Material Selection and Grade Optimization Applied to Aluminum Matrix Composites

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A general model for the optimal use of materials based on structural optimization is derived. The competitiveness of materials is assessed with merit parameters. The competition between materials (*material selection optimization*) and the role of the composition and microstructure for a given material (*grade optimization*) are analyzed. The model is applied to aluminum matrix composites. The influence of matrix material, amount of reinforcement, and value of weight savings is studied. Mechanical properties are analyzed with the aid of published experimental data and available models. The Tsai-Halpin model is used to represent the variation of the elastic modulus with the amount of reinforcement. For yield strength the modified shear lag model is applied. It can satisfactorily describe experimental data and the variation with reinforcement for high-strength matrix alloys. For aluminum alloys of medium and lower strength, the observed increase is larger than the predicted one. This can be explained with the help of more recently developed micromechanical models that take into account the changes in microstructure in the matrix. For structural parts, large values of weight savings are usually necessary to make the particulate-reinforced composites competitive with carbon steel or their parent aluminum alloys. In other applications, combinations of properties are important to make the composites competitive.

Keywords
aluminum, material optimization, merit parameter, metal matrix

1. Introduction

DURING the last decades there has been intense research on metal matrix composites (MMCs). These materials have also found a number of applications, especially aluminum-base materials. Examples are pistons in engines, brake discs in automobiles, and bicycle frames. For surveys of potential and realized applications, see Ref 1 to 4.

However, MMCs are not commercially well established. In fact, for MMCs and many other types of advanced materials, the total number of applications is limited in comparison to the large efforts that have been spent on research and development. There are a number of reasons why it is difficult to achieve commercial success with advanced materials:

- Some materials have excellent values for some properties but have lower values for certain crucial properties than conventional materials do. For example, in some materials the ductility or the toughness can be significantly reduced if the strength is raised.
- The scatter in properties may be large (i.e., it may be difficult to predict which property values a given piece of material actually has). A contributing factor to the uncertainty in property values is the limited database for new materials.
- The processing of advanced materials is complex and expensive. High-precision and high-purity source materials are frequently required.
- Advanced materials are usually tried in high-performance applications to justify their higher cost. Consequently the requirements for high and reliable property values are strict.
- If the ductility or toughness is low, an advanced material is less forgiving than a conventional material, so accurate and systematic design is essential.

It is evident that introducing MMCs into a new application is not a simple task. It is essential to use systematic procedures; nonsystematic or intuitive approaches may lead to solutions that are far from optimal. This paper presents the fundamental principles for judging the competitiveness of advanced materials, and it applies these principles to MMCs.

2. Material Selection and Grade Optimization

2.1 *Problem Formulation*

Optimal use of materials involves many types of problems, such as:

- Finding the material that satisfies all the requirements and has the lowest overall cost
- Finding the material that maximizes performance at a given cost
- Finding the shape of a component that makes the best use of the material (e.g., yields the lowest weight)
- Finding the composition of a material that maximizes the loading capacity

These types of problems have a number of characteristic features:

- Some quantity is minimized or maximized (i.e., optimization is involved).
- Component geometry must be considered.
- Many material properties are important, and some of these properties have a direct influence on the component geometry.
- Both the material and the component have to satisfy a number of requirements.

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- For advanced materials in particular, and often for conventional materials as well, the properties must be adapted to the application in question. This implies that composition and microstructure play a role.

Clearly, several types of variables must be taken into account: geometrical variables, material properties, and microstructural quantities. In many material applications, there is close interaction between these variables.

A mathematical formulation of the problem will now be given. First, an *objective function* w is given. The objective function is assumed to be minimized (this does not imply any limitation because it is only to change the sign of the function that is to be maximized):

$$\min w(\mathbf{x}, \mathbf{P}) \qquad \text{(Eq 1)}$$

For example, w can be the material cost, the weight of the component, or a linear combination of these. **P** is the material propreties.

In general, the objective function depends on the *geometrical variables* $\mathbf{x} = (x_1, x_2, x_3, ..., x_n)$ and the material properties P_{lk}. The section thickness, the height of the part, and the width of the part are examples of geometrical variables, also called *sizing variable*s. They control the dimensions and the shape of the part. The geometrical variables are summarized in a vector, **x**. The vectors in this paper are marked by bold symbols. The geometrical variables typically cannot take just any value but have to lie in a certain interval, because the component has to function in combination with other parts of the product:

$$\underline{x}_j \le x_j \le x_j \ (j = 1, ..., n_x) \qquad \text{(Eq 2)}$$

The total number of geometrical variables is n_x. A bar below or above a variable indicates that it is the lower or upper limit, respectively. Other reasons for having lower and upper limits are the restrictions in manufacturing techniques with regard to the product dimensions. Quantities that are allowed to vary during the analysis are called *design variables*, and quantities that are fixed at the outset of the problem are called *design parameters*.

The value of property l for material k is denoted P_{lk}:

$$P_{lk} = P_{lk}(\mathbf{d}) \ (k = 1, ..., n_M) \ (l = 1, ..., n_P) \qquad \text{(Eq 3)}$$

n_P properties for n_M materials are assumed to be involved. The properties can be, for example, the density, material cost, elastic modulus, or maximum allowable stress. The composition and the condition of a material usually have a strong effect on the properties. In Eq 3 this is taken into account by including the microstructural variables $\mathbf{d} = (d_1, d_2, d_3, ..., d_{nd})$. These microstructural variables can be the grain size, particle sizes, phase fractions, and so on. These variables can typically take values only in a certain range:

$$\bar{d}_m \le d_m \le d_m \ (m = 1, ..., n_d) \qquad \text{(Eq 4)}$$

The requirements on a component are given in the *design specification*. From this specification, *design criteria* or *constraints* are derived. Some of these constraints involve only the geometrical variables and take the form of Eq 2. Such criteria are referred to as *geometrical constraints (gi)*. However, for the component to operate satisfactorily, constraints that depend on both the geometrical variables and the property values are present. The number of such constraints is n_g. For example, restrictions on elastic displacements or plastic collapse take the form of Eq 5:

$$g_i(\mathbf{x}, \mathbf{P}) \le 0 (i = 1, ..., n_g) \qquad \text{(Eq 5)}$$

These conditions are identified as *stiffness* and *strength constraints*. The properties present in the constraints influence the final dimensions of the part, so they are referred to as *sizing properties*.

Another group of properties are important in material selection. The criteria for these properties are simply expressed as:

$$\underline{P}_{lk} \le P_{lk} \, 1 \le \bar{P}_{lk} \qquad \text{(Eq 6)}$$

Manufacturing properties are often specified in this way. Thus, for example, a part that is going to be welded must have a minimum weldability. These properties are referred to as *deselecting properties* or *discriminating properties*, because their function is to ensure that only materials satisfying the conditions in Eq 6 are selected. The values of the deselecting properties do not influence the geometry of the part, so the conditions in Eq 6 can be formulated independently of the geometry.

The formulation presented above can be considered a *structural optimization* model (see, for example, Ref 5 and 6). In its original form, *shape optimization*, it has been used for more than two decades. The model above (Eq 1, 2, and 5) with given material properties represents such a formulation. The geometrical variables are the only design variables. In principle, conventional structural optimization can take material selection into account by also allowing the material to be a variable. Surprisingly few such studies have been performed (Ref 7). One reason might be that the conventional formulation does not make the role of the material explicit and therefore makes it more difficult to analyze and interpret.

There are two types of material optimization. In *material selection optimization* (Ref 8), the performance of the component is maximized by choosing the appropriate grade and commercial condition for existing materials. In *grade optimization*, the performance is maximized by adapting the microstructural variables of a given material. In industrial practice, material optimization is rarely handled as a mathematical optimization problem. Instead, phenomenological or intuitive approaches are used. At the very best, these result in a satisfactory rather than an optimum performance. Within the last few years, formal procedures for selection optimization have been made available (Ref 8-12). In these papers, assumptions equivalent to those in Eq 1 to 5 are made, but with only one sizing variable. The analysis is thus concentrated on the materials aspects.

Ideally, grade optimization should be the formal tool for improving properties of available materials. In practice, however, it is more common to have the goal of improving one or more properties, disregarding many constraints that may be involved in the process. In the mathematical framework above, plain improvement of one property or a combination of properties implies maximizing this combination by varying the microstructural variables. Since the maximization of a property is rarely the ultimate goal when using a material, the optimization of an objective function w under given constraints is something entirely different. With the formulation above, this type of problem is possible to handle.

2.2 *Material Optimization with One Sizing Variable*

Consider the special case with only one sizing variable x, where the constraints $(g_l(x))$ take the form

$$g_l(x) \leq P_{lk} \quad (k = 1, ..., N_M) \quad (l = 1, ..., N_P) \qquad \text{(Eq 7)}$$

and where N_m and N_p are the number of materials and sizing properties involved, respectively. Equation 7 has a common form that applies to stiffness and strength constraints. In each constraint, a specific property is involved. For many elementary cases, $g_l(x)$ can be given an explicit form that applies approximately to a more general class of applications. Equation 7 can be expressed as:

$$\frac{A_l}{x^{n_l}} \leq P_{lk} \quad (k = 1, ..., N_M) \quad (l = 1, ..., N_P) \qquad \text{(Eq 8)}$$

where A_l and n_l are positive constants. The constraints can then be rewritten as:

$$x \geq \left(\frac{A_l}{P_{lk}}\right)^{1/n_l} \quad (k = 1, ..., N_M) \quad (l = 1, ..., N_P) \qquad \text{(Eq 9)}$$

The objective function is assumed to take the form

$$\min w(x) = \rho_k C_k V(x) + \rho_k C_w V(x) \qquad \text{(Eq 10)}$$

where $w(x)$ is the linear combination of the material cost and the weight of the part. Pk is the material density is the material cost per unit weight. The weight constant C_w is the value of saving one unit weight of the material. C_w is therefore called the value of weight savings. In the same way as for $g_l(x)$, $V(x)$ is written as:

$$V(x) = \frac{B}{x^{\nu}} \qquad \text{(Eq 11)}$$

where B and ν are positive constants. Equations 9 and 11 can be given a more general form if needed (Ref 11). Since only one sizing variable is involved, one constraint from either Eq 2 or 9 controls the value of the objective function. Two alternative expressions for $w(x)$ are obtained by combining these constraints with Eq 10 and 11:

$$\min w(x) = \rho_k(C_k + C_w)B\left(\frac{A_l}{P_{lk}}\right)^{\nu/n_l} \qquad \text{(Eq 12)}$$

$$\min w(x) = \rho_k(C_k + C_w)\left(\frac{B}{\underline{x}}\right)^{\nu} \qquad \text{(Eq 13)}$$

The material is selected that minimizes $w(x)$, that is, the inverse of the material-dependent part should be maximized:

$$\max Q_{P_{lk}} = \frac{P_{lk}(\mathbf{d})^{\nu/n_l}}{\rho_k(\mathbf{d})[C_k(\mathbf{d}) + C_w]} \qquad \text{(Eq 14)}$$

$$\max Q_x = \frac{1}{\rho_k(\mathbf{d})[C_k(\mathbf{d}) + C_w]} \qquad \text{(Eq 15)}$$

The expressions $Q_{P_{lk}}$ *and* Q_x are called *merit parameters* (also *merit indices* or *merit factors*, Ref 13). The dependence of the microstructural variables **d** is indicated explicitly. Maximizing the merit parameters $Q_{P_{lk}}$ *and* Q_x, and thereby minimizing the object function w, is an example of material selection optimization. If instead the maximization is performed by varying the microstructural variables **d**, this is material grade optimization.

In a less general form, Eq 14 and 15 were originally presented in Ref 9.

2.3 *Description of Competitiveness*

The competitiveness of two materials, I and II, can be compared with respect to one property, P, with the help of Eq 14. Material II is preferable to material I if the following relation is satisfied:

$$\frac{P_{II}}{P_I} > \left[\frac{\rho_{II}(C_{II} + C_w)}{\rho_I(C_I + C_w)}\right]^{n/\nu} \qquad \text{(Eq 16)}$$

Figure 1 illustrates the relation in Eq 16 for the case where the value of weight savings $C_w = 0$. On the ordinate the minimum property ratio P_{II}/P_I to satisfy Eq 16 is given. For low exponents ν/n an unfavorable cost ratio $\rho_{II}\ C_{II}/P_I\ C_I$ must be compensated with a high property ratio. Exponents $\nu/n < 1$ are much more common in actual design cases than $\nu/n > 1$. This has important consequences for advanced materials, which typically have a high cost ratio in comparison to conventional materials. Still larger property ratios are required. Only for high exponents ν/n can an increase in cost be counterbalanced by a smaller property ratio. Unfortunately, high exponents are encountered only in very special cases.

In Fig. 2 the merit parameter Q_P according to Eq 14 is shown as a function of the ratio of the value of weight savings and the cost of the reference material C_w/C_I. The merit parameter is given as the ratio Q_P^{II}/Q_P^{I}. Only the relative values of merit parameters are important (Ref 11), so the values are often presented in relation to those of another material. From Fig. 2 it is evident that there are two special cases of Eq 14:

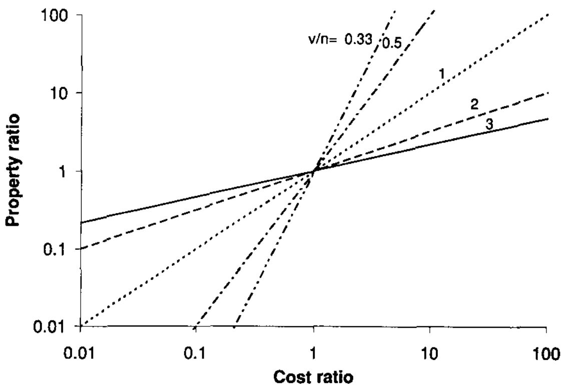

Fig. 1 Minimum property ratio to satisfy Eq 16 as a function of the cost ratio

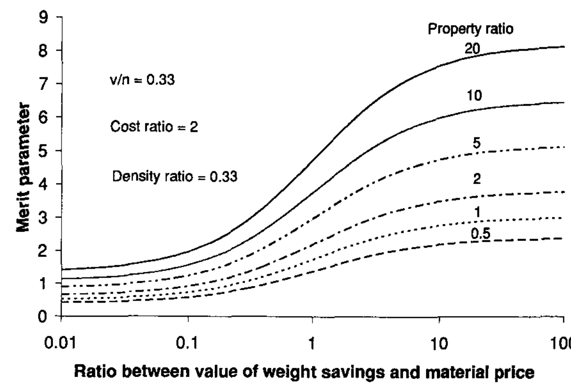

Fig. 2 Merit parameter versus ratio between value of weight savings and material price

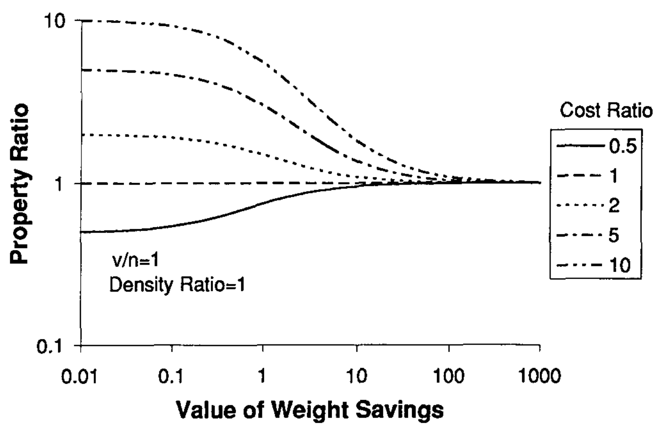

Fig. 3 Minimum property ratio according to Eq 16 as a function of the value of the weight savings at different cost ratios

$$Q_P = \left[\frac{P_{II}}{P_I}\right]^{v/n} \frac{\rho_I C_I}{\rho_{II} C_{II}} \quad (C_w < 0.1 C_I) \qquad \text{(Eq 17)}$$

$$Q_P = \left[\frac{p^{II}}{p^{I}}\right]^{v/n} \frac{\rho_I}{\rho_{II}} \quad (C_w > 10 C_I) \qquad \text{(Eq 18)}$$

In Eq 14, if the value of weight savings C_w is small, the values to be maximized are the ratio between the property value to an exponent v/n_l and the material cost per unit volume. On the other hand, if $C_w >> C_k$ the corresponding quantity is the property value to the same exponent divided by the density.

The presence of the exponent in Eq 18 should be noticed. In the literature, in particular the literature on advanced materials, specific properties are often considered (e.g., the property value divided by the density). According to Eq 18, the specific properties have a clear technical interpretation only when $v/n = 1$ and $C_w > 10\ C_I$, which is often ignored in the literature. By comparing only specific properties, the competitiveness of advanced materials is typically greatly exaggerated. In Fig. 3 the minimum property ratio according to Eq 16 is presented as a function of the value of weight savings at different cost ratios. It is striking how rapidly the competitiveness increases with higher C_w.

If the value of weight savings C_w is neglected in Eq 15, the material cost per unit volume should be minimized. This is done by choosing either the material k or the value of the microstructural variables **d**. It is interesting to compare the role of material cost and the value of weight savings. When one of them is essentially smaller than the other, the former plays no significant role in the same way as in Eq 15. For large values of C_w the density should be minimized in Eq 15.

3. Models for Influence of Reinforcement on Mechanical Properties

The most common way to calculate different properties for MMCs, such as elastic modulus, yield strength, and ultimate tensile strength, is to use the rule of mixtures. A number of models have been developed in which this rule has been modified to improve the results and the agreement with experimental observations. This section summarizes the models that are required to describe the influence of the reinforcement. Composites with particulates are covered. The equations are then used to calculate the merit parameters for structural applications.

3.1 *Elastic Modulus for Discontinuous Fibers and Particulates*

When calculating the elastic modulus for discontinuous fiber- or whisker-reinforced composites, Tsai-Halpin derived equations take into account the ratio between the fiber length l and the fiber diameter d, and the so-called aspect ratio S is used (Ref 14):

$$S = \frac{l}{d} \qquad \text{(Eq 19)}$$

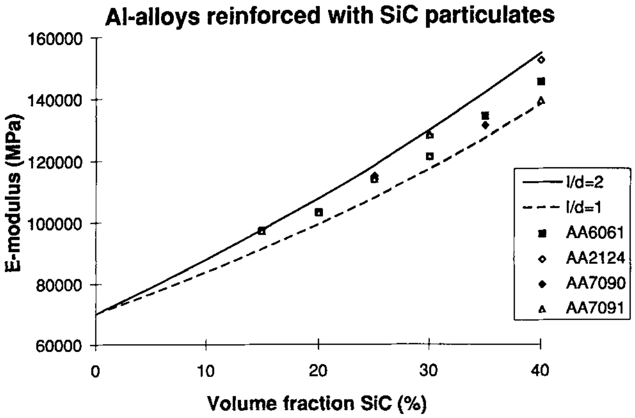

Fig. 4 Elastic modulus versus volume fraction of SiC particulates for different aluminum matrix alloys

The elastic modulus in the fiber direction $E_{//}$ is given by:

$$E_{//} = E_m \frac{1 + 2SbV_f}{1 - bV_f} \quad \text{(Eq 20)}$$

where

$$b = \frac{E_f / E_m - 1}{E_f/E_m + 2S} \quad \text{(Eq 21)}$$

Vf is the volume fraction fibers Fibers. Eq and Em are the elastic moduli of the fibers and the matrix material, respectively. To use the Tsai-Halpin relationship, it is obviously necessary to know the aspect ratios of the fibers. Unfortunately, it is not customary to give the length of whiskers and fibers in the final semiproduct. If the fiber length is presented, it is usually the original length, and original fibers can have aspect ratios up to 100, much higher than in real products. When the composites are cast or wrought, the aspect ratios can decrease to about 4 or 5, which strongly influences the properties.

Another important factor is the fiber alignment. Even if the composite is extruded, the fibers are not perfectly aligned. It has been found, however, that this is only slightly important when the elastic modulus is considered.

The third problem might be an uneven fiber distribution. This seems to be of little significance when estimating the elastic modulus.

Equation 20 can also be used to calculate the elastic modulus for particulate-reinforced composites. Figure 4 shows the elastic modulus versus the volume fraction of SiC(p) for several aluminum matrix alloys. AA 7090 (Al-8Zn-2.5Mg-1Cu-1.5Co) and AA 7091 (Al-6.5Zn-2.5Mg-1.5Cu) are powder metallurgy processed materials, wrought after production (Ref 15, 16). The difference between matrix materials is small, and the results are in agreement with the Tsai-Halpin relationship (Eq 20) for an aspect ratio of 1 to 2, which is reasonable. The particulates usually have an aspect ratio larger than unity, since they are not spherical.

3.2 *Yield Strength of Particulate-Reinforced Composites*

The yield strength of particulate-reinforced composites can be described by the modified shear lag theory. The particulates have been assumed to be in a platelet form; the composite yield strength *R*pc is given by (Ref 17):

$$R_{pc} = R_{pm}\left[\left(\frac{S+4}{4}\right)V_p + V_m\right] \quad \text{(Eq 22)}$$

where *R*pm is the matrix yield strength and *V*m and *V*p are the volume fractions of the matrix and the particulates, respectively. It is important that the value chosen for the matrix yield strength is from a matrix material that was processed in the same way as the composite.

Figure 5 shows the yield strength of the hardenable Al-Mg-Si alloy AA6061-T6 with Al_2O_3(p) (Ref 18). The yield strength of the AA 7090 alloy with SiC(p) is shown in Fig. 6 (Ref 15, 16). This material is produced by powder metallurgy and then extruded. The yield strength seems to decrease at higher values of reinforcement. The agreement with the model is quite acceptable for the material.

If Fig. 5 and 6 are compared, the modified shear lag theory seems to give the best prediction for high-strength alloys. With the help of micromechanical models, this is possible to understand. In high-strength alloys the microstructure is less influenced by the presence of the reinforcement and consequently also the contribution from the microstructure to the strength. It has been claimed that at a high initial yield strength, cracks may form close to the matrix-particulate interface, which reduces the contribution to the strength from the reinforcement (Ref 19, 20). In the modified shear lag theory, it is assumed that the strength of the reinforcement interface is high enough to resist debonding when it is subjected to a load. The distribution of particulates is not usually taken into consideration, even though it is known that commercial composites have reinforcement-dense and reinforcement-free areas. In particulate-free areas, the strength of the matrix dominates, reducing the overall strength of the composite (Ref 17, 21-23).

To fully explain the strength of aluminum composites, the microstructure must be considered. Models have been presented, and the strengthening contributions have been suggested to be linearly additive. The most important contributions are from (Ref 24-26):

- *Grain size strengthening:* The grains are typically smaller in the composite than in the uniform material. The grain size is determined by the recrystallization after the material is thermomechanically processed or heat treated.
- *Substructure strengthening:* This depends on whether the material retains its dislocation structure, which in turns depends on whether the particulates prevent recrystallization on annealing.
- *Work hardening:* This is due to strains between the particulates and the matrix.
- *Quench strengthening:* This is mainly due to an increased dislocation density that is generated because of large differences in the coefficients of thermal expansion between the matrix and the reinforcement.

For a more thorough explanation, see Ref 24 to 26.

Table 1 Materials data used in the merit parameters

Matrix	Cost of matrix, \$/kg	Cost of AMC with 10% particulate, \$/kg	Elastic modulus of matrix, GPa	Yield strength, of matrix, MPa	Density, kg/m^3
AA6061-T6	4	10	70	240	2710
AA2014-T6	4.5	11	73	415	2800
Al-10Si-3Cu-1Ni	3	5	75	...	2700
A356	3	5	75	200	2680
Carbon steel	0.5	...	205	220	7880
Reinforcement particles					
Al_2O_3	≈10	...	300	...	3300
SiC	≈10	...	400	...	3200

AMC, aluminum matrix composite

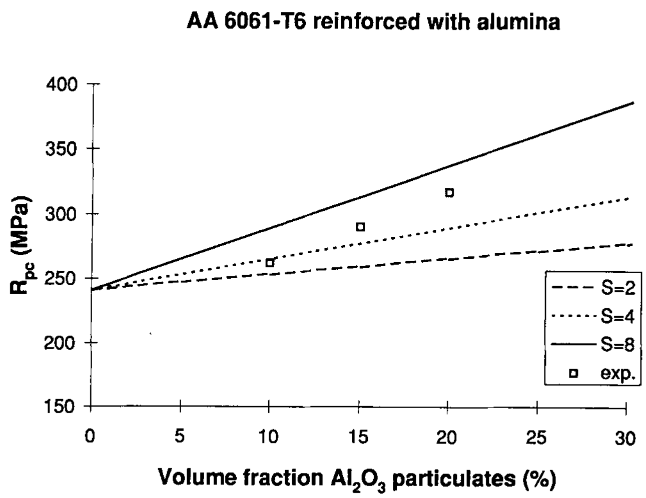

Fig. 5 Yield strength versus volume fraction of alumina particulates for a reinforced AA 6061 alloy with curves representing the theoretical values based on the shear lag analysis according to Eq 22. Source: Ref 18

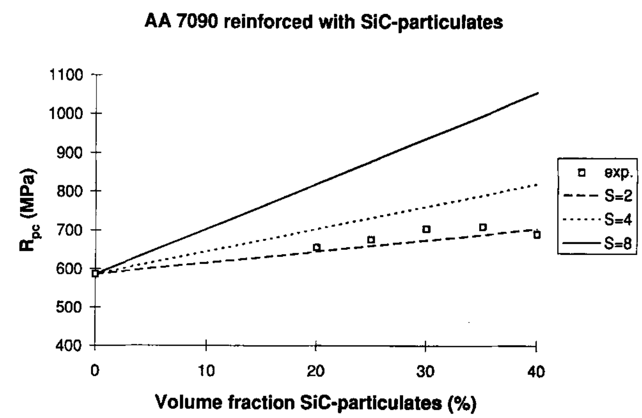

Fig. 6 Yield strength versus volume fraction of SiC particulates for a reinforced AA 7090 alloy with curves representing the theoretical values based on the modified shear lag analysis according to Eq 22. Source: Ref 15

4. Evaluation of Competitiveness Using Merit Parameters

The material data used when computing merit parameters are summarized in Table 1. The material cost is significantly higher for the composite than for the matrix, but cost varies only marginally with the amount of particulates. Material costs are always uncertain and depend on many factors, so the figures in Table 1 should be considered estimates only. The density of the composite was computed with the rule of mixtures from the values of the matrix alloy and the reinforcement. The carbon steel is compared to the composites because this material is used extensively as a structural material. This comparison also makes it possible to study the competitiveness of composites when the reinforcement content is increased.

In Fig. 7 and 8, merit parameters for the elastic modulus are given as a function of the value of weight savings for $v/n_E = {}^1/_3$ and $v/n_E = 1$, respectively. The $v/_{ne}$ value is the same as in section 2.2, where l in $v/_{ne}$ is replaced with the single property E. See also Ref 10,11. The merit parameters are normalized by dividing them with the corresponding value for a carbon steel. Thus, if the merit parameter exceeds unity, the material is competitive with carbon steel; if the merit parameter is below unity; the material is not competitive. The properties for the Al-Mg-Si alloy AA 6061-T6 with Al_2O_3(p) are the same as those derived in the previous section. Hence, the elastic modulus was calculated with the Tsai-Halpin relationship with an aspect ratio of 2, consistent with experimental results.

In Fig. 7, the composite is competitive with carbon steel when the value of weight savings C_w exceeds \$10/kg. However, for the composite to be preferable to the parent metal, C_w must be more than \$80/kg. The amount of Al_2O_3(p) has only a small influence.

In Fig. 8, the situation is reversed for $v/n_E = 1$. The merit parameter of the composite exceeds that of the parent metal at C_w = \$9 to 30/kg, but still higher values are needed to compete with carbon steels. However, the aluminum matrix alloy is never competitive with the carbon steel, as the merit parameter

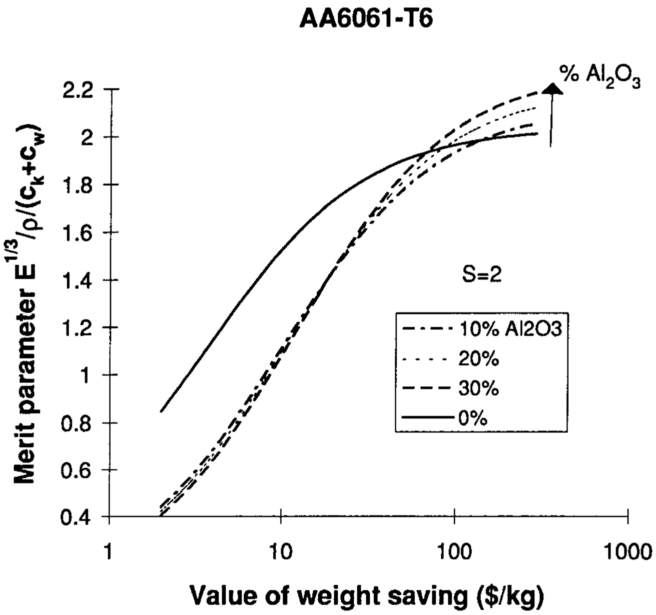

Fig. 7 Merit parameter of the composite divided by the merit parameter of a carbon steel versus the value of weight savings for AA 6061-T6 reinforced with different amounts of alumina. The aspect ratio S is 2.

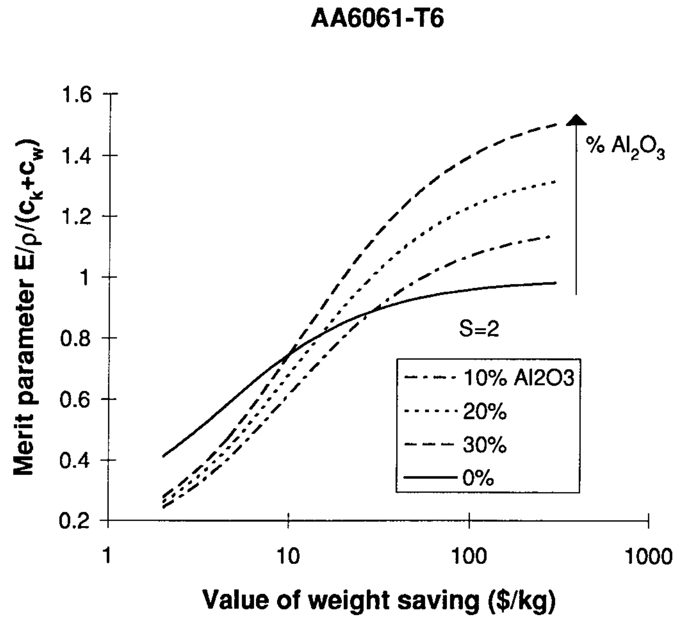

Fig. 8 Merit parameter of the composite divided by the merit parameter of a carbon steel versus the value of weight savings for AA 6061-T6 reinforced with different amounts of alumina. The aspect ratio S is 2.

never reaches unity. For the composite to be of interest, its merit parameter must be significantly larger than both that of the parent metal and that of steel (and other materials). This requires a value of weight savings of at least $50/kg and higher contents of Al_2O_3(p). In addition, the exponent v/n_E must be essentially larger than 1/3

In Fig. 9, three materials are compared with carbon steel at a value of weight savings of $20/kg. The merit parameter increases as a function of volume fraction. The high-pressure die cast material should be considered. The Al-10Si-3Cu-1Ni has the highest values because of low costs. When the yield strength is analyzed, the modified shear lag model is used to derive the merit parameters.

Equation 20 does not take into account the microstructure in the matrix, so an aspect ratio of 2 is not always sufficient to give realistic increases in yield strength. Therefore, two values of S have been used in Fig. 10 and 11. $S = 8$ shows an increase in yield strength with reinforcement, which sometimes represents experimental values better. In Fig. 10, for $v/n_\sigma = ½$ the merit parameters of the composites exceed that of steel, for a value of weight savings of $5/kg. To be competitive with the parent metal, a high aspect ratio and high C_w are needed. In this situation the volume fraction is important. σ is equal to 1 in e.g. Eq. 12. In Fig. 11, values of C_w are lower for $v/n_\sigma = 1$ than for $v/n_\sigma = ½$, which makes the composites competitive. A value σ is equal h 1 in e.g. Eq. 12 of weight savings of about $20 to 30/kg is required for the composite with 30% alumina.

In Fig. 12, the value of weight savings is set to $20/kg. As the volume fraction of reinforcement increases, there is a slight decrease in the merit parameter for AA 2014 because of the low increase in yield strength. For AA 6061 and A 356, the merit parameters increase with particulate content, a consequence of the larger increase in yield strength.

This article has focused on how competitiveness is influenced by reinforcement. However, a thorough examination should include other materials. One example is fiber-reinforced aluminum composites, which are much more expensive than particulate-reinforced composites. In structural applications they become more competitive at high values of weight savings because of higher elastic modulus or higher strength. Other materials to consider are fiber-reinforced plastics, which offer good strength and stiffness properties in relation to their low weight.

5. Discussion

This report has developed a methodology for optimizing the reinforcement content of a composite to achieve the best possible properties for a certain application. The properties depend on the microstructure, the composition of the matrix and fibers/particulates, and the heat treatment and mechanical working (wrought, cast). Merit parameters have been used as a tool where it has been possible to treat the problem as optimization of a larger component instead of just optimization of the microstructure. This method requires that the geometrical form of the component be considered.

Because of the general noncompetitiveness of composites, which is related to their high cost, values of weight savings were also considered, and it was demonstrated that critical areas for using MMCs in structural applications can be found.

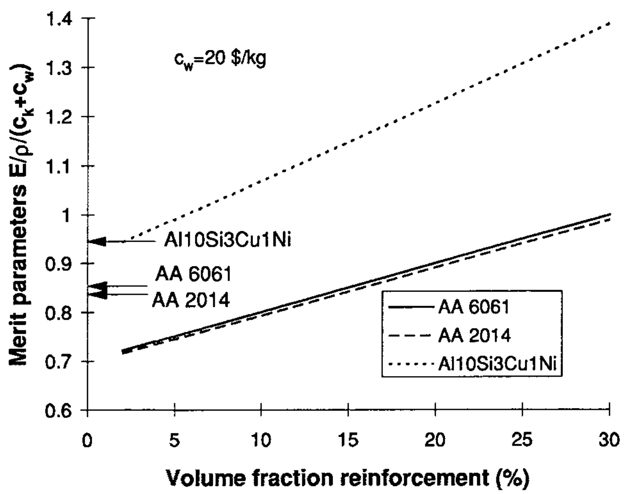

Fig. 9 Merit parameter of the composite divided by the merit parameter of a carbon steel versus the volume fraction of particulates for different materials at a value of weight savings of $20/kg. The aspect ratio S is 2.

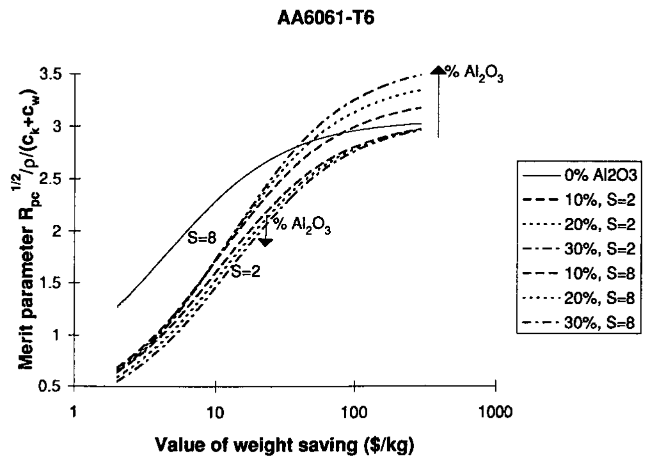

Fig. 10 Merit parameter of the composite divided by the merit parameter of a carbon steel versus the value of weight savings for AA 6061-T6 reinforced with alumina

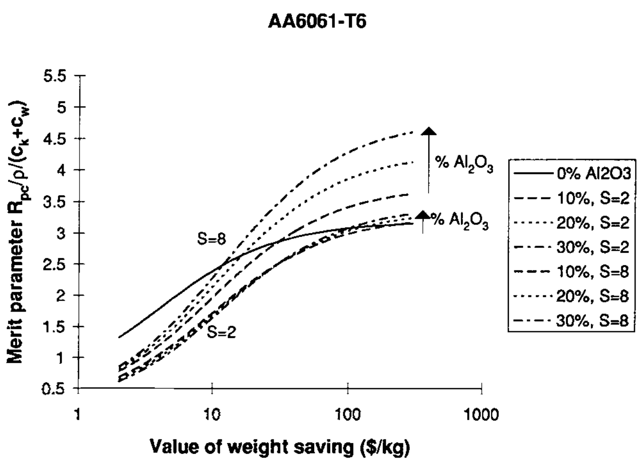

Fig. 11 Merit parameter of the composite divided by the merit parameter of a carbon steel versus the value of weight savings for AA 6061-T6 reinforced with alumina

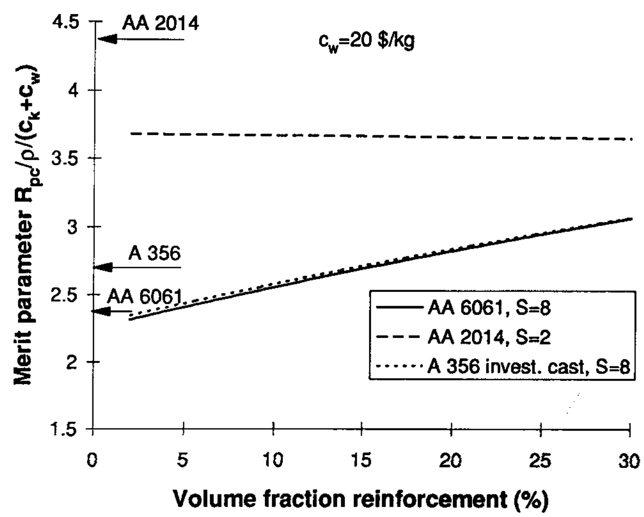

Fig. 12 Merit parameter of the composite divided by the merit parameter of a carbon steel versus the volume fraction of particulates for different materials at a value of weight savings of $20/kg

The literature summarizes values of weight savings that are due to better fuel economy. For example, saved weight is worth about $0.5 to 2/kg in saved fuel in the automotive industry, $100 to 1000/kg in the airplane industry, and $2000/kg or more in the aerospace industry (Ref 3). By comparing different materials, as in the previous section, it is possible to judge when a composite will be competitive with other materials and at what values of weight savings this will happen.

By comparing the costs of different composites, which increase with increased reinforcement content, it is possible to see whether increased reinforcement content will have a positive or negative effect on the competitiveness of the composite. A material property (e.g., elastic modulus or yield strength) must increase more than the cost to make increased reinforcement content worthwhile. This has been evaluated for a few particulate-reinforced materials. Usually, the value of weight savings must be much larger than the composite cost to make the composite competitive with cheaper materials such as steel or the parent material.

Density has a larger influence on the merit parameters when composites are compared to steel than when they are compared to aluminum. This is because the changes in density are small when aluminum is blended with the reinforcements, and at the same time the mechanical properties increase more. The increase in yield strength is lower for the higher-strength alloys, and an increased reinforcement content is then of less use in structural applications. The exponents in the merit parameters have a major influence on when the aluminum composites are competitive. Compared to denser materials, such as steel, the material will be more competitive at lower values of the exponent, while compared to lighter materials, they will be more competitive at higher values of the exponent. It is then possible to compare the required value of weight savings derived and the value of weight savings necessary to make the composites competitive in different applications. It is evident that particulate-reinforced composites can be competitive with conventional aluminum alloys in the airplane industry. The less costly cast ones can be competitive in the automotive industry.

High values of weight savings are usual in sport applications, and many types of advanced materials are used. For example, aluminum composites are competitive for bicycle frames, despite higher cost, because even a small reduction in weight is of great value to the customer. Another example is the choice of an aluminum composite for a golf club head. This, too, is mainly related to weight savings, but some golfers also prefer the feeling of how aluminum hits a ball.

This paper has considered only structural cases, such as cases in which higher stiffness or higher strength is of interest. However, combinations of properties should also be considered, because they can increase competitiveness. For example, this can be the case when wear properties or heat conductivity are to be optimized at the same time that there is a demand on the strength. Consider brake discs in automobiles: Here a low unsprung weight is achieved compared to the case when cast iron is used. Another example is electronic components, in which a low coefficient of thermal expansion and high heat conductivity can prevent thermal fatigue. Combination of properties are also important at high temperatures. For example, for parts in pistons, a low coefficient of thermal expansion is important, again to avoid thermal fatigue, but it is also important to have acceptable wear properties and high-temperature strength, which cannot be achieved by aluminum alone.

6. Conclusion

The role of the reinforcement has been studied for aluminum matrix composites (AMCs). The effect on the mechanical properties has been analyzed with the aid of available models. The models have been used to estimate the competitiveness of AMCs.

- A general model for the optimal use of materials based on structural optimization was derived. In this model the competitiveness of materials can be assessed with merit parameters. Both the competition between materials (*material selection optimization*) and the role of the microstructure for a given material (*grade optimization*) can be analyzed.
- In the model, the Tsai-Halpin equation was used to calculate the merit parameters, since it gives a good representation of the variation of the elastic modulus with the amount of reinforcement.
- The modified shear lag model can satisfactorily describe experimental data for the yield strength of high-strength matrix alloys and its variation with reinforcement. For aluminum alloys of medium and lower strength, the observed increase is larger than the predicted one. This can qualitatively be explained with the help of more recently developed micromechanical models that take into account the changes in microstructure with the introduction of the reinforcement. In particular, the substructure is finer and denser in the presence of the reinforcement, which contributes to the strength.
- With the help of the models for material selection and grade optimization, merit parameters for different design cases were computed. The influence of matrix material, amount of reinforcement, and value of weight savings was studied. Only in special design cases are AMCs competitive with both carbon steel and the matrix alloy. In addition, some other requirements must be fulfilled. For example, when the stiffness is controlling for AA 6061-T6, the volume fraction of Al_2O_3(p) and the value of weight savings must exceed 20% and \$50/kg, respectively. When the yield strength is controlling, the value of weight savings must exceed \$30/kg.
- AMCs can also be competitive in cases where a combination of properties is important, such as strength and wear or strength and heat conductivity.

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