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Analysis of Materials Performance Efficiency

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The Performance Efficiency of a Material (MPE) in a given engineering component is taken as the sum total of the performance indices of the material for various required properties and mandates of design. The performance index for a property is defined as the product of the weight (*W*) of the property among all the requirements (weight being distributed out of 100 total points among all of the required properties and factors) and satisfaction index (SI), a parameter ≤1.0 that defines how efficiently the property of the material satisfies the requirement imposed by design. New methods are given in this paper for estimating the weights and SIs of the various required properties and evaluating the MPE for a chosen material in an engineering application. The method is illustrated considering the steel in use in a low-pressure steam turbine rotor and its possible replacement with a lighter-titanium alloy.

Keywords material engineering index, material selection, materials performance efficiency, mechanical design, performance index, property weight, satisfaction index, steam turbine rotor

1. Introduction

Engineers often face the need to evaluate how good a material is in an engineering application. This is because excellent materials are required for smooth and efficient operation of engineering components over long periods of time. Suitable materials need to be considered and optimum ones selected at the design and product specification stage itself. It should, hence, be feasible to analyze the performance efficiency of selected materials for a given component in a quantitative way in order to decide which one would be the best.

A quantitative method for calculation of efficiency of materials in engineering applications and its utility for optimal material selection during the initial design stages of development of a component are described in this paper. The method also is suitable for critical performance evaluation of a given material in a specific component of an existing system, operating under prescribed conditions. The author refers to an article by Dieter (Ref 1) for prior work on the subject and methods of analysis suggested by others.

2. Method

A simple algorithm is used for determining the Material Performance Efficiency (MPE) or Material Performance Index (MPI) of a chosen material in a given engineering application. The latter would be a rating out of a maximum of 100 points, i.e., it would be given in percentage.

Based on the stated overall design data and product requirements, MPE or MPI greater than 95% can be taken as superior and those in the range 90-95% as very good. A reasonably good range could include efficiencies between 80 and 90%, while the 70-80% range could be considered as marginally adequate, admissible with lots of precaution and protection measures. Values below 70% generally indicate inadequate efficiencies, but how far down in MPE values the materials can be accommodated in a component would depend on several real-life situations and other factors, such as processability, reparability, and cost. These have to be judged on a case-by-case basis, but, in general, one can consider MPE values below 50% to be totally inadequate under any circumstances, and such materials should be discarded from further consideration.

The following activities are performed stepwise to determine the MPE:

Step 1: Based on the design analysis, the required property levels, processing details, cost, etc., are specified first. These are strictly based on design specifications, life expectancy, and performance and maintenance requirements.

Step 2: The required properties and attributes, etc., are then ranked based on the strict adherence to the requirements. The ranking might take into account how important a requirement is. Included in the assessment are the processability, ready-availability of the material in required shapes and sizes, reparability in maintenance scheme, and any other pertinent factors.

Step 3: Taking the total of all weights to be 100, weights to the various requirements are allocated. The most rigorous and important requirement could get a high weight (as high as 50%) and the least important ones may be assigned a weight anywhere from 1 to 5%. Appropriate weight is to be assigned to all of the properties and factors under consideration. A specific method that has been in vogue (Ref 2) and a modified technique adopted in the current work are described later.

Step 4: Considering the material in use or is selected for use, its properties and other characteristics are analyzed in

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line with the requirements posed by the design and operational parameters of the component. For each property or parameter the design-required or specified as well as the material-offered values are noted down. A material Satisfaction Index (SI) is then assigned based on the ratio between the actual property of the material and the property specified to be required, designated as the Property Ratio (PR). This SI can be 1, the maximum possible, if the material property satisfies the requirement perfectly, i.e., if PR = 1. Generally, a property would be acceptable over a small range of values, in which case SI could be taken as 1 over the corresponding range of PR. This means that SI = 1.0 over the range $1-x$ to $1+y$ of PR and corresponding values for x and y would be specified. When assigning SI, consideration should be given to the ability of the material to keep its property steady during use. If the required property level cannot be realized easily and neither consistent and steady values, nor their retention during use could be guaranteed, SI can be progressively reduced to lower levels. If a material can never realize an acceptable value of a given property, the SI is assigned as '0' for the property in question. Detailed guidelines for determining the SI for a given material property or a factor in a specific application are given in a separate section later.

Step 5: The performance index of the material for each of the specified material requirement is then calculated and noted in a table using the equation given below.

The performance index of the material with respect to any required property is the product of the two given above, i.e., weight of the property multiplied by the material satisfaction index for the property in question.

$$\begin{aligned}&\text{Material Performance Index (PI) with respect to a property}\\&= W \times SI = \text{Weight of property}\\&\quad \times \text{Satisfaction Index of the material for that property.}\end{aligned}$$

Step6: The PIs for all of the specified properties and requirements are calculated.

Step 7: The Total Material Performance Index is then obtained by adding the individual performance indices for all of the properties. This then gives the net MPE in percentage.

$$\begin{aligned}&\text{Materials Performance Efficiency (MPE)}\\&= \sum W \times \mathrm{SI} \sum [(\%\ \text{Weight of property})\\&\quad \times (\text{Satisfaction Index for that property})]\end{aligned}$$

MPE is specified in % and the material can then be classified as superior or excellent choice, very good, good or average, inadequate but tolerable, totally inadequate, etc., for the given application, based on the guidelines given earlier.

Step 8: Similar procedure is adopted to calculate the MPE of selected other materials that can be considered for application in the given component as well.

Step 9: The MPE or MPI of the chosen material for the given application is compared with the values derived for other possible materials that can be used, with their MPE values calculated for application in the given component under identical conditions. The selection and application of the chosen material will stand fully justified from its highest MPE value obtained in such calculations and comparisons. Relevant data analysis can be carried out conveniently in two or more tables.

3. Additional Considerations

The following descriptions of procedures to be followed are given as additional details.

Assigning Weight (W) for a property or parameter used in the selection of a material for a component.

The digital logic method, described by Farag (Ref 2), compares a required property with all others that are being required and assigns either 1 or 0 depending on whether the property is more important or less important than the other with which it is being compared. If there are N properties, $N(N-1)/2$ such comparisons will be made, and there shall be $N(N-1)/2$ important ones and a like number of relatively unimportant ones. After performing the comparisons for all properties with all other properties, the number of '1's a property has been assigned is divided by the total number of '1's, i.e., by $N(N-1)/2$, which ratio when multiplied by 100 gives the % weight for that property. In the example given in Ref 1, seven properties are compared with each other, the total number of '1's being 21. In that case the maximum weight any property can get is 6/21 = 0.28 or 28% and the minimum is 1/21 ~ 0.05 or 5%.

The major shortcoming of the digital logic method described above is the assignment of 1 or 0 for relative importance during comparison of a property with another one. Supposing both the properties being compared are equally important or one only slightly more important than the other, the above method does not allow the weight to be prorated. To overcome this problem of extreme overrating or underrating, inherent in the digital logic method, we propose that the unit merit of importance be split appropriately between the two properties that are being compared. For instance, when both the properties are felt to be equally important, each can be assigned a value of 0.5. Alternatively, the split can be 0.67 and 0.33, if one is felt to be twice as important as the other, and 0.75 and 0.25 for one being three times more important than the other, etc. Such relative splits are judgmental, but can represent the importance of a property relative to the other much more effectively. After this procedure the net weight of a particular property can be obtained as before by adding all the numbers, including the fractions. The net total of weight will still come out to be $N(N-1)/2$ (for N properties) and the maximum possible % weight will still be $[(N-1)_x/\{N(N-1)/2\}_{\text{total}}]100$, though this may only be realized rarely, based on the modified procedure suggested. However, the minimum may be shifted from $[1_y/\{N(N-1)/2\}_{\text{total}}]100$, upward or downward. The % weight assigned thereby for any property or factor would thus be much closer to its real value.

In spite of the above refinement, it can still be argued that there may be a need for slight adjustments of the final derived weights based on the discretion of the designer (allowing for additional human intervention). This could be the case if especially one or two properties would dominate overwhelmingly and decide the entire design and material selection criteria. In such situations, the designer could increase the weight for the most important property to a higher level than is obtained by use of the suggested method. Weights could rise to as high as 50 if one property among a few would dominate overwhelmingly over all of the others and the selection is based mainly on that property. Yield strength is one such property in the design of some of the important components.

An example is worked out later to illustrate the principle.

3.1 Method to Determine the Satisfaction Index (SI)

Next in importance in the material selection is finding how efficiently the material property meets the design and application specification. Whereas the design requirement does not change, different materials that are possible candidates (with varying values for the properties in question) will satisfy the design requirements differently. The best match will give rise to total satisfaction and a satisfaction index of 1.0. The index can never be any higher than 1.0. If the property value possessed or offered by the material is appreciably different from the required value, i.e., if PR is below $1-x$ or higher than $1+y$ (Note: SI = 1.0 in the PR range $1-x$ to $1+y$, as stated earlier), the SI will drop down to a value less than 1.0. The drop in SI may be linear or non-linear (following a specified curved path), slow or fast, relative to the variation in PR beyond the $1-x$ and $1+y$ limits.

The following method is proposed to assess the SI for a given property of a candidate material for a specified application.

- Determine the normal mean property that can be expected from or offered by the material. This is the 'property offered by the material.'
- Determine the optimum property value required by design for the material in the given application. This is 'property required of the material.'
- Divide Property offered by the material by the property required of the material. This gives the Property Ratio (PR).

$$\text{Property Ratio} = \frac{\text{Property offered by the Material}}{\text{Property required of the Material}}.$$

- Note that since variations around the mean of both of these properties are very likely and allowed in standards, etc., the PR would also vary slightly around the mean value calculated.
- The SI = 1.0 if PR = 1.0. SI may remain at 1.0 or equal PR in some specific instances for PR around 1.0, and drop below 1.0 beyond a specified tolerance range of $1-x$ to $1+y$. For PR values far away from $1-x$ and $1+y$, beyond certain other specified limits, the material can be considered to be totally unsatisfactory and the SI would be specified as zero. Beyond these secondary limits the SI will stay at zero for all values of PR.
- If PR begins to drop below $1-x$ or increase above $1+y$, then the SI value should be stipulated to be progressively reduced.
- In some instances, the reduction may be required to be very sharp, i.e., SI may be dropped to zero with a slight deviation of PR on the pertinent side. This would rarely be the case, as slight deviations in the required and/or material properties are always allowed. Even so, the fall could be fairly steep beyond such a slight tolerance. Such a drop is denoted by the symbol 'VF' (very fast drop).
- Note that in general the optimum property value required and the tolerable extent of deviation from this required value by the material can be specified, i.e., the perfect tolerance for the variation of the material property beyond the required level can be specified. For example, excess property levels of the material up to 10% (or 25%, etc.), giving rise to PR = 1.1(or 1.25, etc.), might be stated to be fully satisfactory to the requirement. In such cases SI is taken to be 1.0 in the range of PR from 1.0 to 1.1(or 1.25, etc.) ($y = 0.1$ or 0.25 in such situations).
- In some too liberal instances, the SI value can be taken as 1.0 up to the PR value of 1.5, beyond which it may drop off with the same pace as the increase in PR (specified as 'slow drop' and designated by symbol 'S11' or simply 'S'), i.e., the drop is along a straight line with a slope equal to 1. This could be the case, for example, for yield strength, for which high values are tolerable.
- Likewise, if a lower value is specified or as low a value as possible is desired for a property, as for density, then values below a low-specified value could be taken as perfectly satisfactory and the SI can be allowed to stay at 1 for much lower property ratio values, say down to PR 0.5. SI may be allowed to drop off with the same pace as the property ratio at still lower-density levels, i.e., the slope of the drop may be set at 1.0 below PR = 0.5. In such instances how high a value of PR can be tolerated should also be specified. Based on that, SI values can be taken as 1.0 up to a point of $1+y$ of PR and reduced with a slope of 1 with the increase of the property ratio beyond that point, till a set PR value is reached, beyond which it may be made to fall off more rapidly in a fast manner. These are factored into the plots given in Fig. 1.

Several SI drop schemes are possible and these are illustrated below. The symbols S and F are used to denote slow and fast drops, respectively. Subsequent to these symbols two numbers are given, first of which denotes the deviation of PR (not the exact value) and the second the corresponding drop of SI. For example, 12 will mean twice as much drop of SI as the change in PR (F-type), whereas 41 would imply a drop of SI only one fourth as much as the change of PR (S-type).

- SI can be made to drop off much slower than the 1:1 rate of drop (S or S11) with changes in PR. These linear slow drops are designated by the symbols S21, S31, S101 (10,1) etc.
- In cases where the SI is desired to drop off linearly, but faster than the change of PR beyond a specified level, the symbols F12, F13, F14, etc. are to be used to denote SI dropping linearly twice, three times or four times as fast as the variation in PR beyond a specified limit.
- In the case of fast drops, possible nonlinear schemes are suggested. Two such schemes are indicated in the figures. One is the square-rate drop, denoted by $F_{sq,}$ where the SI drops off as the square function of the change in PR. Figure 1(c) shows this drop, wherein the SI drops by the square count of the change in PR, both given in hundredths of a point. For example, a change of 0.05 in PR would drop SI by 0.25, a change of 0.07 of PR would drop SI by 0.49, and so on. This is analogous to the case in the linear F110 drop, wherein a change of PR by 0.1 would drop SI ten times as much, i.e., drop it by 1.0 and bring it to zero.
- The second non-linear drop plot is designated as 'F' in Fig. 2. These drop plots start from SI = 1.0 at specified PR values, for example at PR = 0.75. The plot in that case is designated as 0.75F. The non-linear fast drop plot is arbitrarily based on two functions.

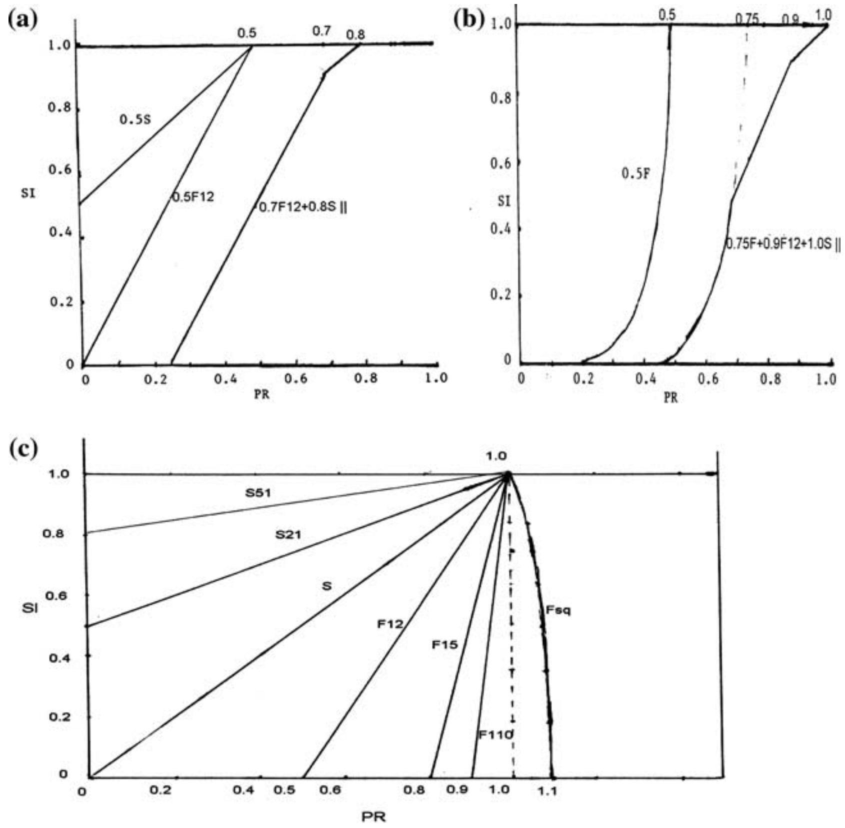

Fig. 1 Representative plot paths to determine SI from PR values of material properties. (a) Linear drop schemes, single and mixed; (b) fast drop, and mixed linear and fast drop schemes; (c) linear slow and linear fast drops, and the square fast drop F_{sq} schemes

$y = A_1x^3/(1-x)$ for x below 0.75, i.e., for the 0.75F and 0.5F plot curves. In this case, A_1 is a constant which is adjusted to yield $y = 1.0$ for the upper limit values of X in the plots. For example, $A_1 = 4$ for the 0.5F plot, whereas it is 0.5926 for the 0.75F plot.

$y = 1/x^{[A_2(x-L)]}$ for x above 0.9, i.e., for the 0.9F, 1.0F, 1.1F, 1.25F, and the 1.5F curves. In these cases A_2 is a constant, arbitrarily taken as 20 and L is the upper or lower limiting value of PR at which $y = 1.0$. Note that L is the highest-limiting value of x in the case of 0.9F and 1.0F (for $x < 1.0$), and the lowest-limiting value in 1.0F (for $x > 1.0$) and in the other cases where the limiting value of x is >1.0. Here A_2 is maintained the same at 20 which makes the curves drop much faster as the limiting value L is increased, as can be noticed in Fig. 2. The value of A_2 can be suitably adjusted such that the drops become nearly similar. However, this has not been carried out in the plots given in Fig. 2.

- Note that the given curve functions were chosen arbitrarily and can be changed as desired.
- In one of the drops designated as F12, the SI drops linearly, twice as fast as the deviation in PR beyond a specified level. Prior to such a linear fast drop, there will usually be a slow drop range. The F12 drop may start at a particular PR level. For example, the F12 drop might start at PR = 0.8 and above that point, SI might be dropping at a slow pace. This will be denoted as 0.8F12. The slow pace itself might have started say at PR = 0.9. This will be given as 0.9S. In this case, SI = 1.0 in the range of 1.0 to 0.9 of PR, below which it drops with a 1:1 pace between 0.9 and 0.8 of PR, after which it will start falling twice as fast as PR. A similar designation, 0.7F12 + 0.8S, is shown in Fig. 1(a). Here SI = 1.0 in the range of PR 1.0 to 0.8, has a value of 0.9 at PR = 0.7, below which SI would drop twice as fast as the reduction in PR. SI would first drop to zero at PR = 0.25 and stay at zero for values of PR < 0.25.
- The nonlinear fast drop may start from SI = 1.0 at any PR value. For example, it is indicated as 0.5F in one curve in Fig. 1(b). The fast drop curve starts from SI = 1.0 at PR = 0.5. This drop is fast at first and asymptotically approaches 0 as PR goes well below 0.5. Since the drop can normally be slow prior to a fast drop, SI may drop falling fast from any value of SI < 1.0. For example, in the case shown as 0.75F + 0.9F12, the fast curve drop is made to initiate from the point on where the fast drop line F12 starting from PR = 0.9 intersects the fast-drop curve coming down from SI = 1.0 starting at PR = 0.75. For the case 0.75F + 0.9F12 + 1.0S || shown in Fig. 1(b), there is also a slow 1:1 drop of SI in the range 1.0 to 0.9 of PR, prior to the initiation of the first linear fast drop.
- Generally, the perfect tolerance levels of property (i.e., the PR range 1–x to 1 + y for SI = 1.0) and the appropriate SI drop schemes to be used for estimating the SI as a function of PR beyond this range on either side are to be specified as accurately as possible. This is termed as specifying the plot path for variation of SI with PR for a specific property. The sign || is used to designate the PR = 1.0 location. The plot paths for finding SI for PR values lower than 1.0 are written to the left of this

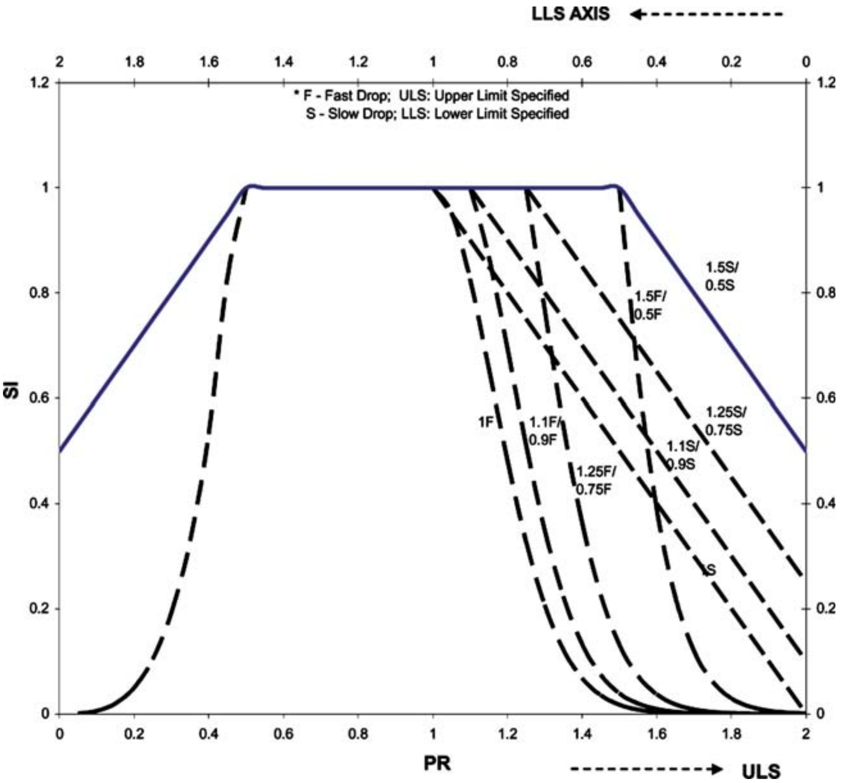

Fig. 2 Selected S11 (S)-, and F-type PR vs. SI plots for determining SI

sign, e.g., 0.75F + 0.9F12 + 1.0S || in Fig. 1(b). Likewise, the plot paths for PR > 1.0 are written to the right of the || sign. An example would be || 1.1S + 1.5F. Here SI = 1.0 in the range of PR from 1.0 to 1.1, drops off slowly on a 1:1 basis in the range of PR from 1.1 to ~1.5 (SI = 0.6 at PR = 1.5), and drops fast from the point where the line corresponding to the linear slow drop meets the fast drop curve coming down from the point SI = 1.0 and PR = 1.5.

- Appropriate SI vs. PR plots in Fig. 1 and 2 can be used (according to specified plot paths) to estimate the SI value for a given property ratio of a property under consideration.

A few cases will illustrate these ideas:

Case 1: For a shaft operating at high speeds, yield strength is specified as an important property. Supposing the design requirement calls for 100 ksi yield strength, materials that would possess yield strength 100 ksi or higher would satisfy the requirement and SI could be assigned as 1.0 for PR values in the range 1 to say 1.5, i.e., up to the yield strength exceeding the required value by 50%. Values of yield strength higher than 150 ksi still satisfy the minimum yield strength requirement, though such very high-strength levels could adversely affect the toughness and ductility, etc., which would not be desirable. In such a case, although the specific property satisfies the requirement, its SI needs to be lowered to below 1.0 when the PR increases beyond a specific limit, in this case 1.5. Since there is a large tolerance level, the decrease in SI value beyond PR = 1.5 need not be fast and a slow drop scheme, i.e., a drop in SI of equal magnitude as the rise in PR, can be recommended. The suggested plot path for SI would in this case be || 1.5S

Case 2: A case where the specified low value of a property can be extended to even lower levels is on the other extreme of the property variation. Density is one such property and for some applications, as in rotating components, as low a density as possible may be desired. This applies, for example, to propellers and impellers, fan blades, air-compressor blades, windmill blades, shafts, etc. It is argued that lower the density, smaller will be the total mass and inertia and it would take less energy to rotate such components, and the system would be energetically more efficient. In such a situation, supposing one requires a mean density of 2.5 (g/cm^3), close to that of an aluminum alloy, lower densities of carbon-fiber polymer composites would be satisfactory as far as density is concerned. In this case the value of 1.0 for SI is stretched down to a density of 1.25 (g/cm^3) for a 50% tolerance on the lower side (down to PR = 0.5) and later allowed to drop at the slow rate of 1:1 below this limit. Since titanium alloys that are light could also satisfy the lightness requirement, the tolerance on the higher side should be extended to densities at around 4.5 (g/cm^3), which implies a tolerance of 80% on the higher side. Note that the line corresponding to SI = 1.0 in Fig. 1 and 2 can be stretched to higher tolerance levels as desired.

However, steels, stainless steels, or other materials with densities similar to steel are normally used in many rotating components. Their much higher-elasticity modulus and density are congenial for minimizing permanent bending, buckling, vibrations, etc. In such situations, although one would recognize and impose the need for low-density levels, much larger allowances have to be made on the higher side. One could suggest taking the density of titanium alloys as the mean requirement for density in lightness-required cases and allow 70% deviation on either side for perfect satisfaction. Taking 4.5

for the specified required density, perfect tolerance level of 70-75% on either side for the property of the material can be specified, such that aluminum alloys and composites on the lower PR side and steels, etc., on the higher side can become totally satisfactory, as far as the density is concerned. If low density were the overriding factor, then steels should get lower SI values based on their PR. In such a case the scheme given previously can be used with the proviso that the SI be taken as 1.0 for all values with 50% tolerance on the lower side, and 80% on the higher side, beyond which it is allowed to drop off at a slow 1:1 pace.

Case 3: Besides the well-defined properties, other properties and factors such as corrosion, weldability, reparability, cost, etc., need to be considered too. For many of these properties that cannot be clearly defined by specific values, a graded value scale from 1 (lowest) to 10 (highest) can be used. A mean required value, its perfect tolerance range, as well as the SI drop scheme for PR values beyond the fully tolerant range can be specified using this scale. For example, for a factor such as cost, if one would need a low cost, a value of 3 may be specified and a full tolerance range of 1-5, i.e., a 67% tolerance on either side, may be suggested. For higher costs, with $\mathrm{PR} \geq 1.7$, the SI could be specified to drop sharply, fast, or slowly, as the case would warrant.

3.2 Material Engineering Index (MEI)

The Material Engineering Index is the same as the "Material Index" specified by Ashby (Ref 3). It is defined as a specific "combination of material properties," derived from design analysis, "which characterizes the performance of a material in a given application." (Ref 3) This parameter that needs to be optimized, i.e., maximized or minimized as the case may be, is first obtained through appropriate consideration of mechanical stresses involved or thermal process analysis from the design data provided. Ashby (Ref 3) gives numerous examples, and several others can be deduced easily using appropriate engineering principles. The MEI should be considered as one of several requirements in the MPI analysis of a material and treated like any other property or requirement.

4. Specific Example

The following is an example for MPE analysis of a material in service in an engineering component. A comparison with a candidate material that could be considered as a plausible substitute is also included.

4.1 MPE Analysis for Materials in a Rotor of a Low-Pressure Steam Turbine

Low-pressure steam turbine rotors are subjected to continuous stresses and high temperatures in a steam-water two-phase environment. The material for the rotors should possess high yield strength, high modulus of elasticity, good thermal conductivity, good machinability, good fatigue strength, and high corrosion and wear resistances to the high-pressure steam environment. The steel designated as 3.5NiCrMoV is the material used for these rotors, wherein it satisfies most of the required properties. An equivalent or even better low-cost, low-density material could be considered for application. A possible candidate material for replacement of the steel is the alloy Ti-6Al-4V. It has comparable yield strength and hardness as the 3.5NiCrMoV steel. However, the major drawbacks of the titanium alloy are its lower fatigue strength and high costs. Though Ti-6Al-4V is highly passive, it is susceptible to hydrogen embrittlement. However, this material is highly resistant to chlorides and services well in chloride-containing environments. Thus, it will survive well, even if the steam is contaminated with the chloride. The steel, however, is a proven strong material that performs well in the clean-steam environment.

The MPEs of both of these materials are computed and compared in the following.

4.2 Design Analysis

For the turbine rotor under consideration, yield strength (YS), elasticity modulus, fatigue and creep strengths, wear resistance, and thermal conductivity are the most important properties to be specified. The density of the material could be as low as possible to enable ease of rotation. However, higher densities would be favorable for reducing the vibrations and for ease in balancing the rotor. Higher cost can be compensated by a longer service life of the material. Eight additional properties and factors are considered in the analysis, see Table 1-3.

The MEI for the rotor can be obtained as follows:

For solid circular shafts, considering no vibration, the optimization is done with the following equation:

$$\sigma_{\max} = \left(\frac{16}{\pi d^3}\right)\left(M_b + \sqrt{\left(M_b^2 + M_t^2\right)}\right) \propto M/I$$

where, $\sigma_{\max}$ = Maximum stress (psi), limited to yield stress σ_y, M_t = Torque (in-lb); M_b = moment due to bending load (in-lb), I = Second moment of inertia (Ref 4), and d = Diameter of the shaft (in).

For this case, one can write that MEI is proportional to the net moment and should be as high as possible.

$$\begin{aligned}
&\text{MEI} \propto M \\
&\text{or, MEI} \propto \sigma_y * I \\
&\text{or, MEI} \propto \sigma_y * m \ \ (m \text{ is the mass, since} I \\
&\quad \text{is proportional to mass)} \\
&\text{or, MEI} \propto \sigma_y * \rho \ \ (\rho \text{ is the density, since } m \\
&\quad \text{is proportional to } \rho)
\end{aligned}$$

4.3 Assigning Weights for the Requirements

The relative weights for the various required properties of the material under the working conditions are obtained as follows:

The properties required to be specified are incorporated in a matrix-type table and each property (termed first) is compared with another one below it (termed second) and its weight as a fraction of '1' is put in the box underneath the property with which it is compared in the horizontal row, parallel to the property. The relative merit of the second property is put in the corresponding box in that property's parallel row in the column of the first property; e.g., see comparison of YS with E in Table 1, each getting a value of 0.5. After comparing each property with all of the others in this manner, the values assigned to each of the specific property in its parallel row are added up horizontally and the sum total is put in the 'Total' column. This is done for each property. The sum for all values

Table 1 Weight determination for properties by assignment of 1 or fraction of 1 for importance of a property in comparison with all other properties

Property	Abbn.	YS	E	MEI	CS	FS	TC	ρ	M	CR	LS	WR	HC	Cost	Av	Re	Fam	Total	W_{cal}	W_{adj}
Yield strength	YS		0.5	0.5	0.6	0.6	0.5	0.5	0.8	0.7	0.5	0.8	0.6	1.0	1.0	0.8	0.6	10.0	8.3	10
Elasticity modulus	E	0.5		0.5	0.5	0.6	0.4	0.5	1.0	1.0	0.5	1.0	0.4	1.0	1.0	0.8	0.6	10.3	8.6	8
MEI (YS*Density)	MEI	0.5	0.5		0.8	0.8	0.5	0.5	0.8	0.7	0.5	0.8	0.6	1.0	1.0	0.8	0.6	10.4	8.7	10
Creep strength	CS	0.4	0.5	0.2		0.5	0.4	0.5	1.0	0.5	0.6	0.8	0.6	1.0	1.0	0.8	0.6	9.4	7.8	8
Fatigue strength	FS	0.4	0.4	0.2	0.5		0.4	0.5	0.8	0.7	0.5	0.8	0.6	1.0	1.0	0.8	0.6	9.2	7.7	8
Thermal conductivity	TC	0.5	0.6	0.5	0.6	0.6		0.5	1.0	0.5	0.8	1.0	0.6	0.8	1.0	0.8	0.6	10.4	8.7	8
Density	ρ	0.5	0.5	0.5	0.5	0.5	0.5		1.0	0.6	0.6	0.7	0.6	0.5	1.0	0.8	0.6	9.4	7.8	8
Machinability	M	0.2	0	0.2	0	0.2	0	0		0	0.4	0.3	0	0.4	0.5	0.6	0.4	3.2	2.7	3
Corr. Res.	CR	0.3	0	0.3	0.5	0.3	0.5	0.4	1.0		0.6	1.0	0.5	0.5	0.7	0.6	0.6	7.8	6.5	6
Life span	LS	0.5	0.5	0.5	0.4	0.5	0.2	0.4	0.6	0.4		1.0	0.5	0.5	0.8	0.5	0.5	7.8	6.5	6
Wear res.	WR	0.2	0	0.2	0.2	0.2	0	0.3	0.7	0	0		0	0	0.6	0.5	0.4	3.3	2.8	5
Heat capacity	HC	0.4	0.6	0.4	0.4	0.4	0.4	0.4	1.0	0.5	0.5	1.0		0.5	1.0	0.5	0.5	8.5	7.1	7
Cost	Cost	0	0	0	0	0	0.2	0.5	0.6	0.5	0.5	1.0	0.5		0.5	0.5	0.5	5.3	4.4	5
Availability	Av	0	0	0	0	0	0	0	0.5	0.3	0.2	0.4	0	0.5		0.5	0.5	2.9	2.4	2
Data reliability	Re	0.2	0.2	0.2	0.2	0.2	0.2	0.2	0.4	0.4	0.5	0.5	0.5	0.5	0.5		0.5	5.2	4.3	4
Familiarity of the material	Fam	0.4	0.4	0.4	0.4	0.4	0.4	0.4	0.6	0.4	0.5	0.6	0.5	0.5	0.5	0.5		6.9	5.7	2
Total weight																		120	100	100

For every property, its relative merit values are given along its row, total for the property under the ‘total’ column, and the calculated and adjusted final weights in % in the last two columns of the table

Table 2 SI determination for individual properties

				3.5NiCrMoV			Ti-6Al-4V		
No.	Property	Reqd. value	SI curve path spec. (a)	Prop. (Ref 5)	PR	SI	Prop. (Ref 5)	PR	SI
1	YS, MPa	800	0.9F + 1.0S ‖ 1.5S	860	1.075	1.0	880	1.1	1.0
2	E, MPsi	28	0.75F + 1.00S ‖	30	1.1	1.0	16.5	0.6	0.6
3	MEI, MPa·g/cm^3	160	0.9F + 1.0S ‖ 1.5S	240.8	1.5	1.0	140.8	0.88	0.85
4	CS, rel	9	0.75F + 0.9S ‖ 1.25S	9	1.0	1.0	6	0.67	0.55
5	FS, MPa	300	0.75F + 0.9S ‖ 1.25S	344	1.15	1.0	240	0.8	0.9
6	TC, W/m·K	~7.5	0.9F ‖ 1.5F	~12.0	1.6	0.32	6.7	0.9	1.0
7	ρ, lb/in^3	0.2	0.5S ‖ 1.5S	0.28	1.4	1.0	0.16	0.8	1.0
8	M, rel.	8	0.75F + 0.9S‖	8	1.0	1.0	4	0.5	0.10
9	CR, rel.	8	0.75F + 0.9S‖	7	0.88	0.9	8	1.0	1.0
10	LS, rel.	10	0.9F ‖	8	0.8	0.6	8	0.8	0.6
11	WR, rel.	8	0.75F + 1.0S ‖	7	0.88	0.88	6	0.75	0.75
12	HC, J/(g·°C)	0.4	0.9F ‖ 1.5S	0.45	1.125	1.0	0.52	1.3	1.0
13	Cost, rel.	5	‖ 1.1S	6	1.2	0.9	8	1.6	0.55
14	Av, rel.	8	0.75F + 0.9S‖	9	1.125	1.0	6	0.75	0.85
15	Re, rel.	9	0.75F + 0.9S‖	8	0.88	0.98	7	0.77	0.87
16	Fam, rel.	10	0.5F + 1.0S ‖	9	0.9	0.9	7	0.7	0.7

(a) In the SI plot path specification, i.e., the plot path to be used to determine the SI value corresponding to a certain PR, 0.7F would refer to the curve of SI variation starting from SI = 1.0 at PR = 0.75 and dropping to lower values for lower PR values in a fast manner, 1.25S would mean, likewise, the variation of SI values as given along the line starting at SI = 1.0 and PR = 1.25 and dropping in a slow 1:1 manner for values of PR > 1.25. (See PR vs. SI plots given in Fig. 1). Also, the symbol ‖ represents the location for PR = 1.0. PR drops to lower values to its left and increases to higher levels to its right. The plots are to be followed starting from PR = 1.0 and dropping to lower PR values using the plot paths shown on the left and for increasing PR values using the plot path given on the right of the symbol ‖. For example, the plot path given for fatigue strength (property # 5) is 0.75F + 0.9S ‖ 1.25S. Here, starting from PR = 1.0 for which the SI = 1.0, SI = 1.0 till PR = 0.9, then it drops slowly according to the 0.9S line for lower PR values and when the linear drop plot meets the curve for 0.75F plot, it switches to the latter and begins to drop faster for lower values of PR. Likewise, on the higher PR side, SI = 1.0 till PR = 1.25 and it begins to drop slowly as in the 1.25S plot as PR is increased. Once the total plot path is laid down in this fashion, the SI value for a specific PR value of the fatigue strength property can be read from the figure. Similar procedure is followed to find the SI for every PR value calculated for all of the properties and factors of interest

in this ‘Total’ column would then indicate the total merits of all of the properties with respect to each other. The values of total merits in the ‘Total’ column should add up to $N(N-1)/2$, where N is the total number of properties and required factors under consideration. Taking the ratio of the summed total merit of any property to the total for all properties and multiplying by 100 gives the relative weight in %, calculated for that property. Table 1 shows the calculated weight values in % (W_{cal}), in the column next to the ‘Total’ column. The weights under the column W_{cal} should add up to 100.

The weights for the properties obtained using the above procedure are later scrutinized in the overall context, considering all of the properties and factors, and appropriate adjustments are made upward or downward such that the

Table 3 Calculation of performance index for each property and total MPE for the two selected materials for the steam turbine rotor

No.	Property	W (W_{adj})	3.5 NiCrMoV		Ti-6Al-4V	
			SI	$W \times$ SI	SI	$W \times$ SI
1	Yield strength, MPa	10	1.0	10.0	1.0	10.0
2	Elasticity modulus, Mpsi	8	1.0	8.0	0.6	4.8
3	MEI, MPa·lb/in^3	10	1.0	10.0	0.85	8.5
4	Creep strength, rel.	8	1.0	8.0	0.55	4.4
5	Fatigue strength, MPa	8	1.0	8.0	0.9	7.2
6	Thermal conductivity, W/m·K	8	0.32	2.6	1.0	8.0
7	Density, lb/in^3	8	1.0	8.0	1.0	8.0
8	Machinability, rel.	3	1.0	3.0	0.1	0.3
9	Corrosion resistance, rel.	6	0.9	5.4	1.0	6.0
10	Life span in use, rel.	6	0.6	3.6	0.6	3.6
11	Wear resistance, rel.	5	0.88	4.4	0.75	3.8
12	Heat capacity, J/g·°C	7	1.0	7.0	1.0	7.0
13	Cost, rel.	5	0.9	4.5	0.55	2.8
14	Availability, rel.	2	1.0	2.0	0.85	1.7
15	Data reliability, rel.	4	0.98	3.9	0.87	3.5
16	Familiarity of the material, rel.	2	0.9	1.8	0.7	1.4
MPE:		100 (max.)		90.2		81.0

relative weight to be assigned for each property is finalized. Table 1 gives the adjusted (W_{adj}) weights for all of the properties and factors in its very last column. These are taken as the final assigned weights for the properties concerned.

4.4 Justification of Adjustments of some of the Weights

The weights denoted for some of the properties can be seen modified slightly in Table 1. Of the considered properties, yield strength and MEI are probably the ones with the highest importance and their weights are improved by 15-20%. Wear resistance should be somewhat more important than projected in Table 1 and its value is raised by about 75%, though its weight is still only one half of the ones with the highest values. Familiarity with the material is rated to be very important in Table 1, and since only familiar materials are likely to be considered for the given application, its importance is reduced by about 65%. The above adjustments can be considered to be reasonable.

4.5 Selection of SI Plot Paths to be Followed

Assignment of appropriate SI plot paths and determination of SI for an individual property using the designated plot path is an important task in the materials efficiency analysis procedure. The PR for each property is calculated and the corresponding SI value needs to be obtained using the respective SI plot paths, specified to be followed. Note that the PR is calculated using the actual values of the properties given in the table (Ref 5) or using the assigned values in the scale of 1-10, 1 being the lowest and 10, the highest, for properties that do not have specific values. The plot paths chosen for the different properties are explained as follows.

(a) For any higher-value favorable property (e.g., toughness, machinability, weldability, etc.), the SI is assigned as 1.0 if the PR is greater than or equal to 1.0, or else the path of the PR-SI plot is decided and specified. Similarly for any lower value favorable property (e.g., cost), the SI is assigned as 1.0 if the PR is less than or equal to 1.0, else the path of the PR-SI plot is specified.

(b) As described earlier, the path given as "0.9F || 1.5F" for thermal conductivity (TC) means for property ratio below 1.0, SI = 1.0 within the PR range 0.9-1.0, and its value drops from 1.0 and follows the fast drop curve 0.9F below PR = 0.9. Likewise, SI = 1.0 till PR = 1.5; thereafter it falls off fast according to the 1.5F curve. Similarly, "0.9F || 1.5S" designated for heat capacity (HC) means that SI = 1.0 for PR between 0.9 and 1.5, it drops fast for PR < 0.9, but drops only slowly with the rate of 1:1 above the property ratio of 1.5 on the higher side of PR.

(c) For Yield strength (YS), the path of the SI curve is specified as 0.9F + 1.0S || 1.5S. Since one can not allow a material with much lower YS than specified for the required application, for values of PR below 1.0 the path follows 1.0S line till PR ~ 0.9, below which (from the point where the line meets the 0.9F curve) it follows the 0.90 fast drop curve. Also, considering that much higher YS than required will affect some of the other required properties, such as fracture toughness, 1.5S linear drop option will be a better path to follow, which will still allow one to consider materials with twice the YS compared to the specified value, albeit with a much reduced SI value. The SI assigned is 1.0 between 1.0 and 1.5 of PR. It will be 0.5 for PR = 2.0 under the slow-fall scheme (1.5S) specified. SI drops to zero at PR = 2.5 and will remain at zero for PR > 2.5.

5. Conclusion

From the MPE calculations (Table 2 and 3) it is clear that 3.5NiCrMoV steel is definitely the better material for low-pressure steam turbine rotor in a clean steam environment. With an MPE of about 90% it supersedes the lighter Ti-6Al-4V, whose MPE works out to be only about 81%. The MPE of the latter is still in the low reaches of the allowable range and it could be used in low temperature, low power systems. With the excellent performance of the alloy steel in the given application, it is easy to see why the steel is still the preferred choice. It should be borne in mind too that the steel rotor being of higher density would be capable of being tuned amicably, avoiding possible vibrations and attendant problems. In cases where chloride corrosion becomes significant in the case of steels, the Ti-alloy can be considered more seriously. Selected nickel-base alloys could provide much higher efficiencies and should be compared with the Ti-alloy then. Further analysis should be based on energy requirements for rotating the rotors made of different types of materials.

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