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A MATERIAL SELECTION METHOD BASED ON MATERIAL PROPERTIES AND OPERATING PARAMETERS

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16. Abstract

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A MATERIAL SELECTION METHOD BASED ON MATERIAL PROPERTIES AND OPERATING PARAMETERS

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SUMMARY

The influence of strength, fracture toughness, and crack-growth resistance on the design stress level has been determined from a mathematical model of crack growth and failure. The results show that to select materials properly, the operating parameters of desired life and initial flaw size must be considered simultaneously with the material properties. To do this, a method for constructing an "operating surface" is derived, discussed, and illustrated.

INTRODUCTION

During the design process, a material must be chosen. Some material properties which are considered while making the choice are the ultimate strength, the yield strength, the fracture toughness, the fatigue strength, and the crack-growth resistance. Some of these properties control design, some do not. The intended operating parameters – which include desired life under cyclic loads, operating stress, and nondestructive inspection capability – influence the relevance of the properties. Because the properties are many, they are seldom all considered at once. Consequently, materials often are chosen by considering only a few properties at a time. Such iterative methods are time consuming and do not always result in the choice of an optimum material.

The purpose of the present paper is to show, by means of an analytical development, how the operating parameters and material properties are interrelated. From the analysis, materials can be compared, and the most appropriate one chosen for the intended use. The paper develops the underlying philosophy, shows which material properties are relevant in various applications, and illustrates how design curves can be developed for use in material selection.

SYMBOLS

a	half-length of a crack in a center-cracked plate
a_o	initial half-length of a crack

a_f	final half-length of a crack
a_c	critical half-length of a crack
C	crack-growth constant
$\bar{C}$	crack-growth resistance constant
$\frac{da}{dN}$	crack-growth rate
K_c	critical stress intensity factor
N	cycles of load
n	crack-growth exponent
S	applied stress
ΔK	stress intensity range between minimum and maximum of load cycle
ρ	material density

DEVELOPMENT OF THE OPERATING SURFACE

Underlying Philosophy

Static- and fatigue-strength properties form the main basis for material selection. Figure 1 shows four basic material strength properties. Figure 1(a) represents the static strength of unflawed material. Figure 1(b) shows how figure 1(a) can be expanded to include the fatigue behavior, represented by the usual S-N curve for unflawed material. Figure 1(c) represents the static strength of the material containing an initial flaw of size a_o. Such static-strength data are normally characterized by the fracture of toughness. Figure 1(d) shows the fatigue crack-growth properties of the material. The fatigue life of a structure with a crack or a cracklike flaw is calculated from such growth data.

The data of figures 1(a), 1(b), and 1(c) can be represented on the coordinate planes of a single three-dimensional plot as shown in figure 2. In this figure, life and initial flaw size are represented on the horizontal axes; the stress is represented on the vertical axis. The crack-growth rate data of figure 1(d) can be integrated to relate life to stress and initial flaw size, and a complete surface like the one shown in figure 2 is obtained. This surface represents the locus of points for which a crack will propagate from an initial crack length a_o to failure in N cycles at stress S. The material properties used in the construction of an operating surface, as shown in figure 2, are the ultimate strength, the density, the fracture toughness, the S-N curve, and the crack-growth resistance. The axes of this three-dimensional operating surface represent the three basic operating parameters, stress (or stress-to-density ratio), life requirement, and initial flaw size.

The last of these, initial flaw size, is regarded as an operational parameter because when any component is inspected nondestructively, the largest undetected flaw depends on the sensitivity of the inspection technique used. Because the probability of finding flaws of a given size varies with the nondestructive inspection (NDI) technique, the design value of the initial flaw size varies with component size, shape, and NDI technique. This gives the initial flaw size the properties of an operating parameter.

Analysis

A simple expression for the rate of fatigue crack growth is the power expression first presented by Paris in reference 1:

$$\frac{da}{dN} = C\ \Delta K^n \tag{1}$$

This equation was rewritten with the crack-growth constant in the denominator to give the constant the properties of crack-growth resistance. The crack-growth law then appears as

$$\frac{da}{dN} = \left(\frac{\Delta K}{\bar{C}}\right)^n \tag{2}$$

For a wide panel containing a central through crack under constant-amplitude, zero-to-tension loading, the stress intensity range has the simple form

$$\Delta K = S\sqrt{\pi a} \tag{3}$$

Failure will occur when $\Delta K = K_c$, where K_c represents the appropriate toughness. This simple case, a central crack in a wide panel under constant-amplitude loading, was used to set up the basic model for the development of the operating surface.

The crack-growth equation (eq. (2)) is integrated as follows:

$$\frac{da}{dN} = \left(\frac{S\sqrt{\pi a}}{\bar{C}}\right)^n \tag{4}$$

$$N = \int_{a_o}^{a_c} \left(\frac{\bar{C}}{S\sqrt{\pi a}}\right)^n da \tag{5}$$

where the integration limits are the initial flaw size a_o and the critical flaw size a_c determined by the fracture toughness. The left-hand side N is the life to failure. Evaluation of this integral results in

$$N = \frac{\bar{C}^n}{S^n \pi^{n/2}\left(\frac{n}{2} - 1\right)}\left(\frac{1}{a_o^{(n/2)-1}} - \frac{1}{a_c^{(n/2)-1}}\right) \tag{6}$$

Substituting fracture toughness and stress for the critical flaw size yields

$$N = \frac{\bar{C}^n}{\frac{n}{2} - 1}\left(\frac{1}{S^n \pi^{n/2} a_o^{(n/2)-1}} - \frac{1}{S^2 \pi K_c^{n-2}}\right) \tag{7}$$

In terms of stress-to-density ratios rather than stresses, the life equation becomes

$$N = \left(\frac{\bar{C}}{\rho}\right)^n \frac{1}{\frac{n}{2} - 1}\left[\frac{1}{\left(\frac{S}{\rho}\right)^n \pi^{n/2} a_o^{(n/2)-1}} - \frac{1}{\left(\frac{S}{\rho}\right)^2 \pi \left(\frac{K_c}{\rho}\right)^{n-2}}\right] \tag{8}$$

Each of the two terms of the bracketed expression has a physical meaning. The first term contains the initial flaw size and the stress-to-density ratio; it represents the life which would result if the crack could grow to infinite length according to the assumed crack-growth equation. The second term contains the stress-to-density ratio and the fracture toughness; it represents a life reduction because the critical crack length is not infinite but equal to a_c, as determined by the fracture toughness. In most cases of practical significance, the second term is very much smaller than the first term. The life equation can then be simplified to contain only the first term, that is,

$$N = \left(\frac{\bar{C}}{\rho}\right)^n \frac{1}{\frac{n}{2} - 1}\left[\frac{1}{\left(\frac{S}{\rho}\right)^n \pi^{n/2} a_o^{(n/2)-1}}\right] \tag{9}$$

or

$$N\left(\frac{S}{\rho}\right)^n a_o^{(n/2)-1} = \left(\frac{\bar{C}}{\rho}\right)^n \frac{1}{\left(\frac{n}{2} - 1\right)\pi^{n/2}} \tag{10}$$

In this form the strong inverse dependence of life on the stress and the initial flaw size becomes apparent. Although the right-hand side of this equation is a material parameter, this parameter itself cannot be used to compare materials because the crack-growth exponent n appears in both sides of the equation.

To make the functional form of the life equation more obvious, consider a material whose crack-growth exponent has a particular value of 4, a typical value for several aerospace materials. Then the life equation becomes

$$N\left(\frac{S}{\rho}\right)^4 a_o = \left(\frac{\bar{C}}{\rho}\right)^4 \frac{1}{\pi^2} \tag{11}$$

Because equation (11) is an especially simple form of the general equation, the relationships between the various parameters can be visualized easily: For constant stress, the life is inversely proportional to the initial flaw size; for constant life, the fourth power of the allowable stress is inversely proportional to the initial flaw size; and for a given initial flaw size, life varies inversely with the fourth power of stress.

The operating surface described by equation (11) is represented by the portion of the surface over region 4 in figure 3. This part of the surface represents real conditions well, except for short-life requirements, where the fracture term – which was ignored – becomes important. A more generally applicable surface can be created from equation (8) which represents real materials even in the short-life region (region 2) and loses accuracy only for very small initial flaw sizes where the crack-growth equation does not apply (regions 1 and 3). These regions of inapplicability detract little from the utility of the equation because most flaws which can be detected by NDI are so large that equation (1), and consequently equation (8), validly predict crack growth. To complete the representation of real materials, the surface is faired into the S-N curve empirically (near the S-N plane) to obtain a complete operating surface like the entire surface shown in figure 2.

Comparison of the Operating Equation With Selected Test Results

Reference 2 contains a set of five crack-growth tests under constant-amplitude, zero-to-tension loading on 2024-T3 aluminum-alloy sheet. The results were used to evaluate the accuracy of the operating surface developed herein.

To use the crack-growth rate data of reference 2, the life expression (eq. (6)) was modified to an expression for the fatigue life during growth from crack length a_o to crack length a_f, the final or last reported crack length. This expression is

$$N = \frac{\bar{C}^n}{S^n\left(\frac{n}{2} - 1\right)\pi^{n/2}}\left(\frac{1}{a_o^{(n/2)-1}} - \frac{1}{a_f^{(n/2)-1}}\right) \tag{12}$$

A set of results of actual lives from crack length a_o to final crack length a_f for five stress levels is presented in table I. The last two columns show the calculated lives and the ratios of calculated life to actual life. The equation parameters used are given in table II. The results of the last column of table I show that for the range of operating conditions tested (greater than two orders of magnitude in terms of life), the relative scatter is approximately 30 percent in terms of life, which is equivalent to a 6-percent error in stress. Discrepancies of such magnitude are common in fatigue work. Thus, the analytical expression for the operating surface has sufficient accuracy for material selection and trade study.

MATERIAL EVALUATION

Characterization of a Material

In this section, the intent is to show that material selection cannot be based on any one material property alone, but instead must be based on both material properties and operating parameters. Figure 3 shows the operating surface divided into four regions. Region 1 represents design operating conditions requiring short lives and short initial flaw sizes. In this region, yield strength and ultimate strength are the dominant material properties. Region 2 represents design operating conditions requiring only short lives and, consequently, relatively large initial flaw sizes. In this region, the fracture toughness is the dominant material property. Region 3 represents design conditions requiring long lives and short initial flaw sizes. In this region, the fatigue properties (S-N data) are the dominant properties. Region 4, the largest region, represents design conditions requiring long lives and long initial flaw sizes. In this region, which is perhaps the most interesting from the design point of view, the crack-growth properties are the dominant properties.

The relative importance of a material property depends upon the region of operation. Yet the region of operation, as shown in figure 3, depends somewhat on the material properties. The reason for this can be seen from either equation (8) or equation (11). Because of the material crack-growth exponent n, the operating parameters and the material properties are inextricably mixed (unless n is equal to 4).

Consequently, the particular values of the operating parameters must be considered jointly with the material properties. A material must therefore be characterized, not only by material properties but by the operating surface which covers the full range of the operating parameters. A projection of the operating surface on the a_o-N plane, in which stress appears as a contour of the original surface, produces the best material characterization for design use. A logarithmic scale on each axis simplifies the chart. As an example, figure 4 shows the properties of a titanium alloy (Ti-6Al-4V, annealed) in this form.

Comparison of Materials

The operating surface presentation shown herein can be used to compare materials under given operating conditions. As an example, three materials, D6AC steel, Ti-6Al-4V annealed titanium alloy, and 2024-T3 aluminum alloy, are compared in figure 5. The criterion was to design a minimum-weight tension member, subjected to repeated loading and containing a given initial flaw. The pertinent material properties are listed in table II.

The operating surfaces for the three materials have been plotted in such a way that only a part of the surface for any one material is visible. The part of the surface shown covers the region in which the material has a higher usable stress-to-density ratio than the other materials.

On this stress-to-density basis, each of these materials has one region in which it is superior to the others. In the small-flaw region, D6AC is superior because of its high strength and its high fatigue properties. The titanium alloy has a high strength and a relatively high toughness, but has a relatively low crack-growth resistance; its region of superiority is limited to medium crack lengths and relatively short lives. For long initial crack lengths and long life requirements, the 2024-T3 aluminum alloy is superior to the other two materials because of its higher crack-growth resistance.

Figure 6 shows the stress contour plot of the combined operating surface. On this plot a trade study was carried out to determine the sensitivity of stress levels or material choice to changes in the operating parameters of life requirement and initial flaw size. As an example, assume that point A in figure 6 represents a set of particular design conditions for the initial flaw size (NDI) and the life requirement. These conditions then define 2024-T3 to have the least stress-to-density ratio for the life and initial-flaw-size coordinates of point A. To improve the available stress-to-density ratio, the design conditions must be changed by going toward point B (improve NDI), going toward point C (improve NDI and sacrifice life requirement), or going toward point D (sacrifice life requirement). For the operating conditions at point C, an additional increase in stress-to-density ratio can be gained by changing from the aluminum to the steel. Another possible trade – without a gain in stress-to-density ratio – is to go toward point E, in which case life requirement is sacrified for a less severe inspection requirement.

CONCLUDING REMARKS

The efficiency of a material, and consequently the lightness of the structure, depend upon the material characteristics and the use of the structure. Therefore, both material characteristics and operating parameters must be considered simultaneously when evaluating the efficiency of a material. The model developed in this paper shows how materials can be compared. The model was derived for the simple case of a through crack in a wide panel under simple constant-amplitude fatigue loading. The model, and consequently the life surfaces produced, take into account the dependence of material efficiency on the operating parameters. Therefore, in spite of the simplicity of the basic model, material selection based on this model and the operating surfaces will be much better than material selection by comparing only properties such as strength, toughness, or crack-growth resistance.

The constant-amplitude model developed herein, of course, does not lead to an accurate life prediction under service loading. Methods for accurately predicting fatigue crack-growth rates under variable-amplitude loading or from very short initial flaw sizes still require a large amount of developmental work. When such methods are available, the material selection can be based on the actual design load spectrum. However, none of the improvements are expected to change the conclusions reached in this study: that the particular values of the operating parameters are as important to the material selection process as are the material properties.

Langley Research Center,
National Aeronautics and Space Administration,
Hampton, Va., March 23, 1973.

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2. Hudson, C. Michael: Effect of Stress Ratio on Fatigue-Crack Growth in 7075-T6 and 2024-T3 Aluminum-Alloy Specimens. NASA TN D-5390, 1969.

TABLE I.- TABLE OF ACTUAL AND CALCULATED LIVES

$\frac{S}{\rho}$, $\frac{MN/m^2}{kg/m^3}$	a_o, mm	a_f, mm	N_{actual}, cycles	$N_{calculated}$, cycles	$N_{calculated}/N_{actual}$
0.074	2.54	15.24	4 850	4 936	1.02
.049	2.54	15.24	23 500	21 200	.90
.037	2.54	15.24	58 500	59 400	1.02
.024	2.54	15.24	228 000	278 900	1.22
.019	2.54	15.24	910 000	740 600	.81
.074	5.08	17.78	2 200	2 331	1.06
.049	5.08	22.86	16 300	11 060	.68
.037	5.08	30.48	47 500	33 650	.71
.024	5.08	40.64	146 000	167 900	1.15
.019	5.08	35.56	420 000	434 400	1.03

TABLE II.- MATERIAL PROPERTIES

Property	Aluminum 2024-T3	Titanium 6Al-4V	Steel D6AC
Tensile strength, MN/m^2	489	900	1 700
Density, kg/m^3	2770	4440	7 890
Fracture toughness, $MN\text{-}m^{-3/2}$ . .	110	110	60
Crack-growth resistance	1000	3043	23 000
Crack-growth exponent	3.64	3.12	2.62

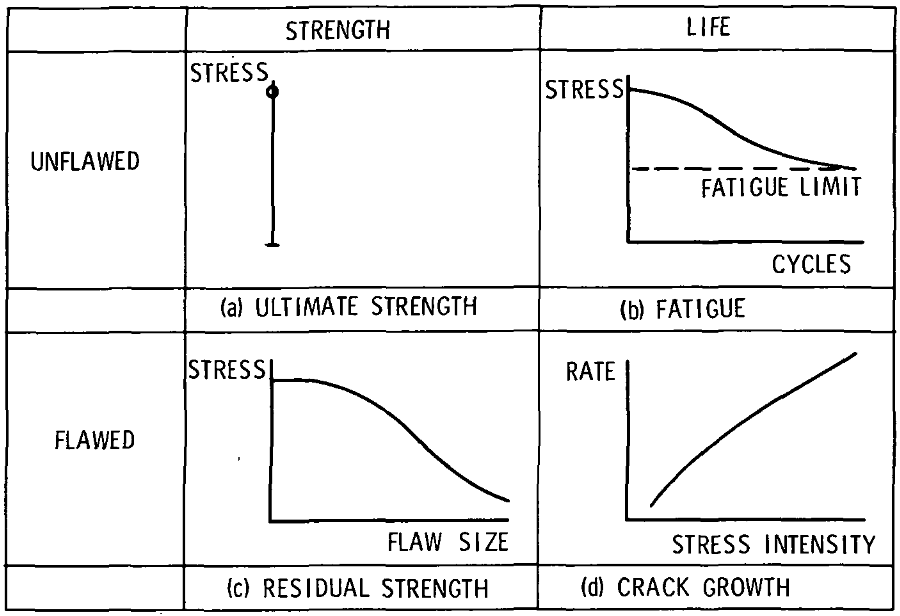

Figure 1.- Representation of basic material data.

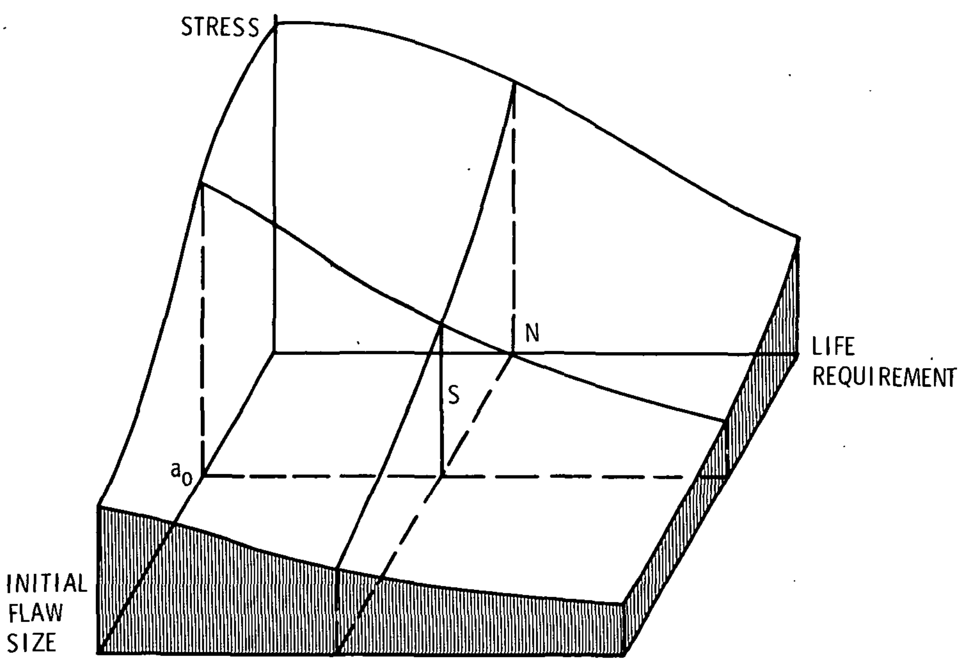

Figure 2.- Three-dimensional representation of material data.

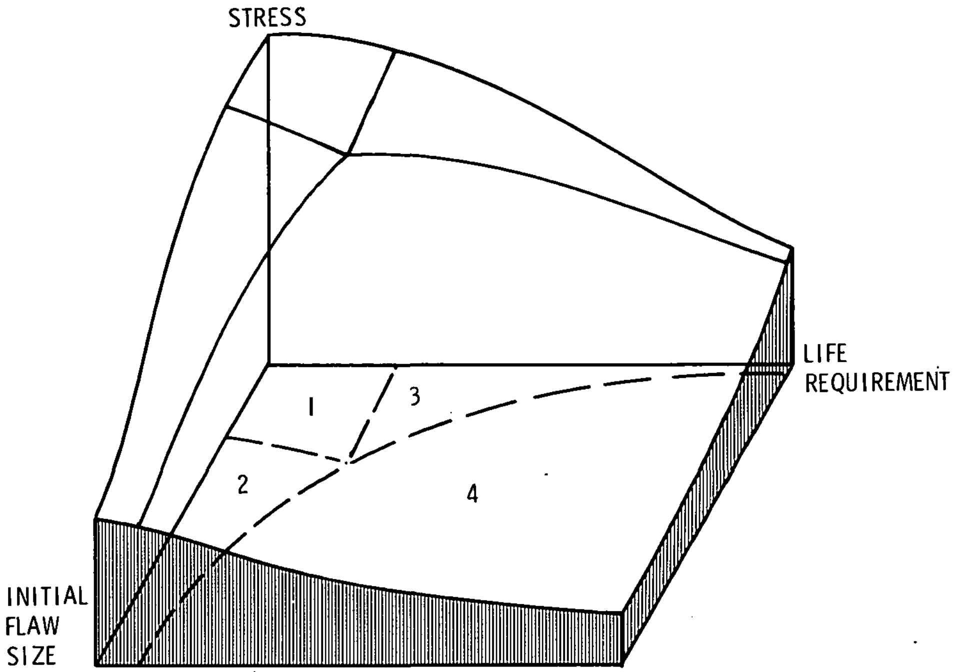

Figure 3.- Regions defining dominant material properties.

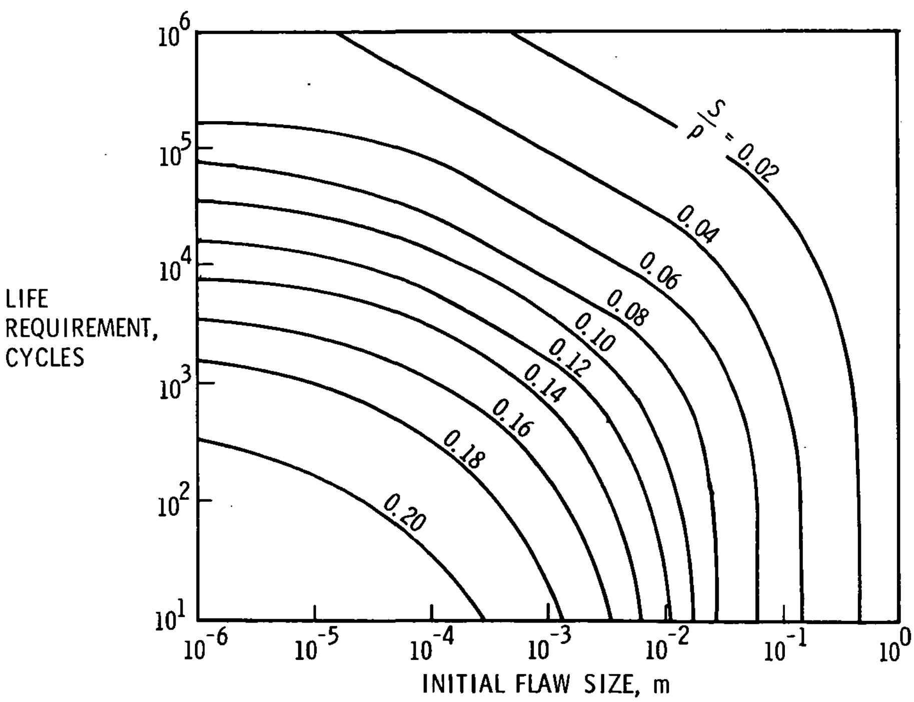

Figure 4.- Material characterization plot for Ti-6Al-4V.
$\left(\frac{S}{\rho} \text{ is given in } \frac{MN/m^2}{kg/m^3}.\right)$

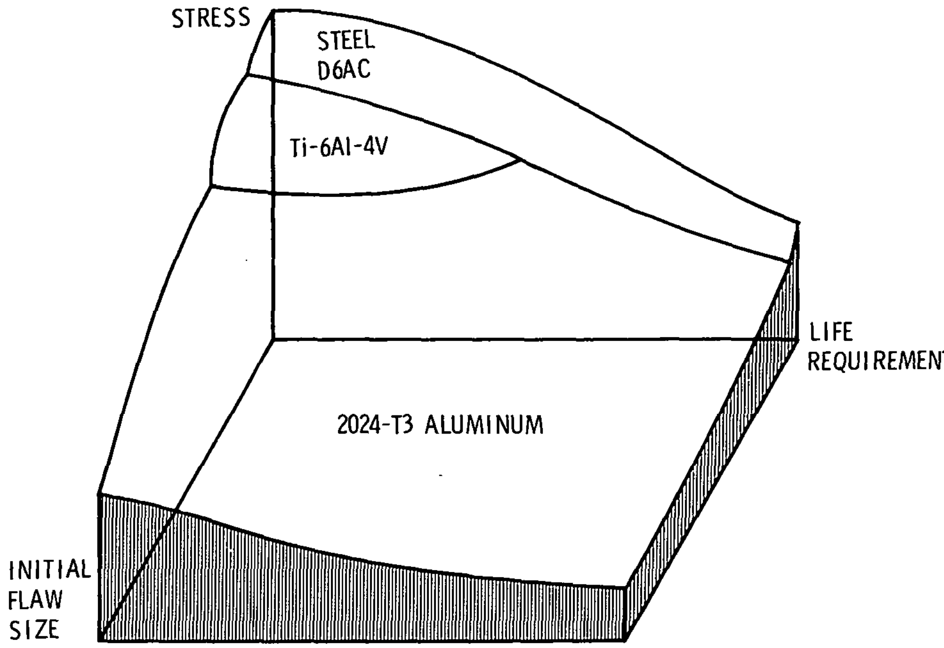

Figure 5.- Comparative operating surface for three aerospace materials.

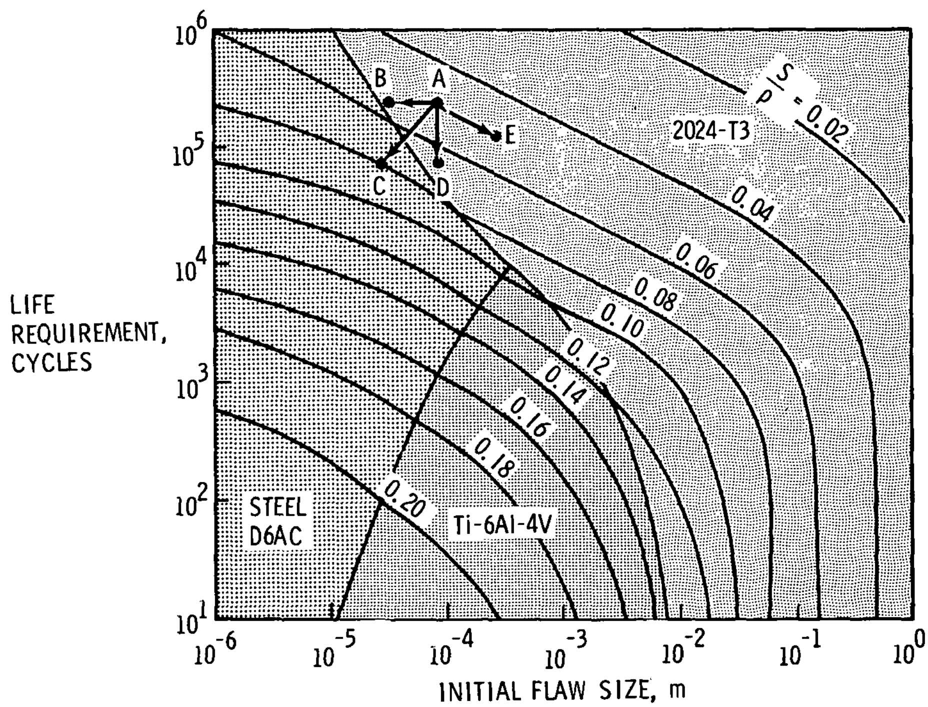

Figure 6.- Compound material characterization plot for material selection. $\left(\frac{S}{\rho}\right.$ is given in $\left.\frac{MN/m^2}{kg/m^3}.\right)$

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