our work, a value of $d_i = 11$ mm (0.43 inch) fits the data quite well. A good combination of resistance to fatigue crack propagation in the case and fracture toughness in the core can be achieved in carburized X-2M steel, suggesting that this material will be useful in heavy duty gears and in aircraft gas turbine mainshaft bearings operating under high hoop stresses.

I. INTRODUCTION

X-2M is a modification of the hot work die steel H-12 (AISI), wherein the carbon content is reduced to about 0.15 pct, and the material is used in the carburized condition. It is being utilized in the VIM-VAR (vacuum induction melted-vacuum arc remelted) condition to produce case-hardened gears for advanced helicopter transmissions.[1,2] In the development of this application there has been considerable work on the carburizing procedures[1,2] and on the fatigue properties of the core steel. In the course of our work on materials for operation as aircraft turbine mainshaft bearings at high values of DN (D = diameter of the bore in mm, N = revolutions per minute), where high tensile hoop stresses are developed, we evaluated carburized X-2M as a potential candidate. Carburizing procedures were developed in the course of this work, and these will be described elsewhere. Heat treatments followed the work of Cary.[3]

In the course of our work, fatigue cracks were propagated through the case and into the core, and the resultant data may be compared with those for two other materials, M-50NiL and CBS-1000M, which are reported in a companion paper.[4] This steel was sufficiently different from the other steels, however, to merit separate consideration. The carburized case is closer to a type A tool steel, rather than a high speed steel, and although these steels exhibit secondary hardening on tempering at about 480 °C (900 °F), they do not have the equivalent high temperature hardness of high speed steels.

Since carburized X-2M is being used for high performance gears, there is considerable interest in the resistance to spalling fatigue and in the fracture toughness of this material. This steel is more difficult to carburize than M-50NiL or CBS-1000M and has a greater tendency toward the formation of massive carbides at the surface. Nevertheless, successful carburization, with good carbon penetration, with surface hardness values of about 62 Rc, and without the presence of massive carbides, was achieved, and the fatigue properties of the case-core combination were evaluated.

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II. MATERIALS

The steel (0.14 C, 4.91 Cr, 1.31 Mo, 1.34 W, 0.42 V) was a VIM-VAR heat produced by Teledyne Vasco. The compact tension bars were cut from 2 ⅝ inch square bars as indicated in the previous paper,[4] and tensile bars were made from 1 1/32 inch diameter rods. The mechanical properties of X-2M are summarized in Table I and compared with those of M-50NiL and CBS-1000M. Tensile properties were measured using 4.75 mm (0.187 inch) diameter test bars with gage sections 50.8 mm (2 inches) long and with shoulder ends. Strain gages and extensometers were used to determine elongation, and grips with spherical seats were used to achieve alignment. The case properties were obtained from specimens which had been carburized completely through the cross section. Carburization was carried out in nitrogen-methanol-natural gas atmospheres at 955 °C (1750 °F) controlled by means of an oxygen-level probe. Typical carbon penetration curves and hardness profiles are shown in Figure 1. Satisfactory hardness levels were achieved without refrigeration. We note that the austenitizing temperature, 1065 °C (1950 °F), and the tempering temperature, 525 °C (975 °F), were somewhat higher than usual for these chromium steels, but the resultant retained austenite contents, as shown later, were low, and the hardness levels achieved are considered to be favorable in rolling contact fatigue resistance. Each specimen was tempered five times.

The fracture toughness of the core material was measured using compact tension specimens with dimensions 12.7 mm (0.50 inch) thick as indicated earlier;[3] these data are summarized in Table I. The fracture toughness of the core, $K_{Ic} = 51$ MPa $\cdot$ m$^{1/2}$ (46 Ksi $\cdot$ in$^{1/2}$) is equivalent to that of

Table I. Mechanical Properties

	X-2M		M-50NiL		CBS-1000M		M-50	
	Case	Core	Case	Core	Case	Core	(1)	(2)
austenitizing temperature, 5 times, °C	1065	1065	1095	1095	1095	1095	1095	1095
°F	1950	1950	2000	2000	2000	2000	2000	2000
tempering temperature, 5 times, °C	525	525	540	540	540	540	540	540
°F	975	975	1000	1000	1000	1000	1000	1000
hardness, Rc	62	44	62	45	61	44	63	61
0.2 pct yield, MN/m^2	2205	1240	2730	1210	2275	1270	2275	
Ksi	320	180	395	175	330	185	330	
ultimate tensile, MN/m^2	2690	1520	2900	1395	2755	1585	2620	
Ksi	390	220	421	202	400	230	380	
elongation, pct	4	16	5	17	4	16	1	
K_{Ic}, $MPa \cdot m^{1/2}$	19	51	17	52	14	49	18	23
$Ksi \cdot in^{1/2}$	17	46	15	47	13	45	16	21

(1) These data are taken from References 4 and 7 for M-50 specimens tempered 3 times.
(2) These data are for M-50 tempered 5 times.

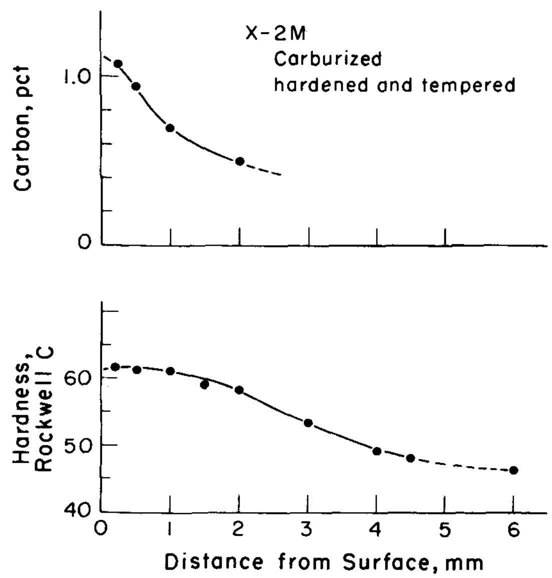

Fig. 1 — Hardness profile and carbon contents of carburized case in X-2M.

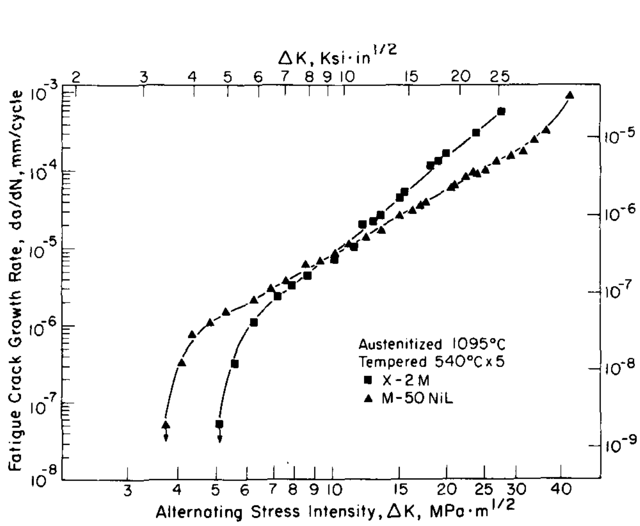

Fig. 2 — Fatigue crack propagation rates in X-2M and M-50NiL core steels.

M-50NiL and is considered to be adequate to resist fracture at the hoop stresses anticipated for bearings operating at DN = 3 × 10^6. Compact tension specimens, 6.3 mm (0.25 inch) thick were also carburized throughout the thickness, with the resultant hardness levels ranging from 62 Rc at the surface to 58 Rc at the center; the resultant fracture toughness values are also listed in Table I. The fracture toughness of the through-carburized X-2M was approximately equivalent to that of through-carburized M-50NiL. Through-carburized M-50NiL and CBS-1000M developed slightly lower fracture toughness than M-50, and this is probably due to the higher carbon contents of the carburized steels.

III. FATIGUE CRACK PROPAGATION

Fatigue cracks were propagated in compact tension specimens in a servohydraulic tensile machine under load control at 50 Hz, using a ratio of minimum to maximum tension, $R = 0.1$. Fatigue crack propagation rates, da/dN, for the core steel are shown as a function of the alternating stress intensity, ΔK, in Figure 2. Data for the core material M-50NiL are also shown in Figure 2 for comparison, and it is evident that the two core materials are similar, although X-2M does exhibit a slightly higher threshold value, ΔK_{th}. Fatigue crack propagation rates for the through-carburized material and for the core steel are shown in Figure 3 along with data for standard M-50[4] for comparison. The through-carburized X-2M has an unusually high threshold value, $\Delta K_{th} = 7$ MPa · $m^{1/2}$ (6 Ksi · $in^{1/2}$).

Fatigue cracks were also propagated at constant values of $\Delta K = 17, 20, 22$ MPa · $m^{1/2}$ (15, 18, 20 Ksi · $in^{1/2}$) through specimens which had been carburized in the notch to an operating depth of 2 mm (0.80 inch), with the operating depth defined as the distance within which a hardness of Rc 58 or higher is attained, and these fatigue crack propagation rates are shown in Figure 4. There is a sharp dip in the propagation rate at about 2 mm from the surface, and this minimum is similar but not as deep as that observed in M-50NiL. Crack propagation at a cyclic load with a constant

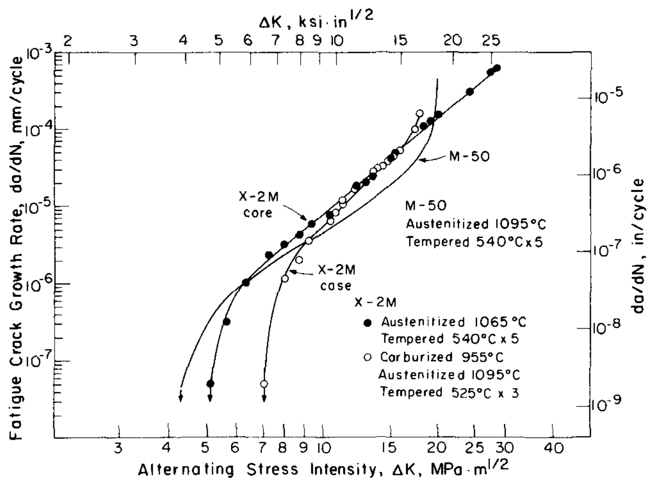

Fig. 3 — Fatigue crack propagation rates in case and core of X-2M and in hardened M-50.

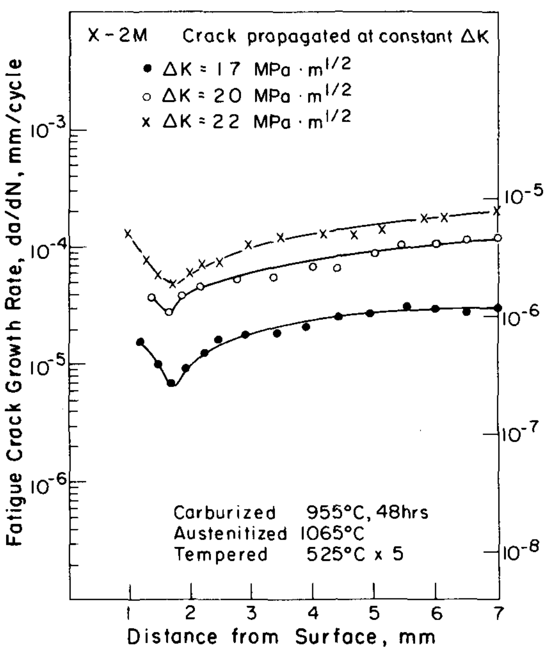

Fig. 4 — Fatigue crack propagation through carburized cases of X-2M at constant values of ΔK.

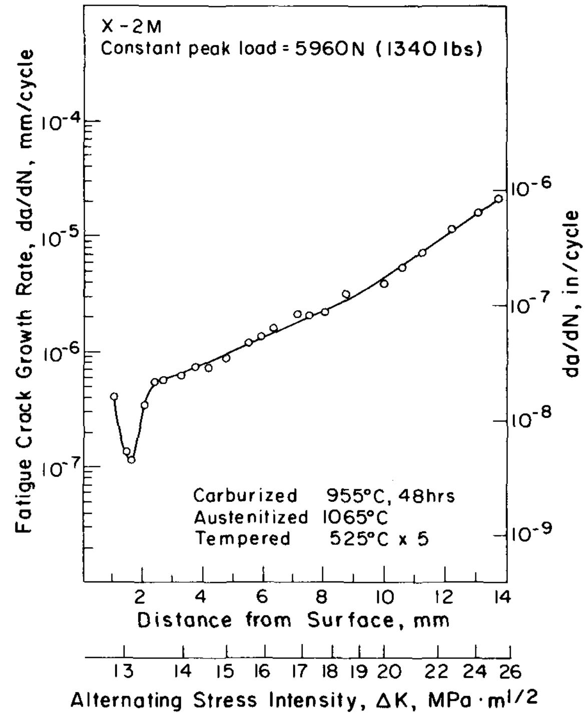

Fig. 5 — Fatigue crack propagation through carburized X-2M at a cyclic load with a constant peak value, 5960 N (1340 lbs).

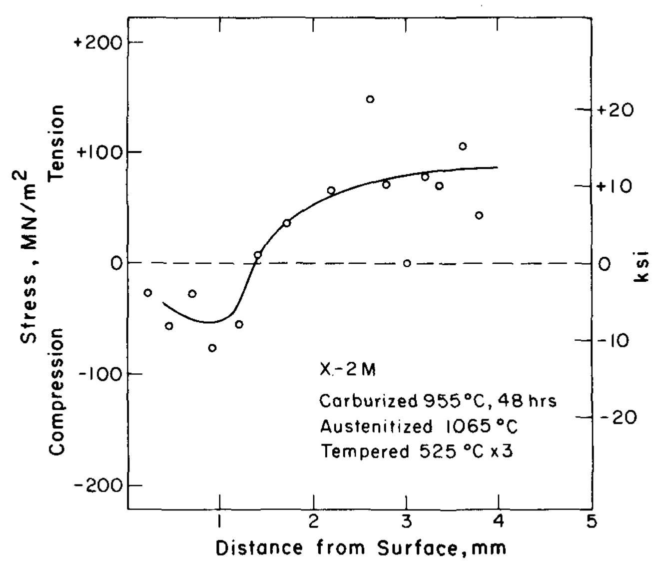

Fig. 6 — Residual stresses in carburized X-2M.

peak value of 5960 N (1340 pounds) is shown in Figure 5. Here, also, there is a minimum in the fatigue crack propagation rate at 2 mm, corresponding to $\Delta K = 13$ MPa · m$^{1/2}$ (12 Ksi · $^{1/2}$), but the notable crack arrest which was observed in M-50NiL was not observed here. Nevertheless, carburized X-2M showed a marked slowing of fatigue cracks through the carburized case, and the cracks progressed at the expected rates through the core after passing through the case. The core is also an effective crack stopper, with $K_{Ic} = 51$ MPa · m$^{1/2}$ (46 Ksi · in$^{1/2}$).

The residual stresses[5] and retained austenite contents[6] were measured by means of X-ray diffraction as a function of depth; these data are shown in Figures 6 and 7. Compressive residual stresses were observed to a depth of almost 2 mm (0.080 inch), but the compression was not as great as that in M-50NiL. The retained austenite contents in the case were low.

Figure 8 shows a scanning electron micrograph of the fatigue fracture surface of a carburized X-2M specimen at a distance of 2 mm from the surface of a specimen cycled at a constant $\Delta K = 20$ MPa · m$^{1/2}$, as indicated in Figure 4. These micrographs can be compared with similar fractographs in the companion paper on M-50NiL and CBS-1000M. Quasi-cleavage facets are prominent with faint striations in some regions. The facets are somewhat larger in X-2M than in M-50NiL or CBS-1000M, and the austenite

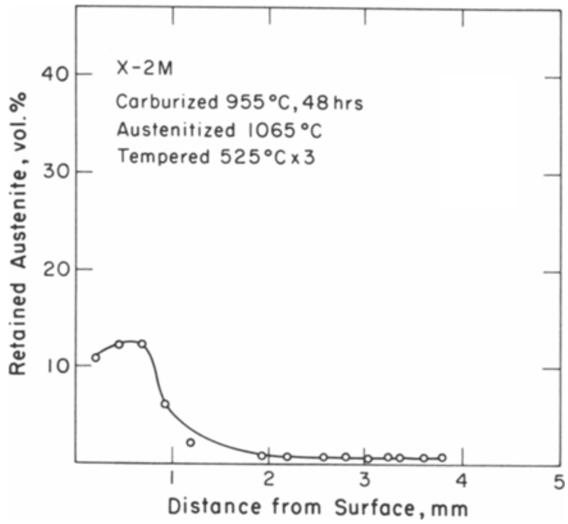

Fig. 7 — Retained austenite in carburized X-2M.

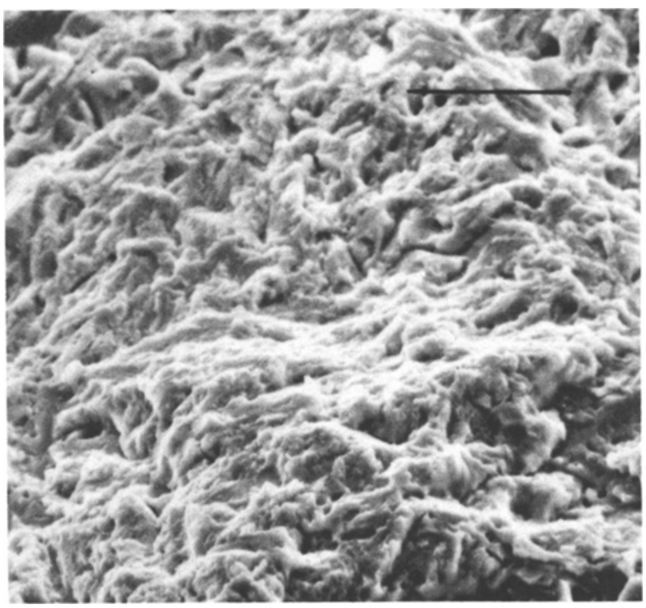

Fig. 8 — Scanning electron micrograph of the fatigue crack surface in carburized X-2M tested at $\Delta K = 20$ MPa $\cdot$ m$^{1/2}$. This fractrograph was taken at 2 mm from the surface, corresponding to the data in Fig. 4. The crack propagation direction was upward. The original magnification was 2000× and a 10 μm bar is indicated.

grain size, which is also faintly discernible here, appears to be larger in this material. The X-2M surface also appears to have somewhat fewer dimples. The undissolved carbides in X-2M were somewhat larger than those in the other two steels, and this may have also contributed to the slightly coarser austenitic grain size and the slightly larger dimples.

IV. DISCUSSION

The same short crack considerations which were discussed in the previous paper apply here as well. The strength level for this steel is high, as shown in Table I, and a short crack would thus be of the order of 10 μm. The dips in the da/dN curves are not as deep as in M-50NiL, but the com-

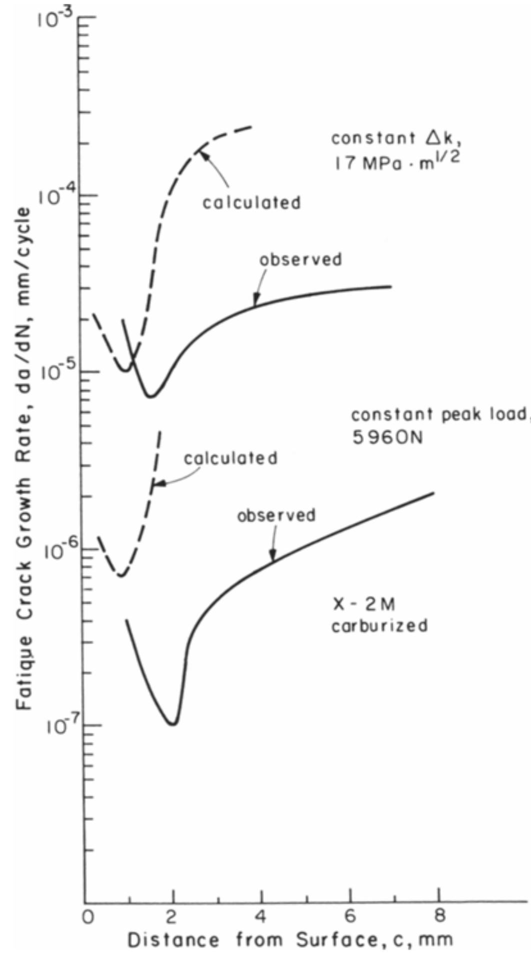

Fig. 9 — Calculated and observed values of da/dN in carburized X-2M.

pressive residual stress minimum is not as low as the one in M-50NiL. We conclude therefore that the da/dN minimum is proportional to the residual compressive stress.

We apply here the same pinched clothespin model used for similar data obtained with M-50NiL.[4] We define an effective value of stress intensity, K_e, where

$$K_e = K_a + K_i \qquad [1]$$

K_a is the applied stress intensity calculated from the applied load and the test specimen geometry, and $K_i = \sigma_i d_i^{1/2}$. The internal stress, σ_i, is taken as positive for tension and negative for compression, and d_i is a characteristic distance associated with the depth of the internal stress pattern arising from the carburized case. We have assumed a value, $d_i = 11$ mm (0.42 inch), as in our calculations for M-50NiL.

Figure 9 shows a comparison between the observed and calculated values of da/dN for cracks propagated at $\Delta K = 17$ MPa $\cdot$ m$^{1/2}$ (Ksi $\cdot$ in$^{1/2}$) and at a constant cyclic peak load, 5960 N (1340 pounds). In arriving at the calculated values of da/dN, we first calculated K_i at each depth, using the residual stresses given in Figure 6, and then calculated the value of K_e. This value was assumed to be equivalent to ΔK in the fatigue crack propagation studies shown for the case in Figure 3. We thus arrived at a new value of da/dN for each depth, and these are reported in Figure 9.

It is evident that this approximate model reproduces the shape of the da/dN curve in the case. As the crack deepens, the effects of stress relaxation become more important and our simple model is no longer adequate. As in the M-50NiL case, the minimum in da/dN does not coincide exactly with the observed value, probably because the internal stresses were measured on a flat surface and not directly in the notch. Nevertheless, the agreement between the experiment and the model is a reasonable first approximation and serves to provide a framework for thinking about crack propagation through carburized steels.

V. CONCLUSIONS

A comparison of carburized M-50NiL, X-2M, and CBS-1000M indicates that X-2M is almost as effective as M-50NiL in slowing a propagating fatigue crack. We did not observe the crack arrest which was obtained in M-50NiL, but there was a marked slowing as cracks propagated through the case. We ascribe the slowing of the crack to the presence of compressive residual stresses in the case.

Our simple model, wherein we define an effective stress intensity, with $K_e = K_a + K_i$, and $K_i = \sigma_i d_i^{1/2}$, appears to account for the crack behavior in the case reasonably well. A value of d_i = 11 mm (0.43 inch), which we associate with a characteristic depth of the stress distribution due to carburizing, seems to provide a reasonably good match with the observed values of crack propagation rates.

X-2M thus appears to be a good selection for applications such as gears and rolling contact bearings, provided that the carburizing is such as to induce residual compressive stresses in the case. Residual tensile stresses would be unfavorable, as was observed in our work on CBS-1000M, but carburized X-2M appears to develop compressive residual stresses in the case under the carburizing conditions used here.

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