THE ROLE OF THE VALUE OF WEIGHT SAVINGS IN THE USE OF ALUMINIUM MATRIX COMPOSITES

J. Eliasson and R. Sandström
Department of Materials Science and Engineering
Royal Institute of Technology
100 44 Stockholm, Sweden

Abstract

A theory for systematic selection of metal matrix composites has been developed and applied to different kind of components. In this way the competitiveness of the composites in comparison to conventional materials is established. In the model the competitiveness of the materials is assessed with merit parameters. These depend on the geometry of the component, the density of the material, its material cost and some property such as the elastic modulus or the yield strength. By using *material selection optimisation*, the competition between different materials is analysed. It is also possible to select the microstructure to increase the competitiveness of a given AMC by using *grade optimisation*. The influence of matrix material, amount of reinforcement and value of weight saving is studied. The model is applied to a carbon steel, an aluminium composite and its matrix material. Only in special design cases AMCs are competitive both with carbon steel and the matrix alloy. A high value of weight saving is required when structural parts are considered.

Introduction

Aluminium matrix composites have been under development for more than twenty years. During this period the materials have been improved and they often offer excellent material properties. Improved room temperature and elevated temperature strength, elastic modulus and wear resistance compared to the basic material are observed. The good properties in combination with the low density of the materials give them a high application potential in areas such as the space and aeroplane. However, in spite of the good properties these materials applications offer they are not yet used to the expected extent. It is of importance to understand why this is the case by analysing the competitiveness of aluminium matrix composites compared to other materials. In the literature quantities such as the specific modulus (E/ρ), where E is the elastic modulus and ρ the density, or specific strength ($R_{p0.2}/\rho$), where $R_{p0.2}$ is the yield strength, are discussed to motivate the use of advanced materials where weight saving is of importance. These quantities are however of interest only in certain situations, mainly in the aerospace or aeroplane industry. Generally it is necessary to make a more complete analysis of the situation. This includes cost aspects, geometrical factors and also the actual magnitude of the value of weight savings in different applications.

Elastic modulus for discontinuous fibres

When calculating the elastic modulus for discontinuous fibre or whisker reinforced composites, Tsai-Halpin derived equations that take the ratio between the fibre length l and the fibre diameter d into account, the so called aspect ratio S, are used (1).

$$S = \frac{l}{d} \tag{1}$$

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

$$E_{//} = E_m \frac{1 + 2SbV_f}{1 - bV_f} \tag{2}$$

The constant b has the following meaning:

$$b = \frac{E_f/E_m - 1}{E_f/E_m + 2S} \tag{3}$$

where E_f and E_m are the elastic modulus of the fibre and the matrix respectively and V_f is the volume fraction reinforcement.

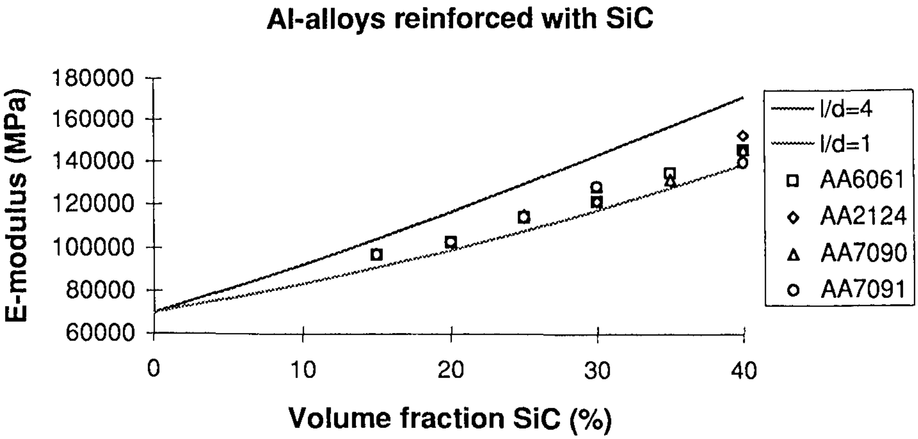

Figure. 1. E-modulus vs. volume fraction SiC- particulates for reinforced AA 6061, AA 2124, AA 7090 and AA 7091 (2, 3) with curves representing the theoretical values based on eqn. (2).

Fig. 1 shows the elastic modulus vs. volume fraction particulates of SiC for different matrix materials. 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 (2, 3). The difference between matrix materials is small and the results are in agreement with the Tsai-Halpin relationship, eqn. (2), for an aspect ratio l/d of 1-2, which is reasonable for particulate reinforced composites.

Evaluation of competitiveness with merit parameters

The technical importance of optimal use of materials is evident to everyone. The steadily increasing number of materials available gives an increased competition between materials. This extensive competition occurs both for conventional materials and for more advanced types. To meet the competition the total material and manufacturing cost of components should be made as low as possible at the same time as the functional requirements should be satisfied. In principle it can be considered as *structural optimisation.* If the structural optimisation is based on the use of materials this can be referred to as material optimisation.

In material optimisation merit parameters are used to analyse the competitiveness of materials. A few examples of specific merit parameters for Al-MMCs will now be discussed. For the elastic modulus and the strength they take the form (4):

$$max\,Q_E = \frac{E^{v/n_E}}{\rho(C_k + C_w)} \tag{4}$$

$$max\,Q_\sigma = \frac{\sigma^{v/n_\sigma}}{\rho(C_k + C_w)} \tag{5}$$

E is the elastic modulus, σ_k the yield or tensile strength, ρ the density, C_k the material cost and C_w the value of weight savings. k is the material index. The merit parameters Q_E and Q_σ should be maximised by choosing the material. The exponent v/n_E and v/n_σ frequently take values in the range from 1/3 to 1 and 1/2 to 1 respectively. Thus for example, subjecting a member to a bending moment and optimising the width, the v/n_E value is unity. If instead the height is optimised, the v/n_E value is 1/3. For the yield strength, the v/n_σ value is unity if the width is optimised. If instead the height is optimised the v/n_σ value is 0.5.

The most common way to represent merit parameters in the literature is to compare the specific stiffness, i.e. the elastic modulus divided by the density of the material, (E/ρ), and specific strength, i.e. the yield strength divided by the density, ($R_{p0.2}/\rho$). In terms of materials optimisation this corresponds most closely to weight minimisation. In eqn.(4-5) this case is obtained by assuming that $C_w >> C_k$ and hence C_k can be neglected. Since it is only the relative values of the merit parameters which are importance the constant C_w can be ignored. Thus the merit parameters take the following form under weight optimisation (5). The presence of the exponents in eqns. (6-7) should be noticed.

$$max Q_{Ew} = \frac{E^{v/n_E}}{\rho} \qquad (6)$$

$$max Q_{\sigma w} = \frac{\sigma^{v/n_\sigma}}{\rho} \qquad (7)$$

When considering Al-MMCs these merit parameters are quite high compared to e.g. steel, and also higher compared to the uniform Al-matrix material, in particular if the exponents are neglected. Unfortunately weight optimisation is not as common in practice as might be imagined. The condition $C_w >> C_k$ is satisfied only in special cases such as aerospace applications and certain sport equipment. For the majority of the engineering applications the material cost must be taken into account.

The value of weight savings C_w is mainly of importance in transport applications. Weight savings play a significant role to save energy. The merit parameters in eqns. (4-5) can then be expressed as $E^{v/n_E}/\rho c_k$ and $\sigma^{v/n_E}/\rho c_k$, respectively. Because of the high costs, MMCs will not automatically be competitive. In most cases both C_w and C_k must be taken into account and the full expressions (4-5) used. In particular in automotive and other transport areas.

In Table 1 the material data used to compute the merit parameters is summarised. Only the elastic modulus is considered in this article. The material cost is significantly higher for the composite than for the matrix. However, the cost varies only marginally with the amount of particulates (~1 $/kg per 10% particulates). It should be recognised that the material costs always depend on many factors. The costs should hence be considered as estimates. The density of the composite is computed with a rule of mixture from the values of the matrix alloy and the reinforcement.

Table 1 Materials data used in the merit parameters

Matrix	Cost, matrix, ($/kg)	Cost, AMC, 10% part., ($/kg)	E-modulus, matrix, (GPa)	Density (kg/m^3)
AA6061-T6	4	10	70	2710
Carbon steel	0.5		205	7880
Reinforcement particles				
Al_2O_3	≈10		300	3300

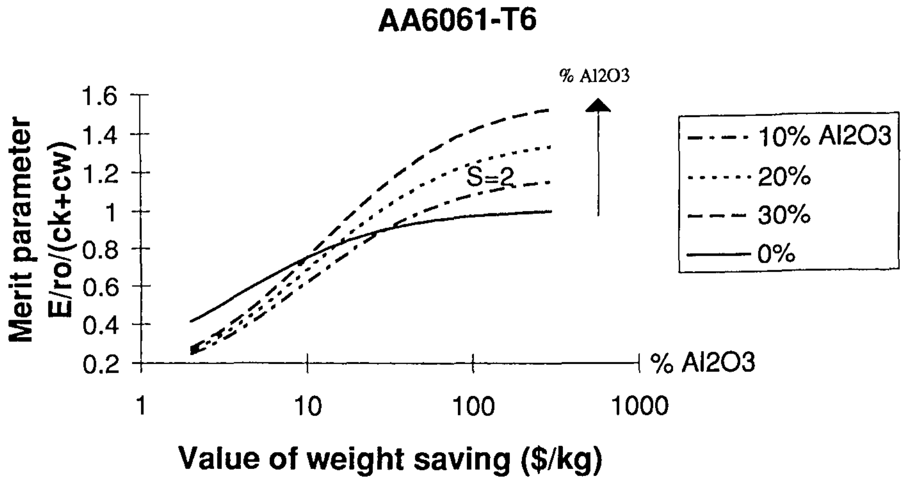

Figure 2. Merit parameter of the composite divided by the merit parameter of a carbon steel vs. value of weight saving for AA 6061-T6 reinforced with different amounts of alumina. The aspect ratio S is 2.

In Fig. 2 merit parameters for the elastic modulus is given as a function of the value of weight savings for $v/n_E = 1$. The merit parameters are normalised 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 it is below unity it is not. The properties for the AA 6061-T6 material 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. The merit parameter of the composite exceeds that of the parents metal at C_w = 9 to 30 $/kg but still higher values are needed to compete with carbon steels. However, the Al-matrix alloy is never competitive with the carbon steel, as the merit parameter does not reach 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).

The same merit parameters as in Fig. 2 are presented as a function of Al_2O_3 (p) content in Fig. 3. Also here the Tsai- Halpin relationship has been used to compute the elastic modulus. In this figure, the competitiveness as a function of reinforcement content can be studied. At low values of weight savings the competitiveness increases only marginally with the reinforcement content. Not until high values there is a larger increase. When $v/n_E = 1$ the value of weight savings must be 50 $/kg to make the composite competitive, see Fig. 3.

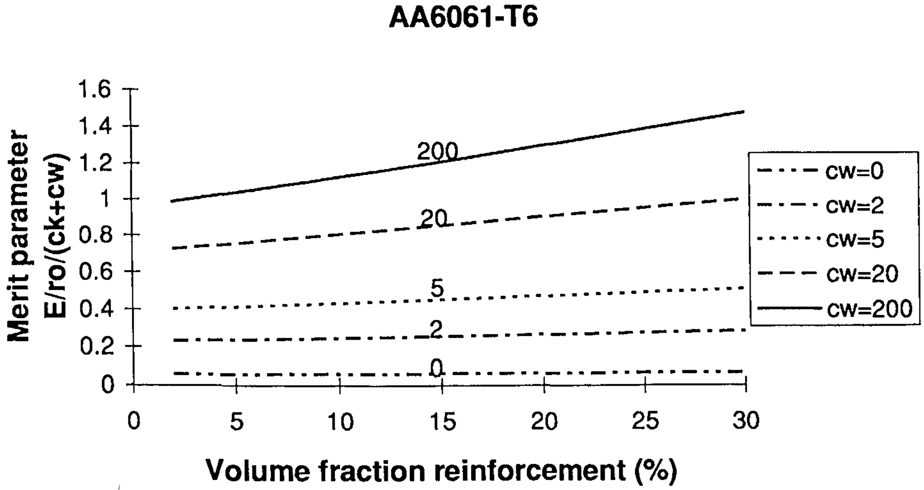

Figure 3. Merit parameter of the composite divided by the merit parameter of a carbon steel vs. volume fraction alumina particulates in AA 6061-T6 at different values of weight savings. The aspect ratio S is 2.

Application to a drive shaft

In the following example merit parameters are applied to an automotive tubular drive shaft. For this component, the dynamic properties play an important role. The critical speed N_c has to be large enough to avoid that the drive shaft becomes unstable (6). The critical speed is given by

$$N_c = \frac{15\pi}{l^2}\sqrt{\frac{E}{\rho}g(R_0^2 - R_i^2)} \tag{8}$$

for a rotating drive shaft with length l, E-modulus E, density ρ, inner radius R_i, outer radius R_0, and g acceleration due to gravity. If the drive shaft is approximated to be a thin walled tube, the equation is reduced to

$$N_c = \frac{15\pi}{l^2}\sqrt{2\frac{E}{\rho}gtR_0} \tag{9}$$

where t is the thickness of the tube. It is possible to maximise the critical speed at a given maximum cost of the material $\overline{L_k}$. The cost of the material is given by the equation:

$$L_k = 2\pi\ R_0 t l \rho\ C_k \leq \overline{L_k} \tag{10}$$

The maximum thickness takes the form

$$t_{max} = \frac{\overline{L_k}}{2\pi\ R_0 L\rho\ C_k} \tag{11}$$

Finally the expression for the maximum speed is

$$Max\, N_C = \frac{15\pi}{l^2}\sqrt{\frac{E\overline{L_k}}{2\pi\ R_0 l\rho^2 C_k}} \tag{12}$$

The merit parameter is derived by extracting the material dependent parameters in the equation. This gives the merit parameter:

$$Q_{NC} = \frac{E^{1/2}}{\rho\ C_k^{1/2}} \tag{13}$$

When value of weight savings is considered, the merit parameter becomes

$$Q_{NC} = \frac{E^{1/2}}{\rho(C_k + C_w)^{1/2}} \tag{14}$$

where E is the E-modulus of the composite, ρ the density, C_k the cost of the material, and C_w is the value of weight savings. By comparing the merit parameters at different values of C_w it is possible to estimate the value of weight savings necessary to make the composite competitive.
In this example a AA 6061/Al_2O_3/20p is considered, where is the E-modulus of the composite is 100 GPa, the E-modulus of the matrix 70 GPa, the density of the composite 2910 kg/m^3, the density of the matrix 2710 kg/m^3, the cost of the composite 11 \$/kg, and the cost of the matrix 4 \$/kg. The composite is also compared to a carbon steel where E= 205 GPa, ρ=7880 kg/m^3 and C_k = 0.5 \$/kg. The required value of weight savings is according to the calculations 25 \$/kg when compared to AA 6061. In comparison to carbon steel a value of weight savings of 4 \$/kg is necessary to make the composite competitive. Thus, at least C_w = 25 \$/kg is needed to make the composite the optimum material.

Conclusions

In this article the Tsai-Halpin model has been used to calculate the elastic modulus for aluminium matrix composites. The model that is in good coherence with experimental data has then been used to compute merit parameters. With help from the merit parameters the competitiveness of materials can be studied. It is possible to study the competition between materials, *material selection optimisation* and the role of the microstructure for a given material, which is *grade optimisation.* For the single case in this article high values of weight savings are needed to make the aluminium matrix composites competitive with the studied aluminium alloy and carbon steel. The model is also applied to a drive shaft.

Acknowledgements

Financial support from the Swedish National Board for Technical and Industrial Development is gratefully acknowledged. Dr. Dag Richter is thanked for supplying data.

References

1. S.V Nair, J.K Tien and R.C Bates, International metals reviews, 30, (1985), 275-290.

2. Engineered Materials Handbook, Vol. 1, Composites, ASM International, (1987)

3. "Increasing focus on silicon carbide-reinforced aluminium composites", Light metal age, June issue, (1986), 7-15.

4. R. Sandström, "Systematic selection of materials in light weight design", IV Scand. Symp. Materials Science, Trondheim (1986), 255-268

5. R. Sandström, "New principles for systematic material selection using merit parameters", Conf. on Modern Design Principles, Tapir, Trondheim (1988), 55-74

6. W. Hoover, Automotive Technology International, (1992), 191-193.