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NOMENCLATURE

q = notch sensitivity = $\frac{K_f - 1}{K_t - 1}$

K_f = fatigue strength reduction factor from notched fatigue tests, $K_f = \frac{\sigma_f}{\sigma_{fK_t}}$ where the fatigue strengths are taken at the same life.

K_t = theoretical elastic stress concentration factor

a = one-half the crack length (of an interior crack)

C, m = material constants

K = stress intensity factor

N = number of cycles, subscript f is number of cycles at failure

σ_f = fatigue strength limit, subscript m indicates the mean value.

σ_{fK_t} = notched fatigue strength limit

R = stress ratio, $\frac{\sigma_{min}}{\sigma_{max}}$

σ = stress, ksi (MPa) subscript u = ultimate

$\tilde{s}$ = statistical parameter

B_x = stress-life characteristics for various (x) percentiles of the population

F_f = maximum failure rate at a given stress level

V_c = critically stressed volume of material

d = grain mean diameter of the material

INTRODUCTION

It is well recognized that fatigue is a major source of compressor valve failures(1). Therefore, high fatigue strength should have prime consideration in selecting a valve material. The present paper concerns itself with presenting fatigue data on some potential valve materials.

Premature failures and greatly reduced fatigue strengths are usually caused by fatigue cracks originating from stress concentrating material flaws or geometrical discontinuities present in the critically stressed areas of the valve. Volume defects like slag inclusions, second phase hard particles, voids, etc., may enter during material manufacturing; and surface defects, like scratches, burrs, micro-cracks, etc., may enter during blanking or stamping, processing, and handling of the coil stock and finished valves. Geometrical discontinuities, like a hole, a groove, a fillet, etc., are usually a part of the valve design. All these defects have varying sizes, shapes, distributions, and severity, and would have different degrees of effectiveness in different materials, section sizes, and loading conditions(2). Under this extremely complex situation, the conventional smooth fatigue S-N curves or Wöhler diagrams are insufficient information for the designer. He also requires some form of data on the quantitative evaluation of defect sensitivity of different materials under representative geometry, loading and environmental conditions. This is particularly important for compressor valve materials because these are mostly high strength steels with ultimate tensile strength, σ_u in the range of 200 to 300 ksi (1400 to 2100 MPa) having limited ability to deform plastically near the defects and thereby partially relieve the stress concentration. In addition, the valves usually require a very thin section, in the range of 0.006 to 0.025 inch (0.152 to 0.635 mm) in which fatigue crack initiation and propagation characteristics may be quite different from those in larger sections.

Recent developments in Notch Analysis of Fracture(3-5) and Sharp Crack Fracture Mechanics(6) have contributed significantly in providing experimentally determinable parameters for a quantitative characterization of different materials for their flaw sensitivity under fatigue loading. In these approaches, the effectiveness of random, natural flaws is simulated by a mechanically introduced notch or a crack in laboratory specimens. The deformation and fracture resistance of the local material near the notch root or the crack tip is assumed to represent the actual resistance of the material against real defects. Accordingly, the notch sensitivity factor, q[7], for cases where crack initiation is the controlling stage, and the crack growth relationship, $\frac{da}{dN} = C\ \Delta K^m$, (where ΔK is the stress intensity factor range, and C and m are material constants) for cases where crack propagation is the controlling stage, characterize the fatigue behavior of materials to be expected in actual service.

The main objective of this paper is to present fatigue data on some prospective valve materials; namely, two specialty high carbon steels with RDC designations, # 2150 and # 2119, a foreign plain carbon steel with RDC # 4958, and a stainless steel with RDC #455, using the above approach. Since the fatigue of high strength materials in thin sections is completely dominated by the initiation stage [8], only notch fatigue tests were performed to determine fatigue strength and q values.

MATERIALS

Table I gives the nominal chemical composition and Table II gives the thicknesses and conventional mechanical properties of all the four materials tested. The two RDC plain carbon steels, # 2150 and # 2119, and the foreign plain carbon steel have their compositions in the same range (comparable to AISI 1095) except for the phosphorus and sulphur contents where the foreign steel shows a better control. The RDC stainless steel has several alloying elements in addition to Cr and Ni. It can be seen, Table II, that there are nominally two thicknesses in which the material strips were available, 0.008 inch (0.203 mm) and 0.012 inch (0.305 mm).

EXPERIMENTAL PROCEDURE

(1) Specimens

The general shapes of the smooth and notched fatigue strip specimens are shown in Figures 1(a) and 1(b), respectively. Because of limitations on the available strip widths, the specimen geometries could not be maintained the same for all the materials. The width of the test section of the smooth specimens, Figure 1(a), of the stainless steel was 0.380 inch (9.6 mm) instead of 0.5 inch (12.7 mm). A standard notch of root radius, ρ = 0.007 inch (0.178 mm) was introduced in all the notched fatigue specimens tested. However, the stainless steel specimens had dimensions W = 0.56 inch (14.2 mm), a = 0.105 inch (2.66 mm), and d = 0.35 inch (8.9 mm) instead of those shown in Figure 1(b). This resulted in a K_t of 5.5 instead of 5.25 for the stainless steel specimens.

The specimens were blanked directly from the as-received coil stock. The edges of the smooth specimens were deburred and polished with a 400 grit stone. The notch profile of the notched specimens was deburred and polished with lapping compound on a 0.014 (0.356 mm) dia. mandrel. Polishing was done under a 10x microscope until all transverse blanking marks were removed. No other finish or special treatments were given.

(2) Testing

The testing program was based on the staircase method recommended by ASTM[9]. A Sonntag universal fatigue testing machine with a fixed frequency of 30 Hz was used for fatigue loading in pulsating tension with a stress ratio of $R = \sigma_{min}/\sigma_{max} = 0$. The cut-off life for the definition of a run-out was set at 2×10^6 cycles. The stresses were raised or lowered by a fixed increment. At the end of the testing of a particular material, about 6 to 9 specimens formed a group or sample size at a particular stress amplitude near the fatigue

TABLE I

CHEMICAL COMPOSITION OF THE VALVE MATERIALS TESTED

Material	% C	Mn	P	S	Si	Cr	Ni
RDC Plain Carbon Steel, # 2150 and # 2119	0.96-1.03	0.30-0.45	0.025 max	0.020 max	0.15-0.30	--	--
RDC Stainless Steel #455	0.05 max	0.50 max	0.025 max	0.025 max	0.50 max	11-12.5	7.5-9.5
	(0.50 max Mo, 0.80 - 1.40 Ti, 1.50 - 2.50 Cu, 0.10 - 0.50 Cb + Ta)						
Foreign Plain Carbon Steel # 4958	1.00	0.45	0.006	0.005	0.25	--	--

limit, and about 27 to 30 specimens formed the total test population. All the tests were carried out at room temperature and in normal air environment.

RESULTS

The staircase method is especially suitable for

TABLE II

CONVENTIONAL MECHANICAL PROPERTIES OF THE MATERIALS TESTED

Material	Thickness Inches (mm)	Tensile Strength ksi (MPa)	E psi (MPa)
RDC Plain Carbon Steel # 2150	0.008 (0.203)	297 (2079)	29.9×10^6 (209×10^3)
RDC Plain Carbon Steel # 2119	0.012 (0.305)	286 (2002)	29.9×10^6 (209×10^3)
RDC Stainless Steel #455	0.010 (0.254)	254 (1778)	29×10^6 (203×10^3)
Foreign Plain Carbon Steel # 4958	0.012 (0.305)	278 (1946)	--

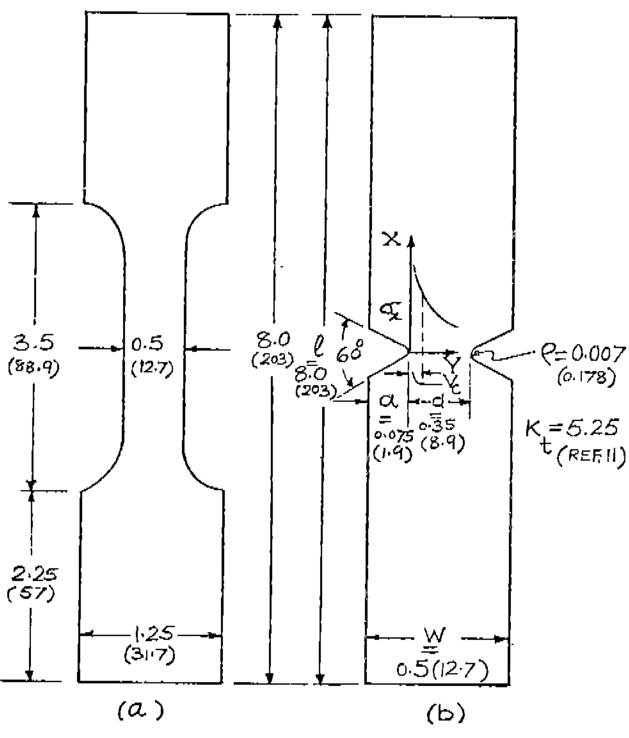

FIGURE 1

Fatigue Specimens from the Strip Material, (a) for smooth fatigue testing, (b) for notched fatigue testing.

estimating the mean fatigue strength at a given life when the sample size is rather limited, as in this case(9). Normal distribution of the fatigue life is presumed in this procedure. Using the appropriate statistical formulas, the mean fatigue strength σ_{mf} and the standard deviation $\bar{s}$ were calculated for each of the materials in both the smooth and notched configurations. Then, the standard deviation was expressed as % coefficient of variation, CV, defined by $\% \text{ CV} = (\bar{s}/\sigma_{mf}) \times 100$. All these values are listed in Table III.

For design considerations, it is usually desirable to obtain a probability σ-N curve for the material showing different failure rates including B_{10} values; i.e., fatigue strength for a 10% failure rate of the total population at any desired life, not necessarily the pre-assigned cut-off life of 2×10^6 cycles. This was accomplished by analyzing the same staircase fatigue data using the Weibull cumulative distribution function(9).

There are three parameters of interest in the fatigue data which are interrelated; the stress level, the average fatigue life, and the cumulative failure probability of the population. By keeping one variable constant, the relationship between the other two can be found.

For example, the staircase data for RDC # 2150 were partitioned by stress level and plotted on the Weibull probability paper, Figure 2, using mean rank of the specimens as the ordinate and life as the abscissa. This gives the relationship between the probability of failure and life at a given stress level. If the data actually follow the Weibull distribution function, they will plot as straight lines, as is the case in Figure 2.

TABLE III

A SUMMARY OF FATIGUE TEST RESULTS ON VALVE MATERIALS

Material	Thick-ness, t Inches (mm)	Smooth Fatigue σ_{mf} KSI (MPa)	Smooth Fatigue Median, B_{50} KSI (MPa)	Smooth Fatigue B_{10} KSI (MPa)	K_t	Notch Fatigue σ_{mf} KSI (MPa)	Notch Fatigue Median, B_{50} KSI (MPa)	Notch Fatigue B_{10} KSI (MPa)	K_f	q
RDC # 2150	0.008 (0.203)	151.6 (1061) (7.09%)*	147.5 (1032)	138.0 (966)	5.25	51.25 (358) (2.26%)	47.5 (333)	42.5 (297)	2.96	0.46
RDC # 2119	0.012 (0.305)	137.5 (962) (6.88%)	132.5 (927)	122.5 (857)	5.25	41.75 (292) (5.70%)	41.5 (293)	38.3 (268)	3.29	0.54
455 Stainless	0.010 (0.254)	135.3 (947) (1.64%)	135.0 (945)	131.0 (917)	5.5	39.3 (275) (5.2%)	39.3 (275)	35.75 (250)	3.44	0.54
Foreign # 4958	0.012 (0.305)	136.7 (956) (7.28%)	137.5 (962)	127.5 (892)	5.25	43.75 (306) (9.5%)	43.5 (305)	37.0 (259)	3.12	0.498

* The percentages in the parentheses are the % CV values

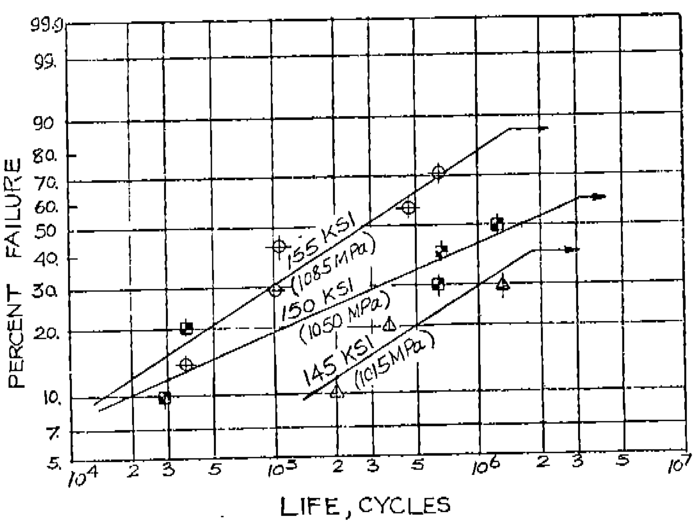

FIGURE 2

Weibull Plot for RDC # 2150 High Carbon Steel, Plain Specimen Fatigue Test

It is seen that the cumulative failure rate in the sample increases as the life desired increases. The horizontal line (and an arrow at the end) drawn for all the stresses represents the F_f value for the respective stresses(9).

F_f gives an estimate of the maximum failure rate expected in a sample at a given stress. If the cut-off life for each sample or group tested at different stresses is the same; e.g., 2 x 10^6 cycles; F_f provides a convenient basis for relating the maximum cyclic stress with the probability of failure. This relationship is shown in Figure 3(a) by a smooth curve where the data points represent F_f for the given stress. The probability of failure in the population increases as the stress level increases.

Figure 4 is the final, desired form of the original fatigue data. This gives the relationship between the maximum cyclic stress and the fatigue life in cycles for a given percentage of failure probability. This probability σ-N curve was derived from Figures 2 and 3(a). The slanting part of the curves is obtained by plotting stresses and corresponding life values for the percentage failure rates of 10% and 50% (median life) in Figure 2. The 50% failure rate curve or B_{50} values will give the median fatigue strength. The horizontal parts were obtained from the curve of Figure 3(a) by noting the stress levels for the above-mentioned failure rates. These are the stresses for which maximum fatigue life will be obtained for the given failure rate. Therefore, these stresses may be termed as fatigue strength limits for the various probabilities. If the stress is below this limit, the average fatigue life of a sample with the same failure rate will be longer than indicated by the point of intersection such as "f" on the 10% line.

It should, however, be noted that the horizontal line (fatigue limit) of the 50% failure curve in Figure 4 indicates the mean fatigue strength obtained from the staircase method, Table III, and

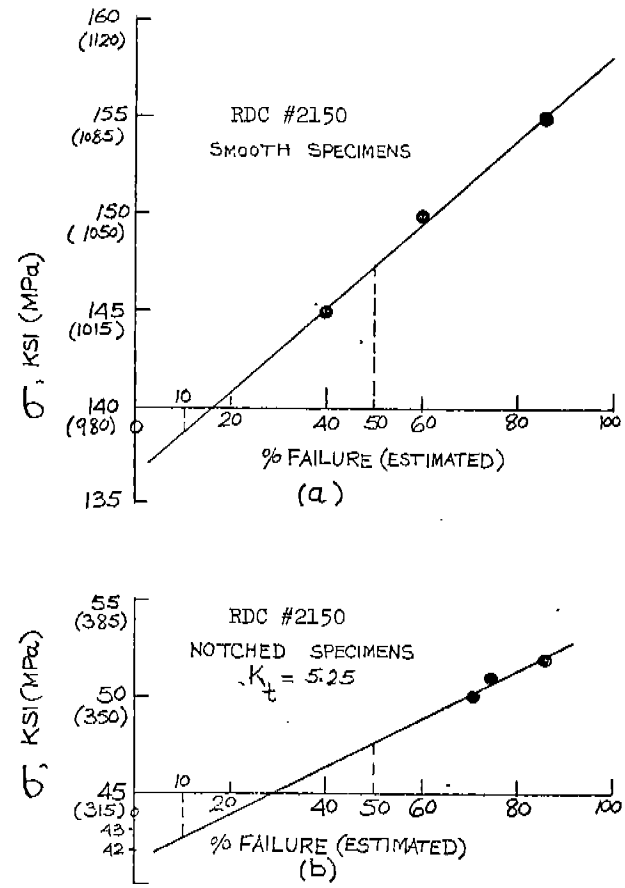

FIGURE 3

Failure Probability Characteristics of: (a) smooth and (b) notched specimens, RDC # 2150 High Carbon Steel

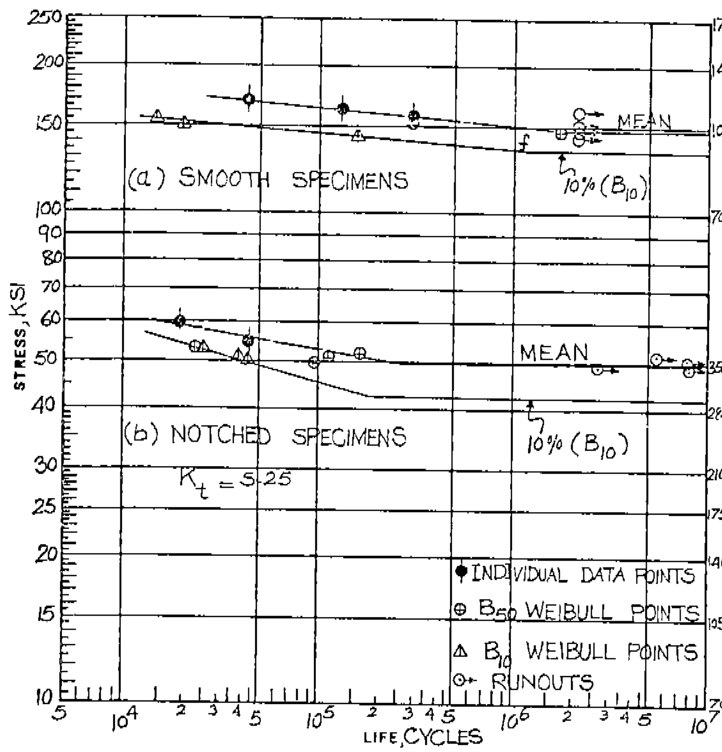

FIGURE 4

RDC # 2150, High Carbon Steel σ-N Curves from: (a) smooth and (b) notched (ρ = 0.007", K_t = 5.25) specimens. R = 0.0

not the median strength obtained from the Weibull method, Figure 3(a). The reason for doing this is that, unlike the mean, the median is not very sensitive to a small number of extreme variations. The fact of survivors after 2 x 10^6 cycles is shown by run-out symbols in Figure 4 for the tests performed at different stress levels.

The same procedure was followed for the notched fatigue data of RDC # 2150, to arrive at Figure 3(b) and the lower curves of Figure 4. Similar probability σ-N curves were obtained for the remaining three materials as shown in Figures 5, 6, and 7 for RDC # 2119; stainless, and the foreign plain carbon steel, respectively. The values of the median fatigue strength (B_{50}) and 10% failure probability (B_{10}) strength of the materials tested are also tabulated in Table III. It can be seen that the presence of a notch of K_t of about 5 reduces the fatigue strength to about one-third of the corresponding smooth value.

DISCUSSION

(1) Fatigue Data

It should be noted that the mean fatigue strength estimates by the staircase method and the corresponding median fatigue strength estimates by the Weibull method, Table III, are fairly close to each other in all the cases analyzed. This also suggests that in the present data the fatigue strength at a given life follows a normal distribution function.

With smooth specimens, the mean fatigue strength and B_{10} values of all the materials tested are comparable to each other, except for RDC plain carbon steel # 2150 which was superior to the others possibly because of a thinner specimen section (0.203 mm instead of 0.305 mm). From these results, the stainless steel does not appear to be any stronger in fatigue than the high carbon steels. However, the scatter in the stainless data (measured by % CV) is comparatively small, which might be expected because of a greater corrosion resistance and relative freedom from harmful slag inclusions.

The notch fatigue performance of the materials should be judged from the values of the fatigue strength reduction factor, K_f, in relation to the theoretical elastic stress concentration factor, K_t, of the notch. If only elastic stresses

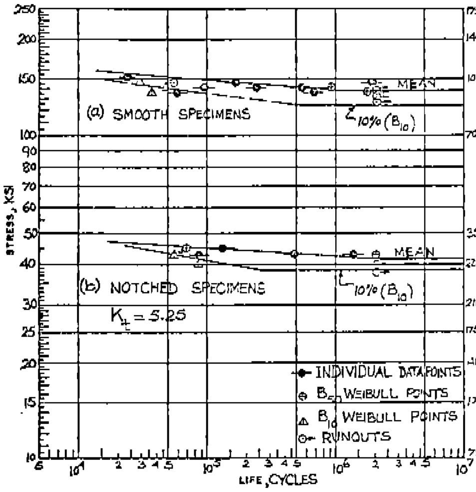

FIGURE 5

RDC # 2119 High Carbon Steel σ-N curves from: (a) smooth and (b) notched (ρ = 0.007", K_t = 5.25) Specimens. R = 0.0

are involved and the material follows a maximum normal stress failure criterion, then $K_f = K_t$. Theoretically, this is the maximum value K_f can have. But because of plasticity, relaxation and redistribution of stresses near the notch root in certain cases, and because of the "size effect" phenomenon, K_f is usually smaller than K_t. This is more so when the notch root radius is small compared to a grain diameter. Then the critically stressed volume near the notch root is small and, consequently, the probability of encountering a critical flaw in this volume, for early crack initiation, is small.

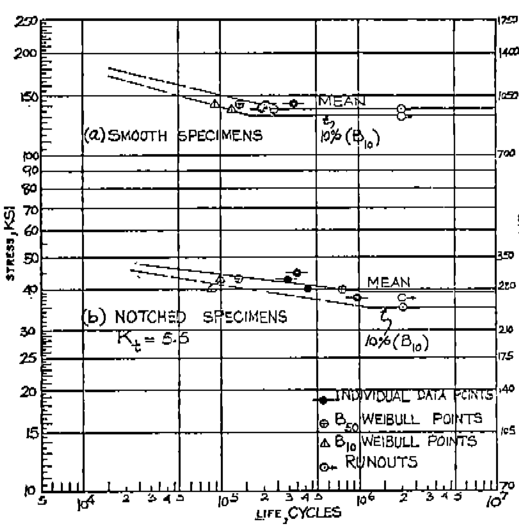

FIGURE 6

455 Stainless Steel σ-N curves from (a) smooth specimens and (b) notched (ρ = 0.007", K_t = 5.5) specimens. R = 0.0

A convenient basis for comparing fatigue notch sensitivity of different materials is the factor "q" defined by: $q = (K_f - 1)/(K_t - 1)$. Since K_f is usually smaller than K_t, q is usually smaller than 1. The smaller the value of q, the less notch sensitive is the material or conversely for perfect notch sensitivity, q = 1. It should be noted, however, that for q to have any meaningful role in comparing notch sensitivity, the notch root radius, ρ should be maintained the same because K_f may vary with ρ (notch size effect) even if K_t is the same. The K_f and q values of all the materials are shown in Table III. Here, again, we can see that the notch fatigue performance of all the materials tested is about the same. The stainless steel is as notch sensitive as the carbon steel. In fact, RDC # 2150 High Carbon Steel appears to be the least notch sensitive among these materials.

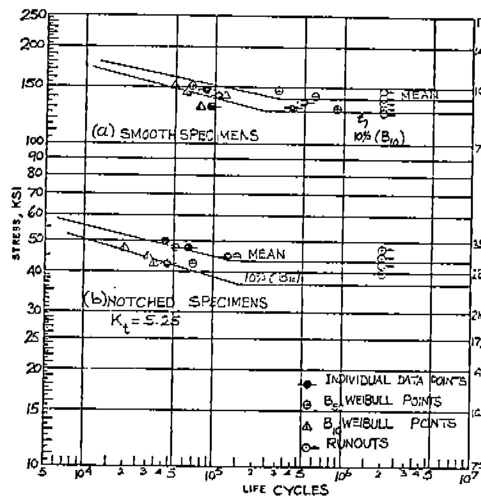

FIGURE 7

Foreign Plain Carbon Steel, RDC # 4958. σ-N curves from (a) smooth and (b) notched (ρ = 0.007", K_t 5.25) Specimens. R = 0.0

(2) The Inclusion Content

Slag inclusions under certain circumstances can act as stress concentrators or notches and reduce the fatigue strength appreciably. However, depending upon the chemical nature (e.g., ductile silicates and sulfides vs. hard and brittle oxides), size, shape, and distribution, some inclusions may be less harmful than others. A detailed analysis is beyond the scope of this study, but it was considered useful to observe the relative cleanliness of the materials tested. Figure 8 shows their polished and unetched appearance through an optical microscope. An attempt was made to select the dirtiest possible area in the section mounted. The foreign sample, as expected from the chemical composition, does appear a little cleaner than the other carbon steel, while the stainless is the cleanest of all.

FIGURE 8(a)

RDC # 2150 Plain Carbon Steel. Polished and unetched photomicrograph. 400 x

FIGURE 8(c)

455 Stainless Steel. Polished and unetched photomicrograph. 400 x

FIGURE 8(b)

RDC # 2119 Plain Carbon Steel. Polished and unetched photomicrograph. 400 x

FIGURE 8(d)

Foreign Plain Carbon Steel, RDC # 4958. Polished and unetched photomicrograph. 400 x

There is a distinct difference between the fatigue performance of the two RDC Plain Carbon Steel. Although an apparently larger size of the slag inclusions in RDC # 2119, Figure 8(b), could have been a contributing factor towards downgrading its fatigue strength compared to that of RDC # 2150; the thickness difference is believed to be the major factor. Monotonic tension testing shows that, other parameters being identical, a thinner strip has a higher tensile strength than a thicker strip. For instance, RDC 2150 (thickness = 0.203 mm) is about 4% stronger than RDC # 2119 (thickness = 0.305 mm), Table II. And if crack initiation is the controlling phenomenon, a stronger material also has a higher smooth fatigue strength[4]. In steels of σ_u of 100 ksi (700 MPa) or over, a relation of $\sigma_{m.f.} = 0.5\ \sigma_u$ is generally acceptable[10]. And if crack initiation is the controlling stage, the notch fatigue strength is proportional to the smooth fatigue strength[5]. Figure 9 shows a typical fracture surface of a smooth fatigue specimen of the stainless steel. The small flat area on the left side edge represents the area of crack initiation and sub-critical crack growth. The rest of the section has a slanting surface representing a fast, shear crack growth. This means that in the present testing crack initiation was the controlling stage. Therefore, assuming that RDC # 2150 and # 2119 represent identical materials, a higher smooth and notch fatigue strength for # 2150 is expected just because of the thickness difference. The experimental values show a 9% increase in the smooth fatigue and an 18.5% increase in the notch fatigue strength in this particular instance.

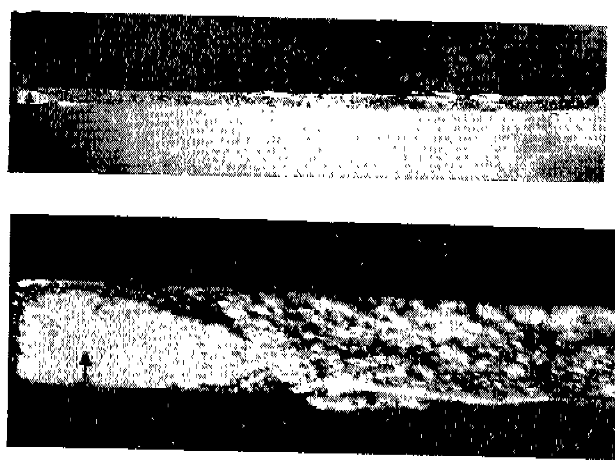

FIGURE 9

Fatigue Fracture Surface of a Smooth 455 Stainless Steel Specimen Showing the Predominance of the Crack Initiation Stage (left end flat area marked by an arrow) in the Total Fatigue Life.

(3) The Critically Stressed Volume and the Notch Size Effect

It is clear from Table III that RDC # 2150 is not only stronger in fatigue, but also shows a lower notch sensitivity ($q = 0.46$ as compared to $q = 0.54$ for # 2119). This can be explained on the basis of the concepts of the critically stressed volume and the notch size effect. If the hypothesis of the statistical flaw distribution in real materials is accepted, the probability of the occurrence of a critical, damaging flaw and hence the probability of failure increases with the increasing volume of the component[10]. But in situations where the high stresses are concentrated in a local area, such as in a notched fatigue specimen, only the flaws occurring in the critically stressed volume would be effective in initiating a crack. Using an approximate elastic stress field solution ahead of the notch and assuming that the linear dimension of the critically stressed volume, V_c, extends only up to the limit where $\sigma_x \geqslant 0.9\ \sigma_{max}$, Figure 1(b), it can be shown that[4]:

$$V_c = 7.2\ \rho^2\ t \times 10^{-3}\ \text{inch}^3 \geq \frac{d^2}{4}\ t$$

$$= 118\ \rho^2\ t \times 10^{-3}\ \text{cm}^3$$

where ρ is the root radius of the notch and t is the thickness of the specimen. Thus, if the thickness is the same, the V_c and hence the failure probability will decrease with decreasing ρ, which is the notch size effect. If ρ remains the same, as in the present testing, a decrease in t will reduce V_c and hence increase the fatigue strength. This latter effect is considered to be the major factor in apparent upgrading of the notch fatigue performance of the RDC # 2150, as compared to the RDC # 2119. Note that the critical volume has a minimum size roughly equal to the grain radius squared times the material thickness. This restriction provides an upper limit on K_t as defects become smaller and sharper. The result is that the effective notch root radius never falls below about half the grain diameter.

CONCLUSIONS

The smooth and notch fatigue tests performed on the three plain carbon steels; two RDC plain carbon steels and one foreign plain carbon steel, and a RDC stainless steel show that these are all highly competitive as potential compressor valve materials. The presence of a notch of $K_t \approx 5$ reduces the fatigue strength to about one third of the corresponding smooth value for all these materials. The fatigue performance of the RDC # 2150 was significantly better than that of the RDC # 2119 of nominally the same composition steel. A difference in the specimen thickness and the slag inclusion size were considered to be the major factors for this difference.

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