MATERIAL SELECTION IN GEAR DESIGN

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Abstract. Materials and process selection are key issues in optimal design of industrial products. Substituting and selecting materials for different machining parts is relatively common and often. Material selection is a difficult and subtle task, due to the immense number of different available materials. From this point of view paper deal with a set of major gear design criteria which are used for gear material selection. The main gear design criteria are: surface fatigue limit index, bending fatigue limit index, surface fatigue lifetime index, bending fatigue lifetime index, wear resistance of tools flank index and machinability index. Using computer allows a large amount of information to be treated rapidly. One the most suitable model, for ranking alternatives gear materials, is ELECTRA, which using a multiple criteria, which all material performance indices and their uncertainties are accounted for simultaneously.

Key words: gear, material, selection

1. INTRODUCTION

Materials and process selection are key issues in optimal design of industrial products. Recently many materials which have long been used in industry are being replaced by newer materials in order to meet demands of cost reduction and better performance [1,2,3].

In the manufacture of mechanical parts, knowledge of material properties, cost, design concepts and their interactions is required. The large number of available materials, together with the complex relationships between the various selection parameters, often makes the selection process a difficult task. When selecting materials, a large number of factors must be taken into account. These factors are mechanical properties, physical and electrical properties, corrosion resistance, environmental friendliness and economy. In mechanical design, however, mechanical properties are the most important. The most important mechanical material properties usually encountered in material selection process are fatigue strength, tensile strength, yield point, hardness, stiffness, toughness, creep resistance and density.

The first step in the material selection is to specify the performance requirements of the component and to broadly outline the main materials characteristics and processing requirements [4-8]. Accordingly, certain classes of materials may be eliminated and other chosen as probable candidates for making the component. Then, the relevant material properties are identified and ranked in order of importance. Then, optimization techniques are used to select the best material. There are a few strategies for material selection: on the base experience, on the base trial and error, Ashby method [4-8], which is advanced Grenoble team [6], graph theory and matrix approach. Ashby [4,5,7] introduced materials selection charts which allow the identification, from among the full range of available materials, the subset most likely to perform best in a given application. He has used a multi-objective optimization method to compromise between several conflicting objectives in material selection. Using computer allows a large amount of information to be treated rapidly. One the most suitable model, for ranking alternatives gear materials, is ELECTRE (Elimination and Choice Expressing the Reality) [6-8], ELECTRE (I, II, III, and IV) is a method for dealing with the problem of ranking alternatives from the best to the worst. This method is suitable for gear material selection.

2. GEAR MATERIAL SELECTION MODELS

Optimal design of gears requires the consideration of the two type parameters:

Material and geometrical parameters. The choice of stronger material parameters may allow the choice of finer geometrical parameters and vice versa. Very important difference among these two parameters is that the geometrical parameters are often varied independently.

On the other hand, material parameters can be inherently correlated to each other and may not be varied independently. An example of which being the variation of the bending fatigue limit (Sbf) with the core hardness (HB) for some steel materials. If these parameters would be varied independently in an optimization case, it may result in infeasible solutions. Therefore, the final choice of material may not be possible within available database.

If gear material and geometrical parameters are optimized simultaneously then it is common to assume empirical formulas approximating a relation between material parameters for example the bending fatigue limit (Sbf) and ultimate tensile strength (Rm) as a function of hardness.

If the choice of material is limited to a list of pre-defined candidates, then two difficulties can be appeared. First, a discrete optimization process should be followed against material parameters. Second, properties of different alternatives materials may not indicate any obvious correlation in the given list. The main goal is to choose material with best characteristic among alternatives.

Table 1. shows suggested nine materials with their characteristics in a gear material selection process.
To choose the best materials, it is recommended [4-8] that individual material characteristics be grouped into a set of characteristics indices to reflect particular design goals. The base of this model [5,7] is material characteristics charts for a wide range of material selection cases. Two main features of the charts are: fundamental relationships between material characteristics and the ability to choose an optimal material for a particular application based on predefined performance. Therefore, this model taking into account a large number of designs and manufacturing alternatives. It is the reason for introducing a computer aided methodology for the selection of a joining procedure [7,8].

3. MATERIAL PERFORMANCE INDICES

The main characteristics considered in the design of gears are:

- surface fatigue limit (Ssf),
- root bending fatigue limit (Sbf),
- wear resistance of tooth’s flank and
- machinability.

Therefore, definition of material characteristics indices should be based on relationships characterizing these criteria. From a material selection aspect, the surface fatigue failure (Fig.1),[9,10] is pitting when due to excessive Hertzain stress, is cyclic loading, relatively smooth - bottomed cavities appear or near contact surfaces. Another form of surface fatigue failure is spalling when areas of the skin flake away due to a continuation of pitting. When gears have surface hardened, this failure can occur due to the formation of cracks in sub-surface or on surface of case [9,11].

The relationship between modified surface limit (Sm) and surface fatigue limit of material can be express as:

\[
S_m = S_{sf} \cdot a_d \cdot b_r
\]

where, \(a_d\) - is the service life factor (for \(10^7\) cycle it is unity),
\(b_r\) - is reliability factor (for 99% reliability it is unity) and
\(S_{sf}\) - is the nominal surface fatigue limit measured in a laboratory condition for \(10^7\) cycle lifetime, 99% reliability.

\(a_d\) and \(b_r\), are dimensionless design factors.

![Fig. 1. The failed gear due to surface fatigue (a), root bending fatigue (b) ](image)

Estimating of \(a_d\) is performed dependence on material and number of cycles (Fig 2), [12].

It is shown that ultimate gear failure in service is begun:
1) when once or more teeth have completely broken away or
2) the gear unit has been damaged that the vibration and noise levels are not acceptable.
When a crack on the root or surface of a tooth is initiated, a gear may still continue working for a few more cycles until the final breakage occurs. In dependence on a given material and stress magnitude, the total number of cycles \( N \) before final bending fatigue [13] of surface fatigue failure [14] can be defined:

\[
N = N_i + N_p
\]  

(2)

where \( N_i \) and \( N_p \) are the number of cycles required for the crack initiation phase and the crack propagation phase respectively. It is important to choose materials with higher resistance to crack initiation. It means that \( N_i >> N_p \). For a given stress magnitude of \( \sigma_i \), \( N_i \) can be estimated by Basquin S-N low (fig. 3), [13,14]:

\[
N_i = N_D (\sigma_i / \sigma_D)^k
\]  

(3)

where: - \( k \) is a material constant, (and when the \( k \) is smaller the crack initiation phase is the longer),
- \( N_D \) and \( \sigma_D \) correspond to the number of cycles and the stress level at the endurance limit.

If we know that the tooth fails under a cyclic load with an amplitude equal to \( R_m \) and the corresponding number of cycles \( N_{Rm} \) (fig.2) then the simile is for \( S_{sf} \) which corresponding \( N_{sf} \) (10^7 cycles), then follows:

\[
N_i = N_{sf} (\sigma_i / \sigma_{sf})^k, \quad \text{where} \ N_i << N_{sf}
\]  

(4)

\[
k = \frac{\log (N_{sf} / N_{Rm})}{\log (R_m / S_{sf})}, \quad \text{where} \ k > 1
\]  

(5)

If is assumed that \( N_i \approx N \) it can be write \( \sigma_i \approx a_{sf} S_{sf} \) and \( a_{sf} \) may defined as:

\[
a_{sf} = (N_i / N_{sf})^{1/k}, \quad \text{where} \ a_{sf} \geq 1
\]  

(6)

If we don’t know the value of \( S_{sf} \) we can approximating with \( R_m \), as:

\[
S_{sf} \approx 0.5 R_m
\]  

(7)

It can be seen from fig.2 that for a given service life factor \( N_i \) the higher then \( R_m / S_{sf} \) ratio, the higher the service life factor (\( a_{sf} \)), and the higher the modified endurance limit (\( S_{sm} \)). When \( R_m / S_{sf} \) ratio is higher it means that the crack initiation phase is longer (constant horizontal line).

On the base for \( S_{sm} \) to be optimal (eq.1) two material-related performance indices should be maximized:

\[
f_1 = S_{sf}
\]  

(8) and

\[
f_2 = R_m / S_{sf}
\]  

(9)

It can be seen from eq. (9) that optimization of the two indices should ideally yield a higher \( S_{sf} \) and \( R_m \).

Another very important material characteristic for gears is bending fatigues. Figure 3 and 4 show the value of bending fatigue limit of picies for two group gear steels [15].

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**Fig. 2. Basquin S-N curve dependence of material and cycle life factor**

**Fig. 3. Smith’s diagram of bending fatigue strength of hardened and tempered specimen steels**

When the induced bending stress on a gear exceeds nominal bending fatigue limit (\( S_{bf} \)), micro-cracks may loading continues. Similar to eq .1, the modified bending fatigue limit (\( S_{mbf} \)) can be defined as:

\[
S_{mb} = S_{bf} \Pi a_{sf}
\]  

(10)

where \( a_{sf} \) is a set of design factors.

Except \( a_{sf} \) in the analyses of the bending fatigue mode is used factor \( C_s \) which is the function of both surface finish and material hardness (HB). Where HB related characteristics index is involved:

\[
f_3 = S_{sf} C_s(\text{HB}) / \text{Mpa} /
\]  

(11)
Concerning the longer service lifetime of the teeth under the bending fatigue mode, a fourth material performance index can be involved:

\[ f_4 = \frac{R_m}{S_{bf}} \text{ /Mpa/} \quad (12) \]

For optimal value of \( f_3 \) index requires a higher \( S_{bf} \) and lower HB core, while an optimal value of \( f_4 \) index implies a higher \( \frac{R_m}{S_{bf}} \) ratio.

It means that the decision model for choosing materials should be one with higher \( R_m \) and \( S_{bf} \). Next important characteristic in materials selection for gears is wear resistance of tooth flank. In gearbox and another gear mechanisms abrasion is occasionally a cause of failure. The ensuring groves are normally formed on the tooth flanks and in the direction sliding surface [10].

The rate of wear depth can be expressed by analytical equation [16] as:

\[ w = \mu \rho^{1/2} /HB_{surf} \text{ /mm/s/} \quad (13) \]

where, \( \mu \) – is dimensionless wear coefficient and depends on the wear type, metallurgical compatibility of contact surface and lubrication condition.

The two identical material m is the same,

\( \rho \) – is the surface interface pressure (Mpa),

\( \nu \) - is the sliding velocity (mm/s) and depend on the gear speed and

\( HB_{surf} \) - is the surface hardness.

On the base eq.13 it can be introduce the fifth material-related characteristics index for gears material selection:

\[ f_5 = \frac{HB_{surf}}{HB} \text{ /HB/} \quad (14) \]

Index \( f_5 \) need to be maximized. A good lubrication and case hardened of tooth can reduce wear failure.

Next worth characteristic in gear material selection is machinability. It is known that the total cost of a gear consist of both, manufacturing and material costs. Hence, between two materials of nearly the same fatigue and wear resistance performance, a design should be able to choose the one with better machinability. Machinability criterion can be defined [16] as:

\[ v = 1150t_k (1-A_r)^{1/2} /HB/ \quad (15) \]

where: \( v \) -is the cutting velocity /ft/min/,

\( t_k \) is /BTU/ht/°F/ is thermal conductivity,

HB is the hardness and

\( A_r \) -is the area of reduction at fracture.

From a gear material selection aspect concerning machinability, material related characteristics index can be expressed as:

\[ f_6 = \frac{HB_{core}}{HB} \text{ /HB/} \quad (16) \]

This index \( f_6 \) need to be minimized according eq.15. It means that the cost of machining depends on the parent material hardness core (HB_{core}).

4. EFFECT OF CHARACTERISTICS CRITERIA

The six characteristics index \( f_i \) (i=1,2,3,6) are applied the data given in tab.1, due to finding the upper and lower limit of each data and assuming the best and worst scenarios. For example, for the index \( f_4 \) in eq.14, the lower value is found when \( S_{bf} \) is maximum and \( R_m \) is minimum. The results are shown in tab.2, which represents a modified matrix where alternatives are nine materials and criteria are the six characteristics index, where in original matrix (tab.1) the criteria were the five mechanical material properties.

Next step in material selections is the ranking of alternatives ones based on one characteristics index (tab.2) and its components \( S_{bf} \) and \( R_m \) (tab.1). In the case when numerous material properties are specified and the relative importance of each property is not clear, determinations of the weighting factors can be largely intuitive, which reduces the reliability of selection.

Fig.5. shows ranking of alternative materials with respect to \( S_{bf} \), \( R_m \) and their ratio (\( f_2 \)). It can be seen from fig.5 that both the \( S_{bf} \) and \( R_m \) criteria prefer material I_7 which has a large k exponent in eq.5, whereas the characteristic index suggests I_3 or I_2 material.

If it is used criteria \( f_1 \) and \( f_3 \), which are in conflict with \( f_2 \), then prefer I_1 due to superior cyclic load bearing capacity. In this case when those are conflict and uncertainties a multiple criteria pseudo-fuzzy material selection model is used.

Therefore, to solve the problem of selection of the best material it is used computer i.e. developing special software tools [4-8].
One of the most suitable models is ELECTRA. This model uses a multiple attribute decision making method. This method is capable of ranking candidate materials from the best to the worst while estimating their incomparabilities and indifferences. This method can be particularly useful to account for material data uncertainties. The reliable material selection should encourage candidates with both the highest and the most stable ranks against all sources of uncertainties.

5. CONCLUSION

On the base of presented it can be concluded:

1. Material and process selection are key issues in the optimal design of industrial products.
2. Material selection is a difficult and suitable task due to the immense number of different available materials.
3. When selecting materials for engineering design, a clear understanding of the functional requirements for each individual component is required and various important criteria or factors need to be considered.
4. Material selection factors include: mechanical properties, physical properties, chemical properties, machinability, formability, weldability, castability, heat treatability, material cost, product cost, product shape, material impact on environment, availability, market trends, recycling, etc.
5. The development of computers allows a large amount of information to be treated rapidly, and has allowed for the implementation of selection methods without tuning the patience of the engineer.
6. One of the most suitable models is ELECTRA which uses a multiple criteria, where all material performance indices and their uncertainties are accounted for simultaneously. This model is particularly suitable for gear material selection.
7. For gear material selection purposes are used six indices: surface fatigue limit index, bending fatigue limit index, surface fatigue lifetime index, bending fatigue lifetime index, wear resistance of tooth flank index and machinability index.

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