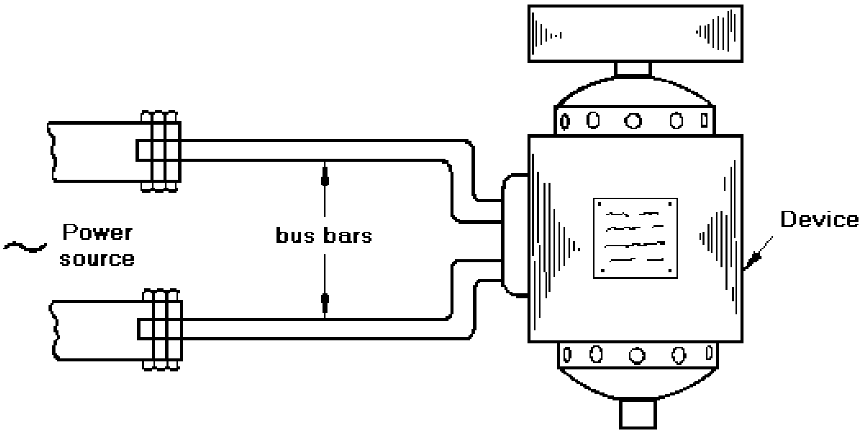
CES EduPack Case Studies:

Electro-Mechanical Applications



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GRANTA
TEACHING RESOURCES

This case study document is part of a set based on Mike Ashby's books to help introduce students to materials, processes and rational selection.
The Teaching Resources website aims to support teaching of materials-related courses in Design, Engineering and Science.
Resources come in various formats and are aimed primarily at undergraduate education.

About These Case Studies

These case studies were created with the help of Prof. Yves Brechet, Prof. David Embury, Dr. Norman Fleck, Dr. Jeff Wood, and Dr. Paul Weaver. Thanks also to Mr. Ken Wallace, the Director of the Cambridge University Engineering Design Centre and to the Engineering and Physical Sciences Research Council for their support of research into Materials Selection.

We are indebted to Ericka Jacobs for her help with proof reading the final manuscript, editing the graphics, and laying-out the entire book.

Contents

1 Introduction

This document is a collection of case studies in Materials Selection. They illustrate the use of a selection methodology, and its software-implementation, the CES EduPack™. It is used to select candidate materials for a wide range of applications: mechanical, thermal, electrical, and combinations of these. Each case study addresses the question: out of all the materials available to the engineer, how can a short list of promising candidates be identified?

The analysis, throughout, is kept as simple as possible whilst still retaining the key physical aspects which identify the selection criteria. These criteria are then applied to materials selection charts created by CES EduPack, either singly, or in sequence, to isolate the subset of materials best suited for the application. Do not be put off by the simplifications in the analyses; the best choice of material is determined by function, objectives and constraints and is largely independent of the finer details of the design. Many of the case studies are generic: those for beams, springs, flywheels, pivots, flexible couplings, pressure vessels and precision instruments are examples. The criteria they yield are basic to the proper selection of a material for these applications.

There is no pretense that the case studies presented here are complete or exhaustive. They should be seen as an initial statement of a problem: how can you select the small subset of most promising candidates, from the vast menu of available materials? They are designed to illustrate the method, which can be adapted and extended as the user desires. Remember: design is open ended — there are many solutions. Each can be used as the starting point for a more detailed examination: it identifies the objectives and constraints associated with a given functional component; it gives the simplest level of modeling and analysis; and it illustrates how this can be used to make a selection. Any real design, of course, involves many more considerations. The 'Postscript' and 'Further Reading' sections of each case study give signposts for further information.

1.1 The Design Process

1. What are the steps in developing an original design?

   Answer

   - Identify market need, express as *design requirements*
   - Develop *concepts*: ideas for the ways in which the requirements might be met
   - *Embodiment*: a preliminary development of a concept to verify feasibility and show layout
   - *Detail design*: the layout is translated into detailed drawings (usually as computer files), stresses are analyzed and the design is optimized
   - *Prototyping*: a prototype is manufactured and tested to confirm viability

1.2 From Design Requirements to Constraints

2. Describe and illustrate the “Translation” step of the material selection strategy.

   Answer

   Translation is the conversion of design requirements for a component into a statement of function, constraints, objectives and free variables.

FUNCTION	What does the component do?
OBJECTIVE	What is to be maximized or minimized?
CONSTRAINTS	What non-negotiable conditions must be met?
FREE VARIABLE	What parameters of the problem is the designer free to change?

2 Materials for Bus-Bars

A bus bar is the element of an electrical circuit which delivers the current from the input source to the device which consumes it (Figure 2-1). The flex of a toaster is a bus bar, though one of low current-carrying capacity. Devices which consume large currents require massive bus bars to minimize the electrical losses external to the machine itself.

The current-carrying capacity of a bus bar is limited by temperature rise. Standards set values for this: it is typically 50°C above ambient, or roughly 90°C maximum. It is determined by the balance between the heat input (i2R) and the heat loss by convection, radiation and conduction. Convection and radiation generally dominate. Using typical values for the constants involved, a copper bus bar with a solid circular section can carry about 2 Amps per mm2 of cross section.

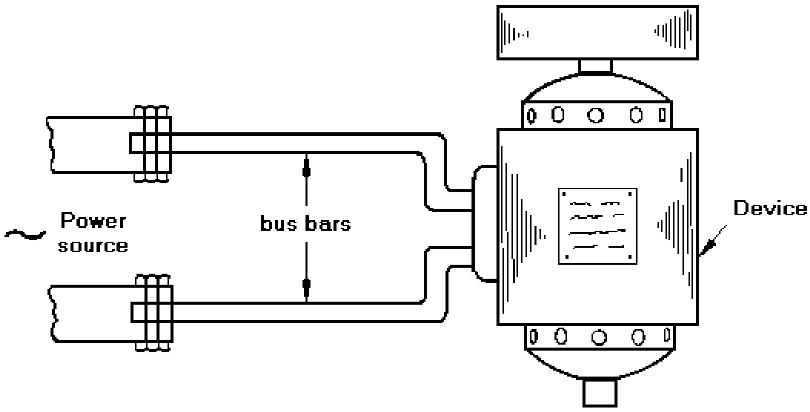

Figure 2-1. Bus bars transmit electrical power from the power source to the device which consumes it.

Bus bars are generally round or rectangular rods. The design criteria include high conductance, low cost, limited temperature rise, sufficient strength to carry self weight and service loads, and corrosion resistance (particularly resistance to oxidation which can create contact resistance at clamped connections). A sensible criterion for choosing a material for a bus bar is that the *life cost* should be minimized. That is, the capital cost, plus the cost of the energy dissipated as heat in the bus bar over its design life should be minimized. If this is used to select the initial subset of materials, other constraints (maximum temperature rise, sufficient strength and so forth) can then be applied. Table 2-1 summarizes the requirements.

Table 2-1. The design requirements

FUNCTION	Bus bar
OBJECTIVE	Minimize life cost (capital cost plus cost of resistive losses)
CONSTRAINTS	(a) Maximum temperature rise < 90°C (b) Adequate strength (c) Adequate oxidation resistance

2.1 The Model

Consider the design of a bus bar to minimize the total life cost, that is, the cost of the material of the bar plus that of the electric losses caused by its resistance. (The shape of the material is simple, so the cost of the bar is almost the same as that of the material.)

The first cost — the material cost — is simply

$$C_1 = C_m \, A \, L \, \rho \qquad \textit{(M 2.1)}$$

where C_m is the cost per kilogram of the material, ρ is its density, A is the cross-section of the bar, and L is its length. The second cost — the resistance loss — is

$$C_2 = C_e i^2 \left(\frac{\rho_e L}{A}\right) t \qquad \textit{(M 2.2)}$$

where C_e is the cost per kilowatt hour of the electricity, t (hours) is the operating life of the bar, and ρ_e the electrical resistivity of the material of which it is made. The life cost is approximately the sum of the two, and it is this that we wish to minimize. A large cross-section, A, gives low resistance but high material cost; a small A does the reverse. We must first locate the minimum value of

$$C = C_1 + C_2 = C_m A \, L \, \rho + C_e i^2 \left(\frac{\rho_e L}{A}\right) t$$

Differentiating this with respect to A and setting the result equal to zero gives the optimum value for the cross-section:

$$A = \left(\frac{C_e \, \rho_e \, i^2 \, t}{C_m \, \rho}\right)^{1/2} \qquad \textit{(M 2.3)}$$

Substituting this back into the cost equation gives the *objective function* as

$$C = 2 \, L \, (C_e \, C_m \, \rho_e \, \rho i^2 \, t)^{1/2} = 2L(C_e \, i^2 \, t)^{1/2}(C_m \, \rho_e \, \rho)^{1/2} \qquad \textit{(M 2.4)}$$

The cost is minimized by selecting the material with the greatest value of

$$\boxed{M_1 = \frac{1}{C_m \, \rho_e \, \rho}} \qquad \textit{(M 2.5)}$$

Strength is important when a bus-bar of large span is unsupported or is exposed to other loads. Then we require a minimum value for the elastic limit, σ_{el}.

2.2 The Selection

Figure 2-2 shows the appropriate chart — the index M_1 plotted against elastic limit σ_{el}, using branches of the materials tree involving conductors.

When strength is not important, the high-conductivity aluminum alloys are the best choice for economical bus bars (Figure 2-2). But this ignores other aspects of choice — particularly those relating to oxidation. Oxidation leads to high contact resistance, and — particularly with aluminum — this causes problems. The next-best choice suggested by Figure 2-3 is that of general purpose (GP) or high-conductivity (HC) coppers, though they are significantly more expensive (lower value of M_1). If strength is also important, the special conductor alloys based on Cu-Be-Co or, under extreme conditions, the composites Cu-Nb(f) or Cu-Al_2O_3(f) become the best choices. Table 2-2 summarizes the selection.

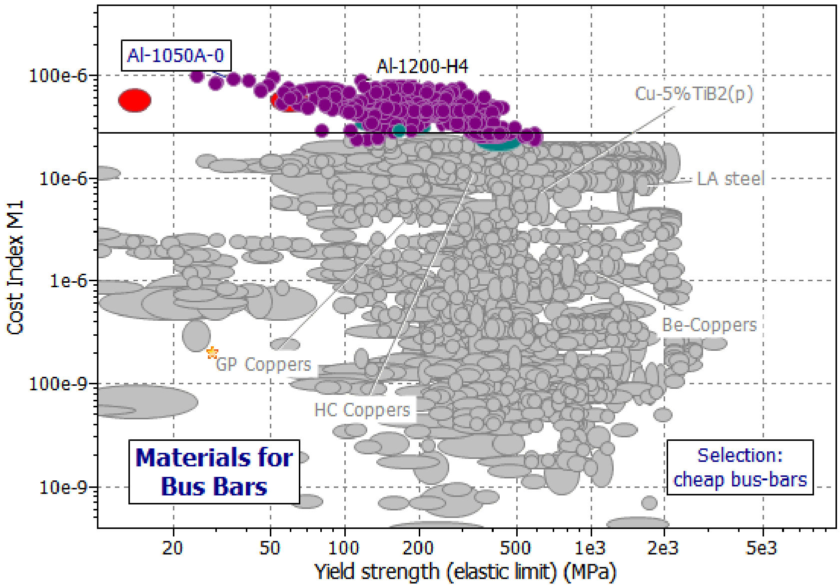

Figure 2-2. A chart of the index M_1 plotted against elastic limit σ_{el}, using branches of the materials tree involving conductors. The selection shows the materials most appropriate for making low cost bus-bars.

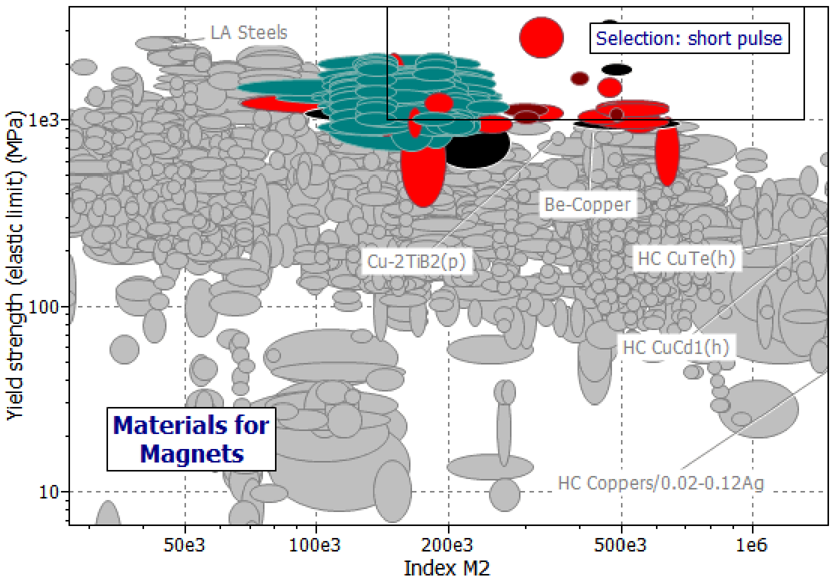

Figure 2-3. A chart of the index M_1 plotted against elastic limit σ_{el}, using branches of the materials tree involving conductors. The selection shows the materials best for making strong bus-bars.

Table 2-2. Materials for bus bars

MATERIAL	COMMENT
1000 series Aluminum alloys	Cheapest, by a substantial margin
HC Coppers, GP Coppers	More resistant to oxidation than Al
Beryllium-coppers	High strength applications
Copper-based composites	Expensive, but strong, low resistance

2.3 Postscript

The optimization of equation (M 2.3) gives the cheapest choice of bus bar as that for which the capital cost and the cost of the power dissipation are about equal. In general this means that the temperature of the bus bar rises when in use. So if the flex of your toaster gets warm when you make the toast, be reassured: your bus bar was designed with your pocket in mind.

2.4 Further Reading

'Copper Bus Bar Design Guide', Copper Development Association, Orchard House, Mutton Lane, Potters Bar, Herts EN6 3AP

3 Windings for High-Powered Magnets

Physicists, for reasons of their own, like to see what happens to things in high magnetic fields. 'High' means 50 Tesla or more, so the only way to get such fields is the old-fashioned one: dump a huge current through a wire-wound coil, water-cooled if necessary (Figure 3-1). Permanent magnets have a practical field strength limit of 1.5T. Superconducting coils currently are limited to 25T.

The current generates a field-pulse which lasts as long as the current flows. The limits on the field and its duration are set by the material of the coil itself; exceed the limits and the coil either blows itself apart or melts. So choosing the right material for the coil is critical. What should it be? The answer — as we shall show — depends on the pulse duration.

Pulsed fields are classified according to their duration and strength as shown in Table 3-1. Except for the ultra-short pulses, the fields listed in the table are generated in coils which are expected to survive during the pulse. The design requirements are summarized in Table 3-2.

Table 3-1. Classification of pulsed magnetic fields.

Classification	Duration	Field strength
Long	100 ms – 1 s	30 – 60 T
Standard	10 – 100 ms	40 – 70 T
Short	10 – 1000 μs	70 – 80 T
Ultra-short	0.1 – 10 μs	> 100 T

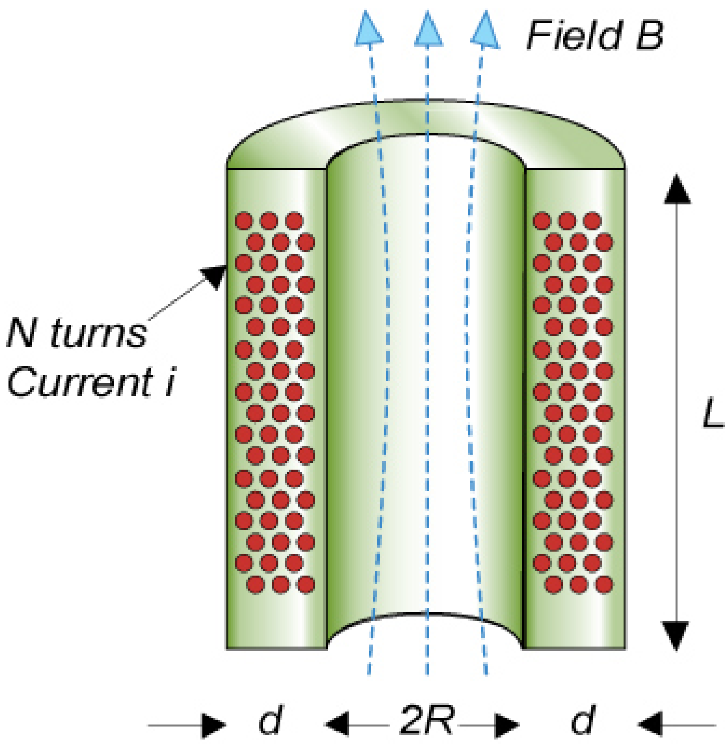

Figure 3-1. Schematic of the high-field magnet

Table 3-2. The design requirements

FUNCTION	Magnet windings
OBJECTIVE	Maximize magnetic field
CONSTRAINTS	a) No mechanical failure (b) Temperature rise < 150°C (c) Radius R and length l of coil specified

3.1 The Model

The magnet is shown schematically in Figure 3-1. We wish to maximize the field and its duration without destroying the windings. First, we consider destruction by magnetic loading. The field, B (units: Weber/m^2), in a long solenoid is:

$$B = \frac{\mu_0 N i}{l} \qquad \text{(M 3.1)}$$

where μ_0 is the permeability of air ($4\pi \times 10^{-7}$ Wb/A.m), N is the number of turns, i is the current and l is the length of the coil. The field creates a force on the current-carrying coil. It acts radially outwards, rather like the pressure in a pressure vessel, with a magnitude

$$p = \frac{B^2}{2\mu_0} \qquad \text{(M 3.2)}$$

This force is a body force, not a surface force. The pressure generates a stress σ in the windings and their casing, given approximately by

$$\sigma = \frac{pR}{d} = \frac{B^2}{2\mu_0} . \frac{R}{d} \qquad \text{(M 3.3)}$$

where d is the thickness of the casing. This stress must not exceed the elastic limit of the windings, and this gives the first constraint on B:

$$B \leq \left(\frac{2\mu_0 \, d\sigma_{el}}{R} \right)^{1/2} \qquad \text{(M 3.4)}$$

The field is maximized by maximizing

$$\boxed{M_1 = \sigma_{el}} \qquad \text{(M 3.5)}$$

It is also important that the windings do not heat up too much. High-powered magnets are initially cooled in liquid nitrogen to -196°C in order to reduce the resistance of the windings. If the windings warm above room temperature, their resistance, in general, becomes too large.

The resistive energy loss in the windings during the pulse is

$$\Delta E = \int i^2 R_e \, dt \;\approx\; i^2 \left(\frac{\rho_e L}{A} \right) t_p \qquad \text{(M 3.6)}$$

where R_e is the resistance of the windings, ρ_e is the electrical resistivity of the conductor material, L is its total length, and A is its cross-section area. For a short pulse, this heat increases the temperature of the windings according to

$$\Delta E = \rho \, A \, L \, C_p \, \Delta T \qquad \text{(M 3.7)}$$

where ρ is the density of the material and Cp is its specific heat capacity.

Equating (M 3.7) and (M 3.7), and eliminating i using (M 3.1) gives

$$\Delta T = \frac{B^2\, l^2\, t_p}{\mu_0\, N^2\, A^2}\left(\frac{\rho_e}{\rho C_\rho}\right) \qquad \text{(M 3.8)}$$

Noting that the geometry of the magnet (Figure 3-1) is such that $NA \approx l\, d$, equation (M 3.8) can be rearranged to give

$$B = \left(\frac{\mu_0^2\, d^2\, C_p\, \rho\, \Delta T}{t_p\, \rho_e}\right)^{1/2} \qquad \text{(M 3.9)}$$

If the temperature is limited to 273 K, then DT ≤ 200 K. The field is maximized by maximizing

$$\boxed{M_2 = \frac{C_p\, \rho}{\rho_e}} \qquad \text{(M 3.10)}$$

The two conditions are independent. They are simultaneously met when the two results for B (equations (M 3.4) and (M 3.7) are equated — that is, on the coupling line

$$\sigma_{el} = \frac{\mu_0\, R\, d\, \Delta\, T}{2\, t_p}\left(\frac{C_p\, \rho}{\rho_e}\right)$$

or

$$\boxed{M_1 = \left(\frac{\mu_0\, R\, d\, \Delta\, T}{2\, t_p}\right) M_2} \qquad \text{(M 3.11)}$$

3.2 The Selection

The selection is illustrated in Figure 3-2, and summarized in Table 3-3. Here we have used the branches of the materials tree involving conductors. The axes are the two indices M_1 and M_2. Two selections are shown, one for short-pulse magnets, the other for those for longer pulses. Each selection box is a contour of constant field, B; its corner lies on the coupling line for that pulse duration.

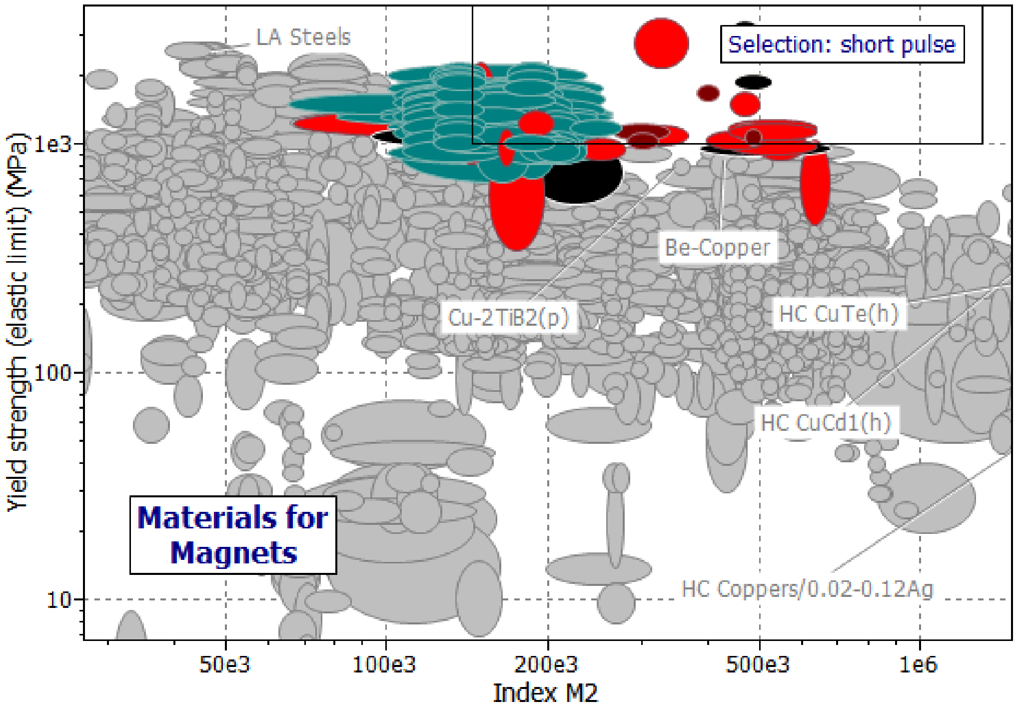

Figure 3-2. A chart showing the strength index, M_1, plotted against temperature-rise index, M_2, using the branches of the materials tree involving conductors. The selection shows those materials best suited to a short pulse.

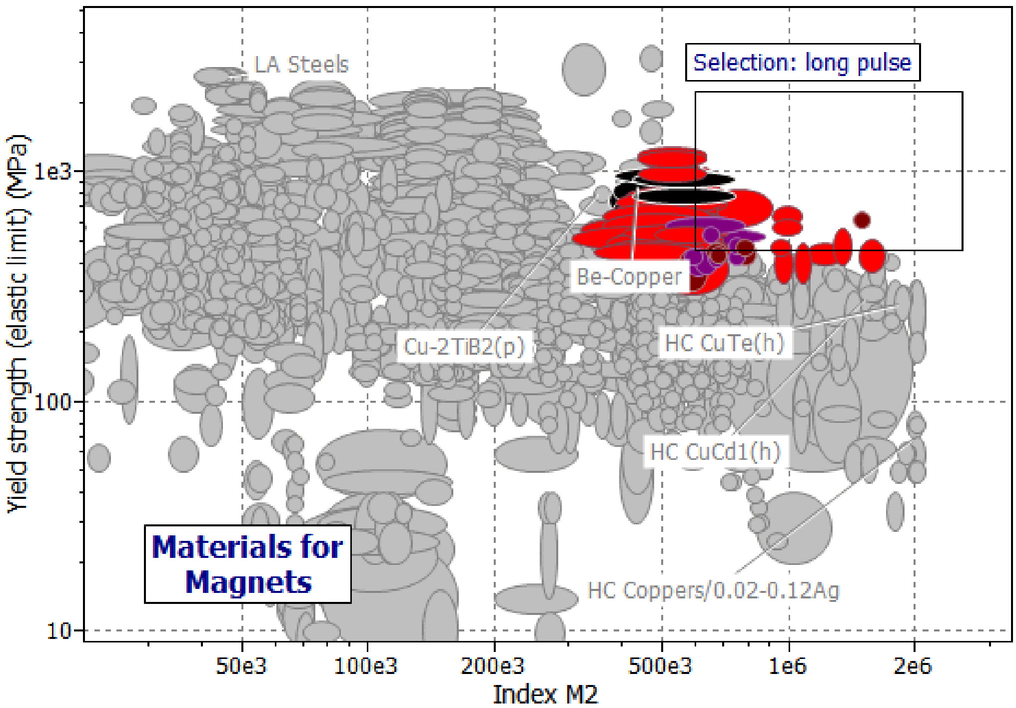

Figure 3-3. A chart showing the strength index, M_1, plotted against temperature-rise index, M_2, using the branches of the materials tree involving conductors. The selection shows those materials best suited to a long pulse.

Table 3-3. Materials for magnet windings

MATERIAL	COMMENT
High conductivity coppers	Best choice for low field, long pulse magnets (heat-limited)
Copper-Al_2O_3 composites (Glidcop)	
H-C Copper Cadmium alloys	Best choice for high field, short pulse magnets (strength-limited)
H-C Copper Zirconium alloys	
H-C Copper Chromium alloys	
Copper-Beryllium alloys	
Drawn copper-niobium composites	

3.3 Postscript

The case study, as developed here, is an oversimplification. Magnet design is, today, very sophisticated, involving nested sets of coils (up to 9 deep), with geometry the most important variable. But the selection scheme for winding materials, has validity: when pulses are long, electrical resistivity is the primary consideration; when they are short, it is strength. Similar considerations enter the selection of materials for very high-speed motors, for bus-bars and for relays. For further information, see (Herlach, 1988).

There are four ways of giving strength to highly-conducting metals: alloying, cabling, macrocomposites and microcomposites. Alloying generally lowers the conductivity too much. Copper cabled with stainless steel wire or aluminum with high-strength steel, gives the strength of one material with the conductivity of the other. Macrocomposites of copper clad in stainless steel, copper-beryllium or titanium have promise. Microcomposites are made by co-drawing two-phase castings or wire bundles of Cu-Nb, Cu-Ta, Cu-V or Cu-Ag, giving sub-micron filaments of one phase in the other, with strength greater than that predicted by the rule of mixtures. All are used to produce high-performance materials for magnet and motor windings.

3.4 Further Reading

Montgomery, DB (1969) ‘Solenoid Magnet Design’, Wiley, Interscience, NY, USA.

Herlach, F (1988) ‘The technology of pulsed high-field magnets’, IEEE Transactions on Magnetics 24, 1049.

Herlach, F, de Vos, G and Witters, S ‘Stresses in coils for strong pulsed magnetic fields’: J. de Physique (1984) 45, C1–915.

Jones, H, Herlach, F, Lee, JA, Whitworth, HM, Day, AG, Jeffrey, DJ, Dew-Hughes, D. and Sheratt, G (1988) ‘50 T pulsed magnets using a copper conductor externally reinforced with stainless steel’: IEEE Transactions on Magnetics 24, 1055.

Saki, Y, Inoue, K, Asano, T, Wada, H and Maeda, H (1991) ‘Development of high-strength high-conductivity Cu-Ag alloys for high-field pulsed magnets’: J. Appl. Phys 57, 2965.

Dew Hughes, D, (1993) ICMC Conference, Kiev (1992) ‘Cryogenics’.

Wood, JT, Embury, JD and Ashby, MF, (1996) ‘An approach to materials processing and selection for high-field magnet design’, to appear in Acta Mater. et Metal.

We wish to thank Dr Jeff Wood and Dr David Cardwell for their help in preparing this case study.

4 Materials for Relay Arms

A relay arm (Figure 4-1) is both an elastic beam and a mini-busbar — that is, a current-carrying conductor in which the i^2R losses must be kept small. The response time of the relay is limited by the lowest natural vibration frequency of the beam, and the dimensions of the beam are also constrained by the requirement that a given opening force, F, can deflect it by the (given) opening deflection, d — that is, its stiffness is prescribed. Furthermore, the beam must not fail by fatigue. We wish to achieve all this while minimizing its electrical resistance. The design requirements are listed in Table 4-1.

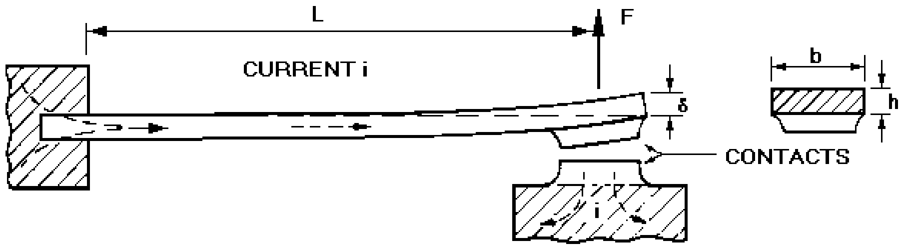

Figure 4-1. A relay arm. It must respond quickly, withstand fatigue loading, and conduct well.

Table 4-1. The design requirements

FUNCTION	Relay arm
OBJECTIVE	Minimize resistive losses
	Minimize response time
CONSTRAINTS	(a) Must not fail in fatigue after > 10^8 cycles
	(b) Length L and opening displacement d specified

4.1 The Model

The arm is modeled as a cantilever beam of length L and section bh (Figure 4-1). The maximum value of width b is fixed by space constraints. The resistive loss when a current i passes along the arm is

$$W_r = i^2\, R = i^2\, \rho_e \frac{L}{bh} \qquad \textit{(M 4.1)}$$

where ρ_e is the electrical resistivity of the material of which the arm is made. This is the quantity to be minimized: it is the *objective function*.

There is a constraint: that of fatigue life. The relay arm, when in the open position, suffers an end-displacement δ, caused by the opening force F. This generates a maximum surface stress in the beam of

$$\sigma = \frac{F\, L\, h}{2\, I} \qquad \textit{(M 4.2)}$$

where $I = bh^3/12$ is the second moment of area of the beam. Force F is related to δ by

$$F = \frac{C_1\, E\, I\, \delta}{L^3} \qquad \textit{(M 4.3)}$$

where C_1 is a constant. (For an end-loaded cantilever, $C_1 = 3$.) Eliminating I by substituting equation (M 4.3) into (M 4.2), and requiring that the stress σ is always less than the endurance limit, σ_e, gives:

$$\sigma = \frac{C_1}{2} E \frac{h\,\delta}{L^2} \leq \sigma_e \qquad \textit{(M 4.4)}$$

This gives an equation for the aspect ratio, h / L of the arm:

$$\frac{h}{L} \leq \frac{2}{C_1} \cdot \frac{L}{\delta} \frac{\sigma_e}{E} \qquad \textit{(M 4.5)}$$

Substituting equation (M 4.4) into the objective function (M 4.1) gives

$$W_r = \frac{C_1}{2} \frac{i^2}{b} \cdot \frac{\delta}{L} \cdot \left[\frac{\rho_e\, E}{\sigma_e}\right] \qquad \textit{(M 4.6)}$$

For a given length L and opening, δ, the resistive loss is minimized by maximizing

$$\boxed{M_1 = \frac{\sigma_e}{\rho_e\, E}} \qquad \textit{(M 4.7)}$$

The second objective is that of minimizing response time. The lowest natural flexural vibration frequency of the cantilever is

$$f = C_2 \sqrt{\frac{E\, I}{\rho\, h\, b\, L^4}} \qquad \textit{(M 4.8)}$$

The frequency is maximized by maximizing

$$\boxed{M_2 = \frac{\sigma_e^2}{\rho\, E}}$$

This is the index for light springs.

4.2 The Selection

Figure 4-2 is a chart with M_1 and M_2 as axes, constructed using the branches of the materials tree involving conductors. The selection depends on the relative importance of the resistive loss and the response time, but it is reasonable, with no further information on this issue, to examine the materials which maximize both: they lie at the top right, and include those listed in Table 4-2. The copper-based composites Cu-Ag(f), Cu-Nb(f) and Cu-Al_2O_3(p) are excellent. Copper-beryllium alloys and phosphor bronzes have outstanding mechanical properties (M_2) but conduct less well.

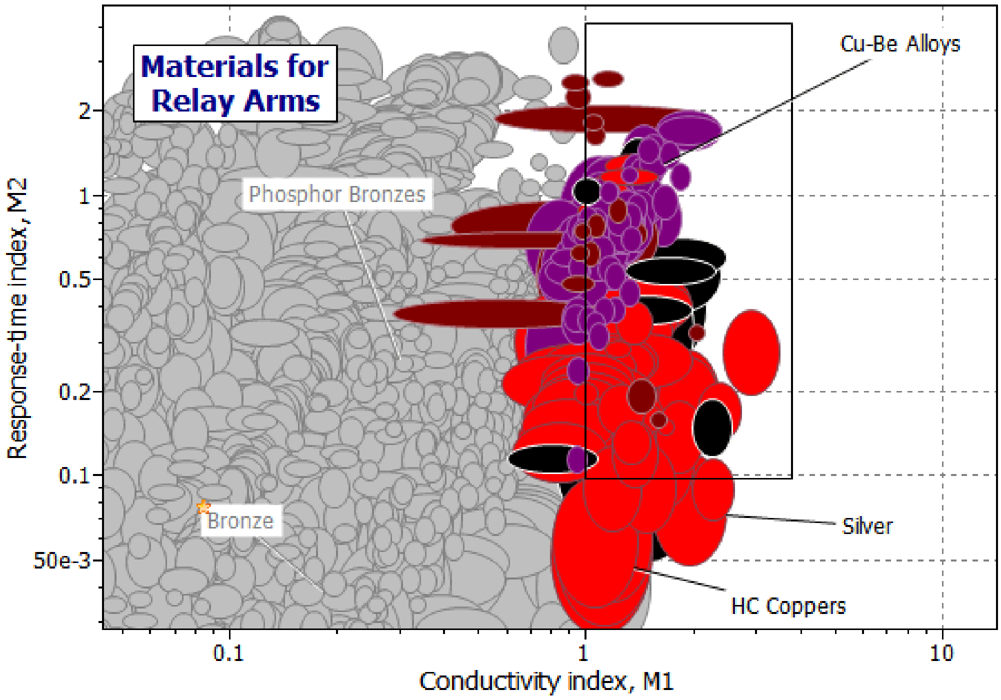

Figure 4-2. A chart with axes of M_1 and M_2, constructed from the Conductors record subset.

Table 4-2. Table 34.2 Materials for relay arms

MATERIAL	COMMENT
Copper-silver composites	Outstanding M_1 and M_2; expensive
Copper-niobium composites	Good M_1, outstanding M_2; expensive
Copper-Al_2O_3(p) composites	Good M_1, outstanding M_2; excellent high-temperature performance; expensive
Cu-Beryllium alloys	Outstanding M_1 and M_2; less expensive than the composites
Phosphor bronzes	Lower performance than Cu-Be, but cheaper

4.3 Postscript

The relay arm is typical of applications in which high electrical conductivity is sought, with the ability to carry repeated flexural loads. Flexible current-loads, spring-contacts and snap-connectors all have this feature.

4.4 Further Reading

Boiten, RG (1963) 'The Mechanics of Instrumentation', Proc. I. Mech. E., 177, No 10, 269–288.

5 Windings for High-Speed Electric Motors

Certain mechanical applications require very high rotational speeds (centrifuges, turbo-molecular pumps, gyroscopes, flywheels). One way of achieving these high speeds is by direct drive from an electric motor (Figure 5-1). The limiting speed may then be set by the motor itself, because the centrifugal forces acting on the rotor windings approach their limiting strength. When this is so, the selection of the material for the rotor windings becomes a critical part of the design. We need a material which is as strong as possible, yet also conducts as well as possible — two conflicting objectives. The design requirements, summarized, appear in Table 5-1.

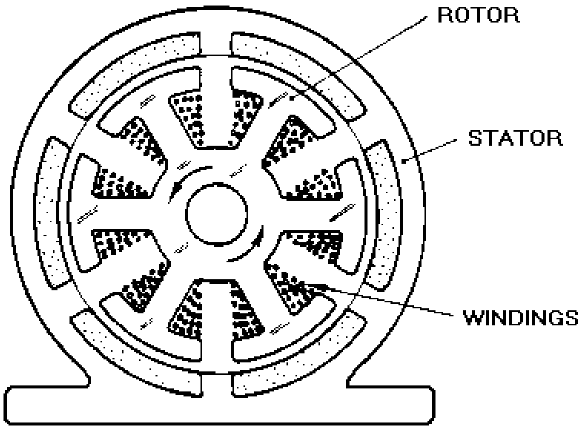

Figure 5-1. An electric motor. The maximum rotational speed can be limited by the strength of conductor used for the rotor windings

Table 5-1. The design requirements

FUNCTION	Rotor windings for high-speed motors
OBJECTIVE	Maximize rotational speed
	Minimize ohmic losses in windings
CONSTRAINTS	Must not fail under centrifugal forces
	Rotor radius prescribed

5.1 The Model

As the motor speed increases, the centrifugal loading on the rotor windings increases also. The maximum stress in a solid circular disc spinning with angular velocity ω is (Young, 1989)

$$\sigma_{max} = \left(\frac{3+\nu}{8}\right) \rho\, R^2\, \omega^2$$

where ν is Poisson's ratio, ρ is its density and R its radius, or, taking ν ≈ 0.3,

$$\sigma_{max} \approx \frac{1}{2}\, \rho\, R^2\, \omega^2 \qquad \textit{(M 5.1)}$$

The rotor is more complex than this, but the stress in it caused by centrifugal forces remain proportional to this value. The stress must not exceed the elastic limit, σ_{el} , of the rotor or its windings, and it is usually the windings which are the weaker element:

$$\sigma_{max} = \leq \sigma_{el}$$

This sets an upper limit to the angular velocity, ω:

$$\omega_{max} = \frac{\sqrt{2}}{R}\left(\frac{\sigma_{el}}{\rho}\right)^{1/2} \qquad \text{(M 5.2)}$$

The best materials to resist the centrifugal loading on the rotor are simply those of high values of the index

$$\boxed{M_1 = \frac{\sigma_{el}}{\rho}} \qquad \text{(M 5.3)}$$

If the motor ran without load or friction (requiring high vacuum and frictionless bearings) the electrical conductivity of the windings would not be important, since they would consume no power. But in general the motor will be required to deliver power, some of it to overcome friction, and some to drive the external device. Then a finite current flows through the windings and — both for reasons of economy and to minimize ohmic heating — we wish to minimize the losses. The ohmic losses are

$$P = i^2\, R_e = i^2\, \rho_e \frac{l}{A} \qquad \text{(M 5.4)}$$

where i is the current, R_e the resistance, ρ_e the electrical resistivity of the material of the winding, l the length of the winding and A is the cross section of the wire of which it is made. The ohmic losses are minimized by maximizing the index

$$\boxed{M_2 = \frac{1}{\rho_e}} \qquad \text{(M 5.5)}$$

5.2 The Selection

Figure 5-2 shows a chart of M_1 plotted against M_2, created using branches of the materials tree involving conductors. The best materials for windings of motors of very high speed but near-zero load are those towards the top left. They are unexpected: low-alloy (LA) steels, copper-beryllium alloys and beryllium itself. This is because M_1 dominates the selection. The best materials for low speed but high power are those the lower right. Here M_1 dominates, favouring the choice of OFHC and other simple high-conductivity coppers.

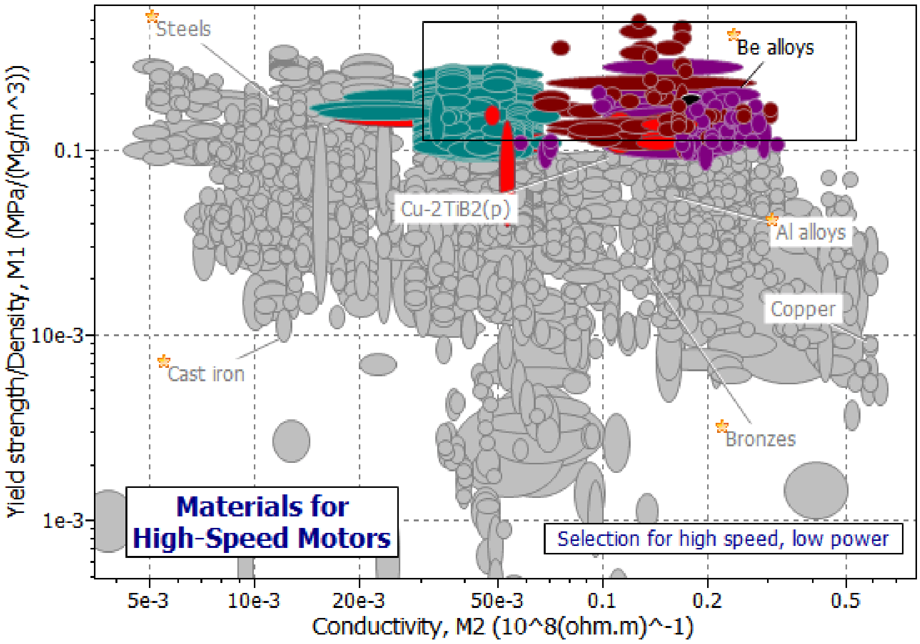

Figure 5-2. A chart of M_1 plotted against M_2, using the branches of the materials tree involving conductors. The selection shows those materials best suited in high speed, low power electric motors.

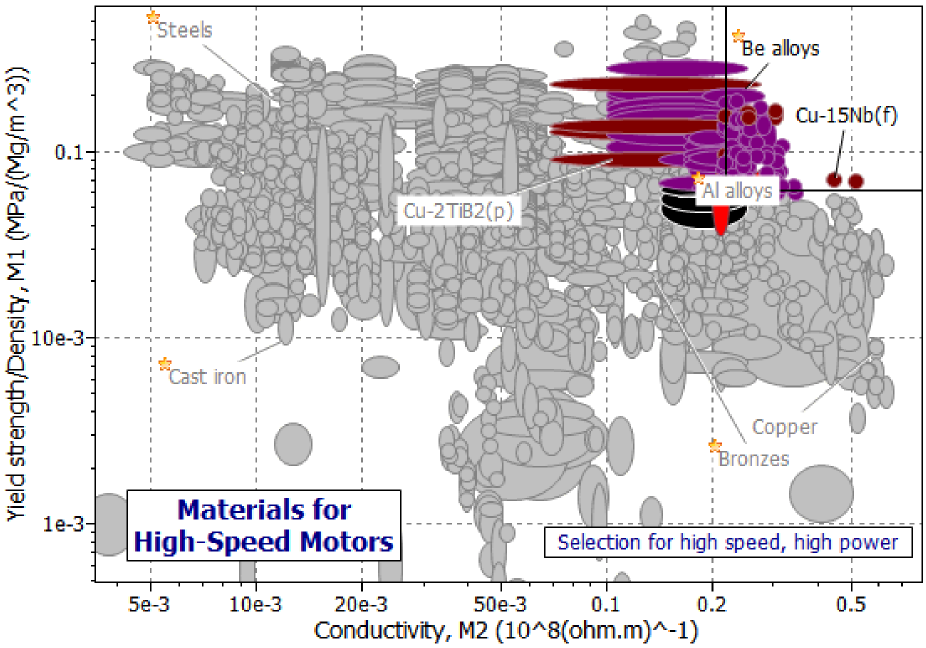

Figure 5-3. A chart of M_1 plotted against M_2, using the branches of the materials tree involving conductors. The selection shows those materials best suited in high speed, high power electric motors.

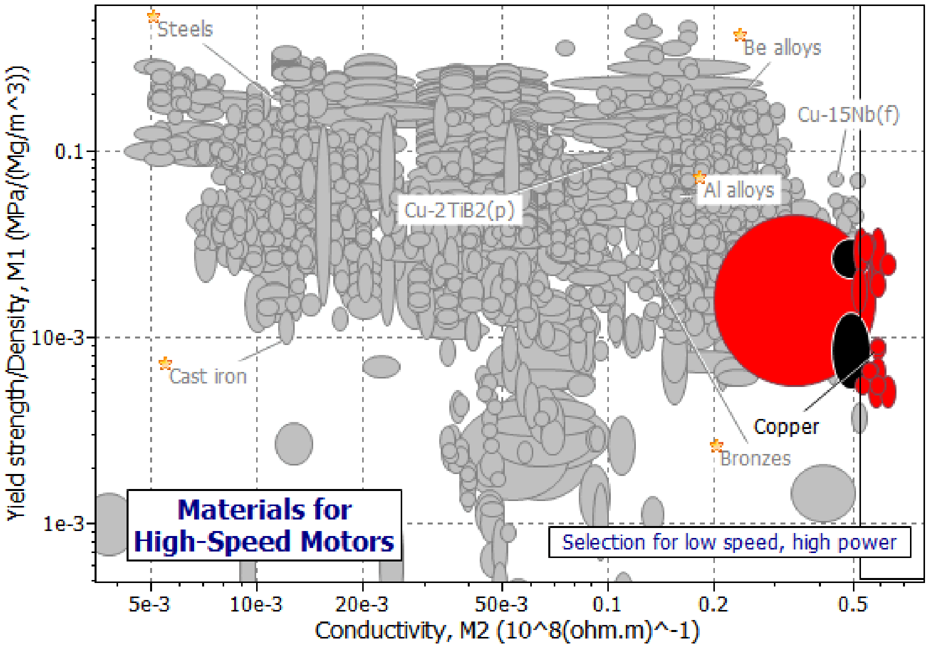

Figure 5-4. A chart of M_1 plotted against M_2, using the branches of the materials tree involving conductors. The selection shows those materials best suited in low speed, high power electric motors.

The real challenge, of course, is the regime high speed and power, requiring high values of both M_1 and M_2. The selection which emerges for this regime (the top right) is summarized in Table 5-2. It is dominated by special high-conductivity high-strength composites. All have excellent performance, but are expensive.

Table 5-2. Materials for windings of high speed motors

MATERIAL	COMMENT
Drawn copper-niobium composites	Excellent strength and conductivity; expensive
Drawn copper-silver composites	Excellent strength and conductivity; expensive
Copper – Al_2O_3 composites (Glidcop)	Excellent strength and conductivity; outstanding high-temperature performance
Copper – Ti B2 (p) composites	Experimental alloys with high strength and conductivity; not readily available
Copper – 40% C (f) composites	

5.3 Postscript

Electric power is flexible, widely available and clean, so electric motors are frequently the first choice as a power source. But under extreme conditions, other power sources become viable. Turbines driven by compressed gas are capable of very high rotational speeds, and, in the limit of zero power-output, steel balls suspended magnetically in high vacuum can be accelerated to their burst velocity merely by shining a beam of light onto one side. One should not overlook alternatives. They of course have their own material-selection problems; but that is another story.

5.4 Further Reading

Montgomery, DB (1969) 'Solenoid Magnet Design', Wiley, Interscience, NY, USA.

Young, WC (1989), 'Roark's Formulas for Stress and Strain', 6th edition, McGraw-Hill, NY, USA, pp. 703–708.

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