

## **TALAT Lecture 1502**

# **Criteria in Material Selection**

36 pages, 38 figures

**Advanced Level I**

**prepared by: Rolf Sandström, Stockholm**

### **Objectives:**

1. To give a background to why, by whom, when and how material selection is performed
2. To understand the pitfalls of non-systematic approaches
3. To understand the concept of preselection and how it is applied
4. To create an understanding about unbiased selection of materials and how it is performed
5. To explain discriminating material selection and how it is applied
6. To create an understanding of optimisation in material selection and how it is applied

### **Prerequisites:**

Elementary background in materials engineering.

**Date of Issue: 1994**

© EAA – European Aluminium Association

# 1502 Criteria in Material selection

## Table of Contents

<b>1502 Criteria in Material selection</b>	<b>2</b>
<b>1502.01 Introduction to Material Selection</b>	<b>3</b>
The Need for Material Selection	3
Intuitive Methods in Material Selection	4
Basics of Systematic Material Selection	5
Connection to Design	6
General Guidelines for Successful Material Selection	7
Function Specification	8
<b>1502.02 Pre-Selection of Materials</b>	<b>10</b>
Purpose of Pre-Selection	10
Intuitive Approach	11
Systematic Approach	12
Examples for Pre-Selection	14
Base Materials for Pre-Selection	15
<b>1502.03 Discriminating Materials Selection</b>	<b>16</b>
Purpose	16
Prerequisite	17
Formulation of Demands	17
Representation of Property Values	19
Examples of Discriminating Materials Selection	21
<b>1502.04 Optimisation in Material Selection</b>	<b>22</b>
Purpose	22
Semi-Systematic Methods	23
Selection of Materials by Minimising the Materials Cost	25
Value of Weight Savings	32
<b>1502.05 List of Figures</b>	<b>36</b>

## 1502.01 Introduction to Material Selection

- **The Need for Material Selection**
- **Intuitive Methods in Material Selection**
- **Basics of Systematic Material Selection**
- **Connection to Design**
- **General Guidelines for Successful Material Selection**
- **Function Specification**
- *Practical Example: Car Body Panels*


### The Need for Material Selection

During the last decades many new materials and material types have been developed. At present of the order of 100 000 engineering materials exist. In addition many materials have successively obtained improved properties. This has been possible due to the development of the materials but also due to the appearance of new production methods. As a consequence of this rapid development many material types can be used for a given component. This also applies to situations where one previously only employed one material for example cast iron in cylinder heads where cast aluminium alloys are also used now. Another example is body panels in cars where low carbon mild sheet steel is still the dominating material but many other materials like high strength sheet steels, aluminium alloys, sheet moulding compounds (SMC), thermoplastics, thermoplastic elastomers and expanded plastics are used. In fact it is quite a common case that many entirely different materials can be used to a given part. As a consequence material selection becomes quite a complex task (see **Figure 1502.01.01**).

### Rapid Development in Material Technology


- Many new materials
- Many new material types
- New manufacturing methods
- Properties of existing materials improved
- Increased use of advanced materials
- Entirely new design configurations feasible
- Increased competition between materials

**Materials selection is both critical and complex**

	Rapid Development in Material Technology	1502.01.01
---	--	------------

## Intuitive Methods in Material Selection

One might imagine that the selection of materials in industrial environments is performed after detailed analyses and according to systematic procedures. This is certainly the case in some situations but other types of procedures are dominating. Some of these common methods are listed in **Figure 1502.01.02**. The simplest way of choosing a material is called the **first best material**. When a new part is to be developed the designer more or less consciously considers one material he is familiar to. It can be a carbon steel or a bulk plastic depending on which material type he is mostly concerned with. When the geometrical modelling of the part is completed it is often adapted to the material in question and to adjust the chosen material at a later stage is far less powerful than for a direct systematic analysis.


Intuitive Methods in Material Selection	
<b>1. First best material</b>	The material is selected among the few materials the design engineer is familiar with.
<b>2. Same material as for a similar part</b>	
<b>3. Problem solving material selection</b>	A property has given rise to problems. A new material is chosen in the same group of material with a higher value of the property.
<b>4. Searching material selection</b>	The designer takes more or less randomly into account one requirement at the time.
<b>Drawbacks with Intuitive Methods:</b>	<ul style="list-style-type: none"><li>- Important requirements have often given rise to failures in operation.</li><li>- First solution at hand is taken which is not very likely to be good solution.</li><li>- Unconventional solutions are not considered e.g. advanced materials are not analysed.</li><li>- The solution is typically far from the optimum giving the part poor competitiveness.</li></ul>
	Intuitive Methods in Material Selection
	1502.01.02

A common procedure is to use the **same material as for a similar component**. This approach is based on the assumption that a material which works satisfactorily in one application will do in a similar one. Unfortunately, this is not the case in many situations. The requirements may be different for example from the environment the component is exposed to. Still another procedure is **problem solving material selection**. The previously employed material does not function well and the property which has caused the problem is identified. A material in the same group is chosen but with a higher value for the critical property. In this way one property is improved without other properties are affected too much. In the method **searching material selection** the engineer is aware that he has a problem and that he cannot solve it by choosing one of the materials he is familiar to. He considers one requirement at the time and tries to find a material that fulfils the requirements. A lot a of time is usually spent on the requirement which is assumed to be the most critical one and less attention is paid to the other ones.

These non-systematic procedures are referred to as intuitive since they are not based on systematic analysis. There are some advantages with these methods. More or less automatically conventional and well established materials that are familiar to the designer are selected. In this way some unpleasant surprises are avoided. However, the drawbacks dominate (see **Figure 1502.01.02**). It is easy to ignore some essential requirement. All requirements may not be fully taken into account frequently giving rise to failures in service. Some requirement may also be over emphasised i.e. unnecessarily expensive materials are chosen to satisfy it. It is very unlikely that new and modern materials are considered. In summary serious mistakes are frequently made when using intuitive methods and it is very improbable that the final solution is close to the optimal cost effective one. As a consequence the solution will typically have poor competitiveness. Part of the reasons for these problems is that the designer is not aware of the fact that the material selection has an important influence on the quality and the value of the final product and therefore warrants considerable time to be spent on the analysis. Sometimes the design engineer does not even realise that he is choosing a material.

### Basics of Systematic Material Selection

To avoid the drawbacks of intuitive approaches systematic methods must be applied. Some basic features are summarised in **Figure 1502.01.03**. The most important motive **why** material selection is performed is to ensure that the component functions well i. e. failures do not occur too frequently. Further reasons are to make full use of the materials and to obtain cost effective components. In fact minimisation of cost is usually the main objective in engineering design at the same time as a number of requirements should be satisfied. Due consideration has also to be taken to the value of weight savings in transport applications. In special cases other objectives like the maximisation of performance may be of importance. This will be further discussed in another lecture.

<b>Material Selection Basics</b>	
<b>Why</b>	<ul style="list-style-type: none"> <li>- To make full use of the engineering materials.</li> <li>- To avoid unnecessarily expensive structures.</li> <li>- To avoid failures.</li> </ul>
<b>When</b>	<ul style="list-style-type: none"> <li>- A new product is developed.</li> <li>- A product is modified and redesigned.</li> <li>- Failures have occurred.</li> </ul>
<b>Who</b>	<ul style="list-style-type: none"> <li>- Design engineers in collaboration with materials engineers.</li> </ul>
<b>How</b>	<ul style="list-style-type: none"> <li>- Specify the requirements for the component.</li> <li>- Transfer the requirements to materials properties.</li> <li>- Find the material <i>groups</i> that satisfy the specification.</li> <li>- Find the <i>individual</i> materials that satisfy the specification.</li> <li>- identify the "best" materials that satisfy the specification.</li> </ul>
	Material Selection Basics
1502.01.03	

Material selection can in principle be made during any stage of the life cycle of a product. However, in practice it is done *when* the component is first designed or when it is redesigned. The reason is simply that the introduction of a new material in general requires the modification of the component geometry. If failures of the part take place it may be necessary to change the material. Such forced material changes are usually costly and should be avoided by proper original design. One common mistake is to ignore material selection when a component is redesigned. Many times even small geometrical changes make a new material the optimum one.

The design engineer is usually the one *who* is responsible for a component under development. This responsibility includes material selection but it is advisable that collaboration takes place with a material specialist.

**How** the material selection is performed can be summarised in five steps (see **Figure 1502.01.03**). These involve the formulation of the function specification of the part, transfer of the requirements to material properties, analysis of the consequences with respect to material types and individual materials and finally optimising the choice of the material and the geometry of the part. The five steps must be performed in the correct order. The only step which can be missed out is the third one on the selection of material types. The various steps will be discussed in more detail below in lectures **1502.02** to **1502.04**.

### **Connection to Design**

There is always a close connection between material selection, the design configuration of the part and the manufacturing method. They should be handled together. However, it is important to recognise that this connection is primarily at the part level (see **Figure 1502.01.04**). A product consists of components which are in turn made out of one or more simple parts. A simple part consists of only one material. **Material selection is performed for simple parts**. Attempts to select materials for several parts simultaneously have usually failed due to the mathematical complexity of the problem. However, if several parts in a component for some reason are to be made out of the same material this is handled simply by adding this as a separate requirement. Then these parts can be analysed together as a simple part.

## Connection to Design

**Material selection is an integral part of the design process**

### Levels in design structure

- Simple part: Consists of one material.
- Component: Consists of one or more simple parts.
- Product: Consists of one or more components.

**Material selection is generally performed only for simple parts and not at the component or the product level.**



Connection to Design: Material Selection Integral Part of the Design Process

1502.01.04

## General Guidelines for Successful Material Selection

Both simple and more serious errors are frequently made during material selection. A few guidelines may be helpful to avoid the more common mistakes (see **Figure 1502.01.05**). It is important to **act systematically**. A typical material selection problem involves hundreds of variables and property data points. A non-systematic approach is bound to fail. All the **requirements** for the component in question must be **formulated in detail**. This is necessary to obtain a well defined problem. A common **misconception** in material selection is that component **requirements are formulated by someone else**. Although the customer typically defines some requirements, most have to be identified and worked out in the framework of the problem solving. One should **proceed stepwise** (see **Figure 1502.01.03**) under „**How**“, and finish one step before the next is entered. For example optimisation is not meaningful until all previous steps in material selection are completed. Material selection should be considered as an **integrated part** of both the **design** and the **manufacturing** processes. As pointed out above the material selection is generally performed for simple parts, not at the component or the product level.

## General Guidelines for Successful Material Selection

- Act **systematically**.
- Formulate all** the requirements on the component in question in detail.
- A common **misconception** in material selection is that component requirements are formulated by someone else.
- Proceed **stepwise** and finish one step, before the next is entered.
- Good knowledge** about material property data is **essential** in order to formulate conditions on the properties.
- Formulating conditions for **properties**, for which data are **not available**, is **not meaningful**.
- Check the consistency of the problem formulation and solution process by testing materials that are **well known to work** in the given application and those that can be ruled out.
- Material selection should be considered as an **integrated** part of both the design and the manufacturing process.
- Material selection is generally performed for **simple** parts, not at the component or the product level.



General Guidelines for Successful Material Selection

1502.01.05

**Good knowledge about material property data** is essential in order to formulate conditions for the properties. A condition for a technological property like weldability depends on the data source. Thus the data source must be identified and the content known to the user before conditions are formulated. Formulating conditions for properties for which data are not available is not meaningful. These conditions can not be taken into account in the selection process anyway.

It is essential to **check the consistency of the problem formulation and solution** process by testing (1) materials that are well known to work in the given application and (2) materials that can be ruled out as candidates in the given application. The first set of materials should remain when optimisation is entered, the second set should have been eliminated during the discriminating stage.


### Function Specification

The first step in every material selection task (and any design case) is to specify the requirements for the part in terms of geometry, the environment it will be exposed to, as well as flows and currents that are transmitted (see **Figure 1502.01.06**).

**Function Specification**


Specify the following for the part:

- ✓ **Geometrical quantities that are fixed or allowed to vary, respectively**
- ✓ **Environment** - Service temperature range  
- Chemical environment  
- External mechanical loading cycle spectrum
- ✓ **Flows and currents**
- ✓ **What is to be optimised** - Weight,  
- material cost,  
- load, or  
- deformation, etc.
- ✓ **Other restrictions or regulations**

 <small>Training in Aluminium Application Technologies</small>	First Step: Specification of Functions	1502.01.06
--	--	------------

This is usually done by setting up a demand profile for the part. A demand profile can be considered as a list of the requirements. It has frequently the form of a check list or a table which is to be filled in. An example of such a check list is given in **Figure 1502.01.07**.



Functional Requirements		
<b>Performance specifications</b>	Basic functions of part, definitions of need	
	Risk with under-specification: . . . . . Safety classification Failure probability Consequences of failure	
	Consequences of over-specification: Competitive situation	
	Serviceability: . . . . . Reliability, maintainability, availability, reparability	
	Design life Recycling, destruction	
<b>Design configuration</b>	Restrictions on size, weight or volume	
	Service temperature range	
	Chemical environment	
	External mechanical loading including load cycle spectrum	
	Flows and currents: . . . . . Electric currents Thermal and other flows	
	Quantity to be produced	
	Quantity to be optimised	
Other constraints or regulations: . . . . . Maximum costs		
 Training in Aluminium Application Technologies	Check List: Functional Requirements	1502.01.07

The **performance specifications** cover the general requirements for the part such as basic functions, definitions of need, consequences of under- and over specification, serviceability and considerations on recycling and destruction. In the **design configuration** service conditions are specified, restrictions on geometry, external mechanical loading, possible flows and currents, etc. It is important to follow some rules when formulating functional requirements (see **Figure 1502.01.08**).

- The requirements should be formulated in a way which is independent of the possible design and material solution(s). The choice of solutions should be a consequence of the specification, not a reflection of anticipated solutions.
- The requirements should not be formulated in terms of material properties. Thus for example the external loading should be identified and it should be specified as forces and momenta but not as stresses.
- All essential requirements must be included.
- The requirements should be formulated in quantitative terms as far as possible. A vaguely formulated specification usually results in an undefined problem. It should be recalled that incomplete specifications is a common cause of material problems.
- Economic requirements are practically always crucial.
- Formulation of the requirements is based on the best information available to the design engineer and should not be considered as exact knowledge. The details of the requirements take always a somewhat personal form.

## Formulating Functional Requirements

- The requirements should be independent of the possible design and material solution(s). The choice of solution should be a consequence of the specification, not a reflection of anticipated solutions.
- The requirements should be expressed in a way which does not involve material properties. For example: External loadings are given as forces and momenta but not as stresses.
- All essential requirements should be included.
- The requirements should be in quantitative terms.  
A vague specification results in an undefined problem, which is a common cause of material problems.
- Economic requirements are practically always crucial.

## 1502.02 Pre-Selection of Materials

- **Purpose of Pre-Selection**
- **Intuitive Approach**
- **Systematic Approach**
- **Examples for Pre-Selection**
- **Base Materials for Pre-Selection**

### Purpose of Pre-Selection

For many reasons it is not suitable to directly select individual materials. Let us take one example. The weldability of carbon steels, stainless steels, aluminium alloys are controlled by entirely different mechanisms. This implies that when requirements for weldability are formulated one must know which type of material is involved. Hence there must be a process where it is decided which groups can be used. This process is called **pre-selection or sifting of material groups** (see **Figure 1502.02.01**). During pre-selection the material types which are possible to apply are identified. At the same time design configurations and manufacturing methods are determined. It is the step in systematic material selection that follows the formulation of the function specification. The purpose is to find suitable materials types at an early stage of the design process. In this way a basic understanding for **which groups of candidate materials can be considered** is created and the total effort is limited by eliminating many material types.

## General Principles for Pre-Selection of Materials

### Definition

During **pre-selection** the material types which are possible to apply are identified. At the same time **design configurations** and **manufacturing methods** are **determined**. It is the step in systematic material selection directly **following the formulation of the function specification**.

### Purpose

It is important to find out the **material types** that are **possible to use** for a given component at an early stage of material selection. There are **two main reasons** for this:

- To create a **basic understanding** for which groups of candidate materials can be considered.
- The **subsequent steps depend on the material types** under consideration. Hence, to limit the total effort one should eliminate as many material types as possible.



General Principles for  
Pre-Selection of Materials

1502.02.01

### Intuitive Approach

A simple way of determining whether a material type can be used or not is to consider its characteristic properties. For aluminium alloys some of these properties are shown in **Figure 1502.02.02**. By comparing these with the part specification a general idea can usually be obtained whether aluminium alloys can be used or not. A slightly better way is to employ a list of negative conditions like in **Figure 1502.02.03** which summarises when aluminium alloys should not be used.

## Characteristic Properties of Aluminium Alloys

- |                      |   |
|----------------------|---|
| <b>Physical</b>      | <ul style="list-style-type: none"> <li>- Low density ~2700 kg/m<sup>3</sup></li> <li>- High electrical conductivity ( ≤ 60% IACS)</li> <li>- Thermal conductivity</li> <li>- Very high electrical conductivity per unit cost</li> <li>- High reflectivity also in infrared light</li> </ul> |
| <b>Mechanical</b>    | <ul style="list-style-type: none"> <li>- High specific static strength</li> <li>- High specific dynamic strength</li> <li>- Brittle failure no problem at lower strength</li> </ul>   |
| <b>Technological</b> | <ul style="list-style-type: none"> <li>- Castable to good tolerances</li> <li>- Can be rolled to thin gauges</li> <li>- Good cold formability at low strength</li> <li>- Many alloys have good extrudability</li> <li>- Easy to surface treat to decorative nuances</li> </ul>              |
| <b>Environmental</b> | <ul style="list-style-type: none"> <li>- Excellent atmospheric corrosion resistance</li> <li>- Not toxic</li> </ul>   |



Characteristic Properties of  
Aluminium Alloys

1502.02.02

## Aluminium Alloys should not be Used

- If the service temperature **exceeds 200°C** or if it **exceeds 100°C** in combination with significant mechanical loads.
- If the part is in **contact with water** or **placed underground** for a longer period of time without protection.
- In **solutions with higher or lower pH**, since the protective oxide layer is not intact.
- When **thermal or electric insulation** is required.
- When thermal expansion should be kept low.
- When **strength** requirements **exceed 500MPa**.
- When **fatigue limit** requirements **exceed 230MPa**.
- When **low elastic deflections** are anticipated.
- When wear is expected to be critical.



Aluminium Alloys should not be Used, If

1502.02.03

### Systematic Approach

The intuitive approach has obvious short comings since it does not provide a quantitative judgement. To avoid those a systematic method should be used. In pre-selection only a limited number of properties are involved (see **Figure 1502.02.04**). In fact only properties where the values are comparable between many types of material can be considered. The electrical conductivity is one such property. Many other **physical and simple mechanical properties** also satisfy this criterion. In addition the conditions must be similar for different material groups. For some properties like strength and toughness the property requirements are strongly dependent on the component geometry. This will be further discussed in section **1502.04**. As a consequence a precise comparison between material types can not be made when they are associated with different design configurations.

## Properties Involved in Pre-Selection of Material Types

- |   |  |
|---|--|
| <b>1. Lowest and highest use temperature</b>          | <ul style="list-style-type: none"> <li>- Spalling, ageing resistance</li> <li>- Physical and chemical degradation</li> </ul>                           |
| <b>2. Environmental resistance</b>                    | <ul style="list-style-type: none"> <li>- Corrosion resistance</li> <li>- UV-resistance</li> <li>- Toxicity</li> </ul>                                  |
| <b>3. Physical properties</b>                         | <ul style="list-style-type: none"> <li>- Electrical and thermal conductivity</li> <li>- Density</li> <li>- Coefficient of thermal expansion</li> </ul> |
| <b>4. Mechanical requirements</b><br>(order of magn.) | <ul style="list-style-type: none"> <li>- Tensile strength</li> <li>- Elongation</li> <li>- Toughness</li> </ul>  |
| <b>5. Material price</b>                              |  |



Properties Involved in Pre-Selection of Material Types

1502.02.04

In the function specification the service temperature interval is given. The highest service temperature must not exceed the **maximum use temperature** of the material. In other case ageing and/or some type of break down of the material will take place. For aluminium alloys the maximum use temperature is of the order 200 - 250 °C. In the same way the lowest service temperature must not be below the **minimum use temperature** of the material. For most materials the minimum use temperature is controlled by the risk for brittle failure. The toughness of aluminium alloys is only mildly temperature dependent due to the face centred cubic structure and many alloys can be used down to temperatures below -200 °C. It is convenient to consider both the maximum and minimum use temperatures as generalised material properties.

If a material is exposed to a **chemical environment** it strongly limits the materials that can be applied. Similar limitations exist for plastics in UV-radiation and **toxicity** for materials in contact with food. This problem has to be analysed for each chemical. Aluminium alloys are usually attacked rapidly in solutions with pH <4 or pH >10.

**Mechanical loading** is usually treated under the optimising part of material selection. For pre-selection only the order of magnitude is of interest. If the elastic modulus exceeds 100 GPa polymers or aluminium alloys with few exceptions can not be used. In this type of analysis one should consider increasing the section size of the part to reduce the requirements on the elastic modulus to allow other materials to be used. Mechanical stresses can be handled in the same way.


In most cases the requirements on **ductility** are material dependent. This applies to demands on forming during manufacture which are very different for metals and plastics for example. This type of demand can not be considered during pre-selection. If, on the other hand, the material is exposed to significant plastic deformation during manufacture or use, the materials can be screened with respect to the elongation. The only thing one should recall is that materials with low elastic modulus such as bulk plastics can take up large pure elastic deflections reducing the requirements on the elongation value.

If values for the **fracture toughness**  $K_{Ic}$  are available they can be employed for pre-selection. In this way e. g. brittle ceramic materials can be eliminated. On the other, it is not suitable to use impact toughness values since their interpretation varies with the type of material. For example impact toughness is of limited practical value for aluminium alloys.


The **material cost** always plays an essential role in material selection and equally in pre-selection. It is important to screen out for example precious metals like gold and platinum which can only be considered in applications where their special properties are crucial and someone is prepared to cover the true cost of the material.

## Examples for Pre-Selection

The principles of pre-selection are illustrated in **Figure 1502.02.05** for a casserole. Obviously aluminium alloys satisfy the requirements for availability and manufacturing. Concerning use properties the corrosion resistance and toxicity limits the application of aluminium alloys to those without copper.

<b>Example on Pre-Selection: Casserole</b>		
<p><b>Usage Requirements</b></p> <p>Max. use temperature (&gt;150°C)            Good heat conductivity            Corrosion resistance in household chemicals            Non toxic</p> <p><b>Manufacturing</b></p> <p>Conventional methods available</p> <p><b>Availability</b></p> <p>Low price            Conventional material</p>	<p><b>Aluminium alloys feasible</b></p> <p>Yes            Yes            Yes            for Cu-free alloys</p> <p>Spinning, deep drawing</p> <p>Yes            Yes</p>	
<p><b>Other feasible materials</b></p> <p>Pure copper (needs surface treatment), ferritic and austenitic stainless steels, cast irons</p>		
	<p>Example on Pre-Selection: Casserole</p>	<p>1502.02.05</p>

For the ladder in **Figure 1502.02.06** in the same way Cu-free alloys can be used. With the given specification glass fibre reinforced polyester (GRP) can not be employed because of a too low E-modulus. Neither steels nor carbon reinforced epoxy satisfy the cost requirement.


<b>Example on Pre-Selection: Ladder</b>				
Usage requirements	Aluminium alloys	C-Steel	GRP	C-fibre comp.
Max. use temperature (>50°C)	Yes	Yes	Yes	Yes
Yield strength (>100°C)	Yes	Yes	Yes	Yes
Elastic modulus (>50 GPa)	Yes	Yes	No	Yes
Corrosion in atmosphere	Yes	Must be painted	Yes	Yes
Low density	Yes	Yes	Yes	Yes
<b>Manufacturing</b>				
Conventional methods available	Extrusion		Poltrusion	Winding
<b>Availability</b>				
Low price	Yes	Yes	Yes	No
Conventional material	Yes	Yes	Yes	No
<b>No other feasible engineering materials</b>				
	<p>Example on Pre-Selection: Ladder</p>			<p>1502.02.06</p>

In **Figure 1502.02.07** a case for a self-supported electric cable is considered. Evidently, the conventional cable materials aluminium alloys, carbon steel and pure copper can be

employed. It is important to recognise that in this process there is no way of deciding which of the material types is the preferable one, nor is it possible to say anything about individual alloys.

Example on Pre-Selection: Self Support Cable			
Usage requirements	Aluminium alloys	C-Steel	Pure Cu
Max. use temperature (>100°C)	Yes	Yes	Yes
Yield strength (>50MPa)	Yes	Yes	Yes
High electrical conductivity (>30% IACS)	Yes	Yes	Yes
Corrosion in atmosphere	Yes	Must be protected	Yes
<b>Manufacturing</b>			
Wire drawing	Yes	Yes	Yes
<b>Availability</b>			
Low price	Yes	Yes	Yes
Conventional material	Yes	Yes	Yes
Product form	Wire	Wire	Wire

 <b>TALAT</b> Training in Aluminium Application Technologies	Example on Pre-Selection: Self Support Cable	1502.02.07
--	--	------------

### Base Materials for Pre-Selection

As pointed out above the purpose of pre-selection is to eliminate unsuitable material types which do not satisfy requirements on overriding properties. Pre-selection only considers groups of materials, never individual materials. In this way one avoids analysing materials that never could have been used anyway. It is also a way to prevent that important materials are erroneously disregarded in unbiased material selection.

In many applications demands on the properties in **Figure 1502.02.04** do not generate very severe restriction. If for example carbon steels or bulk plastics can successfully be applied then a more expensive material often does not imply any economic benefit. If one knows the property which is controlling the dimensions of the component then it is possible to indicate the material type that should be tried first (see **Figure 1502.02.08**).

## Base Material for Pre-Selection

### Controlling quantity

Strength  
Stiffness  
Volume (geometrical condition)  
Electrical conductivity  
Thermal conductivity

### Type of material

Unalloyed steel  
Unalloyed steel  
Bulk plastics  
Al-alloys  
Al-alloys

### 1502.03 Discriminating Materials Selection

- **Purpose**
- **Prerequisite**
- **Formulation of Demands**
- **Representation of Property Values**
- **Examples of Discriminating Materials Selection**

#### **Purpose**

In the function specification a number of requirements on a component is identified. They have to be transferred to the material to be used. Not all materials satisfy these requirements. It is the purpose of the sorting stage of materials selection to find out which materials can be used (**Figure 1502.03.01**).



## Discriminating Material Selection (Sorting)

**Purpose** In the **function specification** a number of **requirements** on a component is **identified**. They have to be transferred to the material to be used. Not all materials satisfy these requirements. It is the purpose of the sorting stage of materials selection to find out which materials can be used.

**Prerequisite** The pre-selection has been performed and one or more suitable combinations of **design configuration**, **material type and manufacturing method** have been identified. If more than one combination is to be analysed the sorting stage has to be repeated for each one. The reason is that the transfer of the function specification to requirements on properties can not otherwise be done in a well defined way.



Discriminating Material Selection (Sorting)

1502.03.01

### Prerequisite

The pre-selection has been performed and one or more suitable combinations of **design configuration, material type and manufacturing method** have been identified. If more than one combination is to be analysed the sorting stage has to be repeated for each one. The reason is that the transfer of the function specification to requirements on properties can not otherwise be done in a well defined way.

### Formulation of Demands

In material selection requirements for many properties are specified as minimum or maximum values. Mathematically this can be expressed as (**Figure 1502.03.02**).

## Demands on Material Properties

### Discriminating Demands:

During sorting the requirements on properties are in general expressed in the simple form

$$E_i \geq \underline{E}_i$$

$$E_i \leq \bar{E}_i$$

$E_i$  is the value of the  $i$ -th property.  $\underline{E}_i$  and  $\bar{E}_i$  are upper and lower limits on property  $i$ .

If an improvement of the property corresponds to an increase in the value the demand is usually expressed as a minimum value and vice versa.

Writing the **demands** in the above form implies that the condition must be **strictly satisfied**.

This is referred to as a **discriminating requirement** since only materials satisfying the condition can be considered further in the analysis.



Demands on Material Properties

1502.03.02


$$E_i \geq \underline{E}_i \quad (1a)$$

$$E_i \leq \overline{E}_i \quad (1b)$$

$E_i$  is the value of the  $i$ -th property.  $\overline{E}_i$  and  $\underline{E}_i$  are upper and lower limits of property  $i$ . If an improvement of the property corresponds to an increase in the value the demand is usually expressed as a minimum value (1a) and vice versa (1b).

Writing demands in the form of Eq. (1) implies that the condition must be **strictly satisfied**. This is referred to as a **discriminating requirement** since only materials satisfying the condition can be considered further in the analysis. If it is just desirable that the property has a good value this is expressed in other ways.


The weldability must be above a certain lower level in order that one component can be joined to another one. The corrosion resistance must have a minimum value to give a component a sufficient lifetime in an aggressive environment. A given material can not be used independently of how good the other properties are if the corrosion resistance is not adequate. In another example the heat flow through the component should not be too large, which yields a criterion that the thermal conductivity may not exceed a certain value. For a given application of this kind the number of requirements is typically between 5 and 20. As a consequence a large amount of data must be available for many properties for successful selection (see **Figure 1502.03.03**). The use of material databases is important in this respect. Some important data sources are listed in **Figure 1502.03.03**.

<h2 style="color: blue;">Requirements for Materials Selection</h2>		
Data for many materials Data for many properties Accurate property data		
Traditional sources of continued importance but not adequate for modern demands Access to materials databanks essential		
<b>Examples of Sources of Engineering Data for Aluminium Alloys</b>		
<b>Material databases</b>	<ul style="list-style-type: none"> <li>- Metals datafile (Institute of materials)</li> <li>- MAT. DB (ASM, Ohio)</li> <li>- ALUSELECT (European Aluminium Association, Brussels)</li> <li>- MAterials Technology EDucation System (MATEDS), (Skan Aluminium, Oslo)</li> </ul>	
<b>Handbooks</b>	<ul style="list-style-type: none"> <li>- Aluminium Taschenbuch (Aluminium-Verlag, Düsseldorf)</li> <li>- Metals Handbook (ASM, Ohio)</li> </ul>	
	Sources of Material Specification	1502.03.03

To find the maximum and minimum requirements  $\bar{E}_i$  and  $\underline{E}_i$  the function specification is transferred to property values. Formulating this material specification involves the steps shown in **Figure 1502.03.04**

## Material Specification

- 1) **Identify materials properties** of relevance for the function specification.
- 2) **Find sources** for the corresponding property data.
- 3) Use 1) and 2) to **transfer the function specifications** to requirements **on properties**.




Steps in Material Specification

1502.03.04

This process is illustrated in **Figure 1502.03.05**. For many properties this transfer is straight forward. Sometimes it is, however, a fairly complex task but that case will not be dealt with here.

## Relation between Specification and Materials Properties

<b>Type of specification</b>	<b>Examples of properties involved</b>
<b>Environment</b> Service temperature range Chemical environment External mechanical loading	Max. and min. usage temperature Corrosion resistance E-modulus, Yield strength, fatigue limit
<b>Flows and currents</b> Electric currents Thermal and other flows	Electrical conductivity Thermal conductivity, reflectivity, transparency
<b>Contact</b> Tolerances Wear	Coefficient of thermal expansion Wear resistance
<b>Manufacturing</b> Processing Forming Working Joining Surface treatment	Extrudability Bendability, drawability Machinability Weldability Anodising



Relation between Specification and Materials Properties

1502.03.05


### Representation of Property Values


The properties that give rise to requirements in the form of Eqs. (1a) and (1b) are called **discriminating** since they are only of importance for deciding whether a material can be

considered or not. The properties are divided into three groups depending on whether they are of relevance for the **use, manufacturing and availability**. Corrosion and wear resistance are examples of use properties. Machinability and weldability belong to the manufacturing group and the material price describes availability.

Many technological properties can be considered as discriminating. Examples of technological properties are given in **Figure 1502.03.06**.


Values of technological properties are frequently given as index. In the databases ALUSELECT and MATEDS the indices are defined as in **Figure 1502.03.07**.


<h2 style="color: blue;">Examples of Technological Properties</h2>																	
<ul style="list-style-type: none"> <li>❑ <b>Use properties</b> (properties of relevance for the use of materials) Corrosion resistance Wear resistance</li> <li>❑ <b>Manufacturing properties</b> (properties of relevance for the manufacturing of materials)</li> </ul>	<table style="width: 100%; border: none;"> <tr> <td style="width: 33%;">Anodising</td> <td style="width: 33%;">Formability</td> <td style="width: 33%;">Weldability</td> </tr> <tr> <td><i>Bright</i></td> <td><i>Deep drawability</i></td> <td><i>Electron beam weldability</i></td> </tr> <tr> <td><i>Decorative</i></td> <td><i>Stretch formability</i></td> <td><i>Shielded arc weldability</i></td> </tr> <tr> <td><i>Protective</i></td> <td>Machinability</td> <td><i>Spot weldability</i></td> </tr> <tr> <td>Castability</td> <td>Solderability</td> <td></td> </tr> </table>	Anodising	Formability	Weldability	<i>Bright</i>	<i>Deep drawability</i>	<i>Electron beam weldability</i>	<i>Decorative</i>	<i>Stretch formability</i>	<i>Shielded arc weldability</i>	<i>Protective</i>	Machinability	<i>Spot weldability</i>	Castability	Solderability		
Anodising	Formability	Weldability															
<i>Bright</i>	<i>Deep drawability</i>	<i>Electron beam weldability</i>															
<i>Decorative</i>	<i>Stretch formability</i>	<i>Shielded arc weldability</i>															
<i>Protective</i>	Machinability	<i>Spot weldability</i>															
Castability	Solderability																
	Examples of Technological Properties	1502.03.06															


<h2 style="color: blue;">Representation of Property Values</h2>	
<b>Mechanical and physical properties</b>	Numerical values in the conventional way
<b>Technical properties</b>	<p>Representation with indices. In ALUSELECT and MATEDS the indices takes values from 1 to 7 where 7 is best:</p> <ol style="list-style-type: none"> <li>7. <b>Exceptionally high value</b>, frequently the result of special development (cf. machinability of free cutting alloys).</li> <li>6. <b>Excellent value</b>. The material can normally be used without problems.</li> <li>5. <b>Very good value</b>. Normal demand level if the property is of considerable importance.</li> <li>4. <b>Good value</b>. Normal demand level if the property is of some importance.</li> <li>3. <b>Unsatisfactory value</b>. The use of material with index 3 should be avoided unless special precautions are taken.</li> <li>2. <b>Low value</b>. The use of material with the index 2 should be avoided.</li> <li>1. <b>Property is not defined</b> for the material in question.</li> </ol>
	Discriminating Property Values for Technological Properties
	1502.03.07

## Examples of Discriminating Materials Selection

Examples of formulation of property demands are given for a car bumper (see **Figure 1502.03.08**) and an electric transmission cable (see **Figure 1502.03.09**). Both examples are much simplified for pedagogical reasons.

<h3>Requirements for Car Bumper in Aluminium</h3>		
<b>Specification</b>		
<b>Availability:</b>	The alloy must be available in the form of extruded profile.	
<b>Manufacturing:</b>	The cold formability must exceed a minimum value, index $\geq 4$ (2-7, 7 best) (or elongation > 5%). It should be possible to apply protective anodising, index $\geq 4$ (2-7, 7 best).	
<b>Strength:</b>	Yield strength $\geq 400$ MPa.	
<b>Corrosion:</b>	The corrosion resistance in air must be good, index $\geq 5$ .	
	Example: Requirements for Car Bumper in Aluminium	1502.03.08

<h3>Self-Supported Electric Transmission Cable</h3>		
<b>Specification</b>		
<b>Availability:</b>	The alloy must be available in the form of wire.	
<b>Manufacturing:</b>	The cold formability must exceed a minimum value, index $\leq 4$ (2-7, 7 best).	
<b>Strength:</b>	Tensile strength $\geq 100$ MPa.	
<b>Corrosion:</b>	The corrosion resistance in air must be good, index $\geq 5$ . The stress corrosion resistance in air must be good, index $\geq 5$ .	
<b>Conductivity:</b>	The electric conductivity must exceed a minimum value $\geq 55\%$ IACS.	
	Example: Self-Supported Electric Transmission Cable	1502.03.09

<b>Factors which prevent the Optimum Material to be Selected</b>		
<b>Lack of Information</b>		<ul style="list-style-type: none"> <li>- Service conditions</li> <li>- Material properties</li> <li>- Production costs</li> </ul>
<b>No Availability</b>		<ul style="list-style-type: none"> <li>- Material</li> <li>- Production resources</li> </ul>
<b>Lack of Competence</b>		<ul style="list-style-type: none"> <li>- Use of new materials</li> <li>- Material selection methodology</li> </ul>
<b>Lack of Time to Test New Materials</b>		
<b>Requirements on</b>		<ul style="list-style-type: none"> <li>- Rationalising of materials over several products</li> <li>- Market trends (fashion, appearance)</li> </ul>
	Limits to Optimum Material Selection	1502.03.10

There are many reasons why material selection can not be performed with full precision (see **Figure 1502.03.10**). The exact choice of demands depends on the industrial situation. In particular the manufacturing properties and availability must be considered in this perspective. As a first hand alternative materials in stock at the company are used. In addition materials for which a good experience is at hand are chosen. Often special requirements appear that give rise to additional demands. The practical way of handling lists of demands is to start with the most critical ones in order to reduce the total number of materials as rapidly as possible.

## **1502.04      Optimisation in Material Selection**

- **Purpose**
- **Semi-Systematic Methods**
- **Selection of Materials by Minimising the Material Costs**
- **Value of Weight Savings**

### **Purpose**

After the discrimination stage a large number of materials typically remain which satisfy all the requirements on discriminating properties. The procedure to find the best one(s) of these is referred to as optimisation. A target (objective) function is chosen which is minimised or maximised.

## Sums of Weighted Property Values

Properties for which it is desirable to have good values can be included in a weighted sum  $W_{lin}$ , which should be maximised.

$$Max W_{lin} = \sum_i \frac{\alpha_i E_i}{R_i} \quad \text{where } \begin{array}{l} E_i \text{ is the value of the property } i. \\ R_i \text{ is the reference value} \\ \alpha_i \text{ is the weight factor} \end{array}$$

It is convenient to make the following assumption:

$$\sum_i |\alpha_i| = 1$$

For some of the properties there are discriminating demands

$$E_i \geq \underline{E}_i$$

$$E_i \leq \bar{E}_i$$

$\bar{E}_i$  and  $\underline{E}_i$  are upper and lower limits on property  $i$ .



### Semi-Systematic Methods

There is a number of procedures that involve weighting of property values to find a suitable material. In the methods a mathematical expression in terms of properties is used which is maximised. Since a mathematical formula is employed the methods can give the impression that a high precision is involved. This is however typically not the case. Two methods will be discussed here. It is important to understand the limitations of the methods and to know how to reduce these limitations.

According to the procedure **linear weighting of property values** materials are chosen in such a way that the following sum is maximised (**Figure 1502.04.01**).

$$\text{Max } W_{lin} = \sum_i \frac{\alpha_i \cdot E_i}{R_i} \quad (1)$$

$$\text{where } \sum_i |\alpha_i| = 1 \quad (2)$$

$\alpha_i$  are weight factors with a sum of the absolute values equal to unity according to Eq. (2). The weight factors have no dimension. The weight factor is positive ( $\alpha_i > 0$ ) if it is valuable that the property value increases and negative ( $\alpha_i < 0$ ) if it is disadvantageous. For a cable there is a benefit with a high electrical conductivity and consequently  $\alpha_i > 0$ . For a thermal isolator there is a disadvantage that the property value increases and the corresponding weight factor is negative.  $R_i$  are reference values that have the same dimension and usually the same order of magnitude as the corresponding property.

There are three types of decisions which must be made in Eq. (1):

- Properties (terms) to be included in Eq.(1)  
Only properties for which an increased absolute value represents a genuine benefit should be taken into account. This condition is in fact more restrictive than one might first imagine. Consider a case where corrosion resistance is of major importance. Hence a minimum value should be specified. However, it is not self evident that corrosion resistance should be included in Eq.(1). If the corrosion protection is fully adequate by just satisfying the minimum value, a raised property value would not imply any further technical benefit. If that is the case it would be misleading to incorporate corrosion in Eq.(1) since materials with a very high corrosion resistance and which are probably also expensive would obtain a major premium for which there is no purpose.
- Choice of reference values  $R_i$  (**Figure 1502.04.02**)  
For properties with specified requirements it is natural to set the reference values to the property criteria values. Thus the reference values are usually chosen in the following way

$$R_i = \underline{E}_i \quad (3a)$$

or

$$R_i = \overline{E}_i \quad (3b)$$

depending whether a lower or an upper limit is involved. However, there are exceptions. If for example the limits are very low in relation to typical property values the corresponding term in Eq.(1) can become too large and the reference value has to be increased. When setting  $R_i$  for a property  $i$  for which no criterion has been specified a value typical for the material under consideration should be taken. In the literature one sometimes finds that  $R_i = 1$  is used for all properties. Such an assumption practically always leads to meaningless results and should be avoided.

- Choice of weight factors  $\alpha_i$   
According to Eq. (2) the absolute value of the weight factors must be smaller than unity. A property that is more critical to the successful use of the component should be given a higher value than a property that is of less significance.



## Parameter Values in Weighted Sums

If there is a demand on the property value this limit is usually chosen to be the reference value

$$R_i = \overline{E}_i \quad \text{or} \quad R_i = \underline{E}_i$$

If there is no limit on the choice of  $R_i$  is fairly free. It is common to take an average of  $E_i$  for the materials types of interest or simply a typical value of  $E_i$ .

Concerning the selection of the weight factors the following principles are followed:

- An important property gets a high absolute value of  $\alpha_i$  the less important ones lower values.
- If an improvement of the property corresponds to an increase in its value the weight factor is positive, otherwise negative.
- The sum of the absolute values of  $\alpha_i$  should be equal to unity.

It is important to recognise that the selection of the weight factors is based on engineering judgement rather than fundamental principles.



Choice of Reference Values

1502.04.02

An approved version of Eq. (1) is the following equation

$$\text{Max } W_{\text{exp}} = \sum_i \alpha_i \left( \frac{|E_i - g_i| n_i}{R_i} \right)^{n_i} \quad (4)$$

where

$$g_i = \underline{E}_i \quad (5a)$$

or

$$g_i = \overline{E}_i \quad (5b)$$

There is one main difference between Eqs. (1) and (4). As before only materials satisfying all the discriminating demands should be analysed with Eq. (4). However, the influence of the property value  $E_i$  on the sum  $W_{\text{exp}}$  is non-linear. In general the exponent  $n_i$  is smaller than unity which reduces the effect of large property values in Eq. (1). A more gradual increase is obtained for large property values. For  $n_i=1$  a linear behaviour is obtained in the same way as in Eq. (1).

### Selection of Materials by Minimising the Materials Cost

Rather than presenting the theory for materials optimisation in detail the general principles will be illustrated with the help of an example (example 1). The example involves an engineering beam. The beam has a rectangular cross section with triangular load distribution with a total load of  $F = 0.01$  MN and it is freely supported (see **Figure 1502.04.03**). The width  $b$  and length  $l$  are 100 and 800 mm. The material cost is minimised by selecting a suitable material and at the same time adapting the height  $h$  of the beam section. The design criteria are that the maximum elastic deflection should not

exceed  $\Delta_2 = 20$  mm and that the largest stress is smaller than the characteristic strength  $\sigma_{char}$  of the selected material divided by a safety factor of  $f_s = 1.2$ . The characteristic strength  $\sigma_{char}$  divided by the safety factor  $f_s$  is called the design stress  $\sigma_{des}$

$$\sigma_{des} = \frac{\sigma_{char}}{f_s}$$

For a beam with rectangular section the largest deflection and stress which both appear at the middle of the beam are given by

$$\Delta = \delta \frac{Fl^3}{Ebh^3} \leq \Delta_2 \quad (6)$$

$$\sigma = \mu \frac{6Fl}{bh^2} \leq \frac{\sigma_{char}}{f_s} \quad (7)$$

The constants  $\delta$  and  $\mu$  depend on the load case and how the beam is fixed to the supports. With a triangular load distribution for a freely supported beam the constants take the values

$$\begin{aligned} \delta &= 1/60 \\ \mu &= 1/6 \end{aligned}$$

Another condition must be taken into account, namely that the height  $h$  can not be chosen arbitrarily small because of design or manufacturing restrictions.

$$h \geq h_1 \quad (8)$$

where  $h_1$  is assumed to take the value 5 mm. The material cost  $L_k$  of the beam is

$$L_k = l_{tot} b h \rho c_k \quad (9)$$

where  $\rho$  is the density and  $c_k$  the price per unit weight of the material. To minimise the material cost the height  $h$  should be chosen as small as possible. According to Eqs. (6) and (7) the following restrictions on the height are obtained.

## Material Optimisation: Example for an Engineering Beam

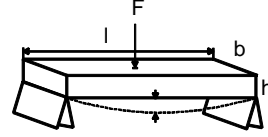
### Problem Formulation

#### Design criteria

Elastic deflection:  $\Delta = \delta \frac{Fl^3 12}{Eb h^3} \leq \Delta_2$

Maximum stress:  $\sigma = \mu \frac{6Fl}{bh^2} \leq \frac{\sigma_{char}}{f_s}$

Geometric condition:  $h \geq h_1$



#### Objective function

Material cost to be minimised:  $L_k = l_{tot} b \rho c_k$

Parameters to be varied: Beam section height  $h$  and the material.

#### Values of the design parameters in the example

$F = 0.01\text{MN}$ ;  $l = 0.1\text{m}$ ;  $b = 0.1\text{m}$ ;  $h_1 = 0.005\text{m}$ ;

$f_s = 1.2$ ;  $\Delta_2 = 0.02\text{m}$ ;  $\delta = 1/60$ ;  $\mu = 1/6$



Material Optimisation: Example for a Beam  
Subjected to Bending

1502.04.03

$$h \geq h_{\Delta} = \left( \delta \cdot \frac{Fl^3 12}{Eb \Delta_2} \right)^{1/3} \quad (10)$$

$$h \geq h_{\sigma} = \left( \mu \cdot \frac{Fl 6 f_s}{b \sigma_{char}} \right)^{1/2} \quad (11)$$

Together with Eq. (8) an expression for the lower limit of  $h$  is derived (**Figure 1502.04.04**).

$$h_{min} = \max \left[ \left( \delta \frac{Fl^3 12}{Eb \Delta_2} \right)^{1/3}, \left( \mu \frac{Fl 6 f_s}{b \sigma_{char}} \right)^{1/2}, h_1 \right] \quad (12)$$

If this expression is inserted into Eq. (9) the minimum material cost is found for a given material.

$$L_{kmin} = l_{tot} b \rho c_k \max \left[ \left( \delta \frac{Fl^3 12}{Eb \Delta_2} \right)^{1/3}, \left( \mu \frac{Fl 6 f_s}{b \sigma_{char}} \right)^{1/2}, h_1 \right] \quad (13)$$

### Solution Principle

1) Derive the expression for the minimum material cost

$$L_{k\min} = l_{tot} b \rho c_k \max \left( \left( \delta \frac{Fl^3 12}{Eb \Delta_2} \right)^{\frac{1}{3}}, \left( \mu \frac{Fl 6 f_s}{b \sigma_{char}} \right)^{\frac{1}{2}}, h_1 \right)$$


2) Derive the merit parameters [(inverse) material dependent part of objective function]

Elastic deflection (E-modulus) controlling  $Q_E = \frac{E^{\frac{1}{3}}}{\rho c_k}$

Maximum stress (characteristic strength) controlling  $Q_\sigma = \frac{\sigma_{char}^{\frac{1}{2}}}{\rho c_k}$

Geometry controlling:  $Q_{ht} = \frac{1}{\rho c_k}$


3) Find the material with the largest merit parameter for the controlling property.  
 4) Amongst the materials with the largest merit parameter find the one with the lowest material cost.

 Training in Aluminium Application Technologies	Solution Principle for the Beam Subjected to Bending	1502.04.04
---	--	------------

In this example a fully unbiased materials selection will not be performed. Only a set of aluminium alloys will be considered (see **Figure 1502.04.05**). The material price is expressed with an index which is unity for the pure aluminium alloy AA1050A. This unit is called  $p_{i0}$  here.

### Used Material Data and Merit Parameters in Example 1


Material	Composition, wt. %	Temper	Price index $p_{i0}$	Density $\text{kg/m}^3$	Young's modulus MPa	Yield strength MPa	Tensile strength MPa	$Q_{ht} \times 10^{-4}$	$Q_E \times 10^2$	$Q_\sigma \times 10^{-3}$
AA6061	Al1.0Mg0.6SiCuCr	T6	1.05	2700	70000	270	310	3.53	1.45	5.79
AA6082	Al0.9Mg1.0Si0.7Mn	T6	1.06	2710	70000	310	340	3.49	1.44	6.14
AA7020	Al4.5Zn1.2MgMnCrZr	T5	1.12	2780	70000	315	375	3.22	1.33	5.71
AA2014A	Al4.5Cu0.8Mn0.7Si5Mg	T6	1.19	2800	73000	425	485	2.99	1.25	6.17
AA6005A	Al0.6Mg0.7SiMnCr	T5	1.05	2710	69500	240	270	3.50	1.44	5.42
AA6063	Al0.7Mg0.4Si	T6	1.02	2700	69500	210	245	3.64	1.50	5.27
AA6082	Al0.9Mg1.0Si0.7Mn	T4	1.06	2710	70000	170	260	3.49	1.44	4.55
AA6061	Al1.0Mg0.6SiCuCr	T4	1.05	2700	70000	140	235	3.53	1.45	4.17
AA5083	Al4.5Mg0.7MnCr	0	1.20	2660	71000	145	300	3.14	1.30	3.79
AA1050A	Al99.5	0	1.00	2700	69000	35	80	3.70	1.52	2.19

 Training in Aluminium Application Technologies	Used Material Data and Merit Parameters for the Example (Bending of Beams)	1502.04.05
---	--	------------

The evaluation of the smallest allowable height of the beam  $h_{min}$  is tabulated (**Figure 1502.04.06**). According to Eq. (12)  $h_{min}$  is the largest of the three expressions (10), (11) and (8). Since the first two represent the limitation in the elastic deflection and the largest stress respectively, they are designated  $h_\Delta$  and  $h_\sigma$ . Values of  $h_\Delta$ ,  $h_\sigma$  and  $h_1$  are given in **Figure 1502.04.06**. With the assumptions made,  $h_1 = 5$  mm is independent of the material. Since the only material parameter, on which  $h_\Delta$  depends, is the E-module,

$h_{\Delta}$  has about the same value for all aluminium alloys. There are only small differences in the E-module between aluminium alloys ( $E \cong 70\,000$  MPa).  $h_{\sigma}$  decreases according to Eq. (11) with increasing yield strength. Eq. (12) shows that the largest of  $h_{\Delta}$ ,  $h_{\sigma}$  and  $h_l$  corresponds to lowest allowable height  $h_{min}$ . This value is underlined in **Figure 1502.04.06**. The  $h$  parameter which is the largest is called controlling (or sizing) parameter.

Optimisation Parameters for Example 1							
Material	Main Composites	Temper	$h_{\Delta}$ mm	$h_{\sigma}$ mm	$h_l$ mm	$h_{min}$	$L_{kmin}$
AA6061	Al1.0Mg0.6SiCuCr	T6	<u>0.0194</u>	0.0189	0.0050	1.94*10 <sup>-2</sup> mm	4.40
AA6082	Al0.9Mg1.0Si0.7Mn	T6	<u>0.0194</u>	0.0176	0.0050	1.94*10 <sup>-2</sup> mm	4.45
AA7020	Al4.5Zn1.2MgMnCrZr	T5	<u>0.0194</u>	0.0175	0.0050	1.94*10 <sup>-2</sup> mm	4.82
AA2014A	Al4.5Cu0.8Mn0.7Si0.5Mg	T6	<u>0.0191</u>	0.0150	0.0050	1.91*10 <sup>-2</sup> mm	5.11
AA6005A	Al0.6Mg0.7SiMnCr	T5	0.0195	<u>0.0200</u>	0.0050	2.00*10 <sup>-2</sup> mm	4.57
AA6063	Al0.7Mg0.4Si	T6	0.0195	<u>0.0214</u>	0.0050	2.14*10 <sup>-2</sup> mm	4.70
AA6082	Al0.9Mg1.0Si0.7Mn	T4	0.0194	<u>0.0238</u>	0.0050	2.38*10 <sup>-2</sup> mm	5.45
AA6061	AlMg0.6SiCuCr	T4	0.0194	<u>0.0262</u>	0.0050	2.62*10 <sup>-2</sup> mm	5.94
AA5083	Al4.5Mg0.7MnCr	0	0.0193	<u>0.0257</u>	0.0050	2.57*10 <sup>-2</sup> mm	6.55
AA1050	Al99.5	0	0.0195	<u>0.0524</u>	0.0050	5.24*10 <sup>-2</sup> mm	11.33

	Optimisation Parameters for the Example (Bending of Beams)	1502.04.06
---	--	------------

The reason for this nomenclature is that the corresponding design criteria (8), (10) or (11) is the most critical one and thus called controlling. The three design criteria are often identified by the material property involved. (10) and (11) are referred to as the E-module and the strength criteria, respectively. (8) is called the geometric criterion. For lower yield strengths the characteristic strength is controlling whereas the E-module is controlling at higher ones (see **Figure 1502.04.06**). When a certain strength has been reached more material can not be saved by increasing the strength further since the criterion for the deflection would not be satisfied. The lower limit  $h_l$  does not affect the result since the criteria (10) and (11) are more difficult to satisfy in this case.

When  $h_{min}$  is known the material cost  $L_{kmin}$  can directly be calculated with the aid of Eq. (9). The result is given in **Figure 1502.04.06**. For aluminium alloys the material cost only increases marginally with increasing strength. Hence a marked increase in yield strength can be obtained for a modest increase in material price. The most advantageous material is typically found at the transition from where the characteristic strength is controlling to where the elastic modulus is dominating. This is clearly the case in **Figure 1502.04.06**.

To convince oneself that the chosen solution is the optimum, one can go through all the materials one by one. There are, however, much more efficient methods available using merit parameters. The merit parameters are obtained by extracting the material dependent part of the minimum material cost in Eq. (13). When  $h_{\Delta}$  is controlling i.e. when the first member of the square bracket is largest, then the material dependent part is given by

$$Q_E = \frac{E^{1/3}}{\rho c_k} \quad (14)$$

The corresponding factors when  $h_{\sigma}$  and  $h_1$  are controlling are

$$Q_{\sigma} = \frac{\sigma_{char}^{1/2}}{\rho c_k} \quad (15)$$

$$Q_{h_1} = \frac{1}{\rho c_k} \quad (16)$$

The inverse of the factors are provided in Eqs. (14) - (16) since these should be maximised when the material cost is minimised.  $Q_E$ ,  $Q_{\sigma}$  and  $Q_{h_1}$  are the **merit parameters** of the problem. The values of the merit parameters are shown in **Figure 1502.04.05**. Since the material cost is inversely proportional to the controlling merit parameter it gives a ranking of the materials. For the first four materials in **Figure 1502.04.06**, the E-module is controlling. From **Figure 1502.04.05** one finds that the first material AA6061 has the highest merit parameter  $Q_h$  of these four. Consequently this material also gives the lowest cost, cf. **Figure 1502.04.06**.

For the six last materials in **Figure 1502.04.06**,  $\sigma_{char}$  is controlling and thus the merit parameter  $Q_{\sigma}$  should be considered. From **Figure 1502.04.05** one finds that AA6005A has the largest merit parameter of the six materials and hence also the lowest material cost, cf. **Figures 1502.04.05** and **.06**. One can conclude that either AA6061 or AA6005A is the optimal material. From **Figure 1502.04.05** it is evident that AA6061 gives the lowest overall cost. Directly from the material parameters it is not possible to decide which of these two materials is the optimal one. There are methods for assessing that but they will not be discussed in this context.

The main advantage of using merit parameters is that they are independent of the design parameters. Hence they are independent of the size of the external load, load distribution, type of beam support, beam geometry, etc. If these parameters are changed there is no need of recalculating the merit parameters. Thus by just considering the values of the merit parameters a ranking of the materials can be obtained. It is for example possible to show that if all merit parameters for one material are smaller than for another the former material can never be the optimal one. From **Figure 1502.04.06** it is evident that AA7020-T5, AA2014A-T6, AA6082-T5 and AA5083-O can not give a lower material cost than AA6082-T6 since all the three merit parameters are larger for

the latter material. In the same way AA6005A-T5 and AA6061-T4 can be disregarded in relation to AA6061-T6. If these materials which can never be the optimal ones are removed, **Figure 1502.04.06** is reduced to **Figure 1502.04.07**. In fact only four materials remain namely AA6061-T6, AA6082-T6, AA6063-T6 and AA1050A-O. Thus the size of the computations can significantly be reduced in this way.

### Reduced Table for Optimisation Parameters of Example 1

Material	Main composition	Temper	$h_E$ mm	$h_\sigma$ mm	$h_l$ mm	$h_{min}$	$L_{kmin}$
AA6061	Al1.0Mg0.6SiCuCr	T6	<u>0.0194</u>	0.0189	0.0050	$1.94 \cdot 10^{-2}$ mm	4.40
AA6082	Al0.9Mg1.0Si0.7Mn	T6	<u>0.0194</u>	0.0176	0.0050	$1.94 \cdot 10^{-2}$ mm	4.45
AA6063	Al0.7Mg0.4Si	T6	0.0195	<u>0.0214</u>	0.0050	$2.14 \cdot 10^{-2}$ mm	4.70
AA1050A	Al99.5	0	0.0195	<u>0.0524</u>	0.0050	$5.24 \cdot 10^{-2}$ mm	11.33



Reduced Set of Optimisation Parameters  
for the Example

1502.04.07

### Advantage of Using Merit Parameters

1. Independent of the design parameters such as size of the external load, load distribution, type of beam support, beam geometry, etc.
2. If the design parameters are changed there is no need of recalculating the merit parameters.
3. A ranking of the materials can be obtained without carrying out the optimisation and computing the material cost.
4. If all the merit parameters for one material are smaller than for another one the former material can never be the optimal one.

### Factors Controlling the Form of the Merit Parameters

1. The parameters depend on the shape of the component being analysed but not on the dimensions. In the example the shape of the beam section is of importance. If for example the shape is changed to solid circular or tubular the merit parameters will be modified.
2. The geometric parameter which is adapted to the material has a direct influence on the merit parameters. If the width of the beam instead of the height is fitted the exponent in the merit parameters takes the value unity.



Advantage of Using Merit Parameters and  
Factors Controlling their Forms

1502.04.08

## Value of Weight Savings

### Typical Values of Weight Savings

Cars: 0.5-1 £ per kg saved weight.  
 Trucks: 1-10 £ per kg saved weight.  
 Air Applications: 100-1000 £ per kg saved weight.

### To Take the Value of Weight Savings into Account

Replace the material price by the sum of the value of weight savings  $c_w$  and the material price  $c_k$ .

$$C_k \rightarrow C_k + C_w$$

In the example the merit parameters take the form

$$Q_E = \frac{E^\alpha}{\rho(c_k + c_w)} \quad Q_\sigma = \frac{\sigma_{char}}{\sigma(c_k + c_w)} \quad Q_{h_1} = \frac{1}{\sigma(c_k + c_w)}$$



The form of the merit parameters depends on the component being analysed. In the example the geometry of the beam section and the geometric parameter which is adapted to the material have a direct influence on the merit parameters. If the width of the beam instead of the height is fitted the merit parameters for the elastic deflection and the strength take the following form.

$$Q_E = \frac{E}{\rho c_k} \tag{17}$$

$$Q_\sigma = \frac{\sigma_{char}}{\rho c_k} \tag{18}$$

In Eqs. (17) and (18) the exponent is changed in comparison to Eqs. (14) and (15). In Eqs. (17) and (18) the merit parameters are linear in the E-module and the characteristic strength respectively.

### Value of Weight Savings

For aluminium alloys the low density plays an important role in many applications. In particular for vehicles of all kinds and equipment which is frequently moved it is important to save weight. In many cases this can be achieved by using aluminium alloys. The value of weight savings varies between different situations. For cars a figure of 0.5-1 £ per kg save weight is typically quoted. For trucks the corresponding figures covers a wider range namely 1-10 £ per kg. In air applications the value of weight savings is about two order of magnitude larger, 100-1000 £ per kg. To take the value of weight



savings into account is straightforward. The material price is just replaced by the sum of the value of weight savings  $c_w$  and the material price  $c_k$ .

$$c_k \rightarrow c_k + c_w \quad (19)$$

In the example the merit parameters in section 1502.04.03 are replaced by

$$Q_E = \frac{E^{\alpha}}{(c_k + c_w)^{\beta}} \quad (20)$$

$$Q_{\sigma} = \frac{\sigma_{char}}{(c_k + c_w)^{\beta}} \quad (21)$$

$$Q_{h_1} = \frac{1}{(c_k + c_w)^{\beta}} \quad (22)$$

For  $\alpha = 1/3$  and  $\beta = 1/2$  Eqs. (20) and (21) correspond to Eqs. (14) and (15), for  $\alpha = 1$  and  $\beta = 1$  to Eqs. (14) and (15). Eq. (22) is the modified form of Eq. (16). The effect of  $c_w$  on the merit parameter for the characteristic strength in Eq. (21) is illustrated in **Figure 1502.04.11** and **12** for  $\beta = 1$  and  $\beta = 1/2$  respectively. Three aluminium alloys and three steels are included in the figures. The steels have a yield strength of 220, 380 and 690 MPa representing a mild, a high strength and an extra high strength steel. The merit parameters are given in relation to that of Steel 220.

$$Q_{\sigma} = \frac{\sigma_{char}}{(c_k + c_w)^{\beta}} / Q_{\sigma}^{Steel 220} \quad (23)$$

This is possible since it is the relative values of the merit parameters that are of importance not their absolute values. According to Eq. (23)  $Q_{\sigma}$  is equal to unity for Steel 220. In **Figure 1502.04.11** for  $\beta = 1$  Steel 380 and Steel 690 have higher merit parameters than Steel 220. This difference increases up to a value of weight savings  $c_w$  of 10 £/kg and then stays constant. Below about  $c_w = 1$  £/kg the aluminium alloys have lower  $Q_{\sigma}$  than the steels, However above  $c_w = 2-5$  £/kg they are significantly higher than for Steel 220, AA2014 and AA6082 are even above Steel 690. At higher  $c_w$  the cost savings of AA2014 in relation to carbon steel (Steel 220) is more than a factor of five.

In **Figure 1502.04.12** for  $\beta = 1/2$  the differences between steel and aluminium alloys are equally pronounced. The transition where aluminium alloys become competitive takes place at  $c_w = 2-3$  £/kg. Above  $c_w = 10$  £/kg the three aluminium alloys give a material cost which is two to four times lower than for mild steels. Even in relation to extra high strength steels the advantage is quite significant.

## Value of Weight Savings (continued)

The merit parameters are often given in relation to another material for example mild steel (Steel 220).

$$Q_{\sigma} = \frac{\sigma_{char}^{\beta}}{\rho(c_k + c_w)} / Q_{\sigma}^{Steel220}$$

This is possible since only the relative values of the merit parameters are of importance.

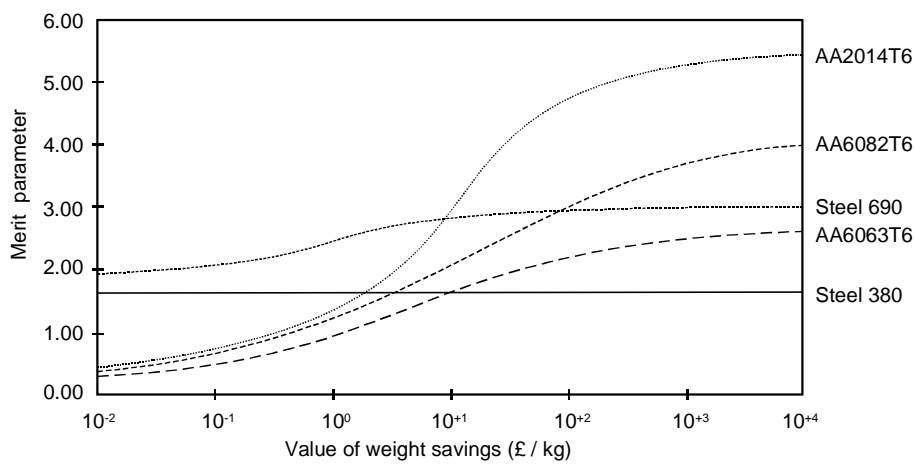
Aluminium alloys typically become competitive in comparison to carbon steels above  $c_w = 2.5 \text{ £/ kg}$  when strength is the controlling property.



Relative Merit Parameters: Value of Weight Savings

1502.04.10

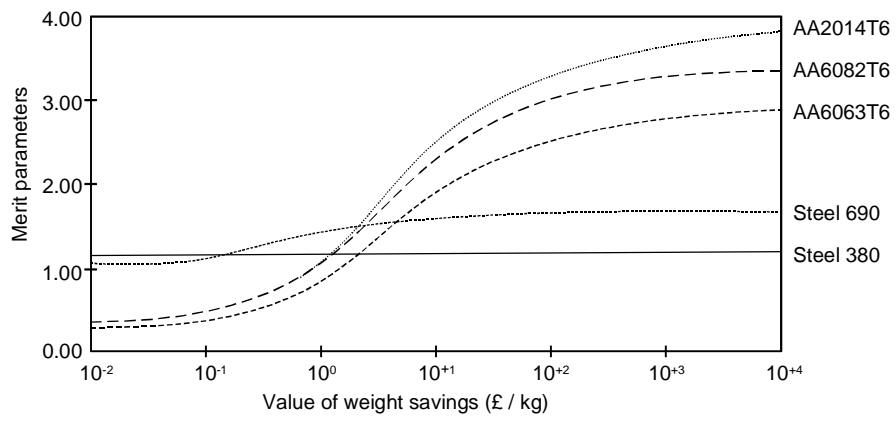
## Linear Strength



Material Selection Based on Linear Strength

1502.04.11

## Square Root of Strength



## 1502.05 List of Figures

Figure Nr.	Figure Title (Overhead)
1502.01.01	Rapid Development in Material Technology
1502.01.02	Intuitive Methods in Material Selection
1502.01.03	Material Selection Basics
1502.01.04	Connection to Design: Material Selection Integral Part of the Design Process
1502.01.05	General Guidelines for Successful Material Selection
1502.01.06	First Step: Specification of Functions
1502.01.07	Check List: Functional Requirements
1502.01.08	Formulating Functional Requirements
1502.02.01	General Principles for Pre-Selection of Materials
1502.02.02	Characteristic Properties of Aluminium Alloys
1502.02.03	Aluminium Alloys Should Not be Used, If ...
1502.02.04	Properties Involved in Pre-Selection of Material Types
1502.02.05	Example on Pre-Selection: Casserole
1502.02.06	Example on Pre-Selection: Ladder
1502.02.07	Example on Pre-Selection: Self-Supported Cable
1502.02.08	Base Material of Pre-Selection
1502.03.01	Discriminating Material Selection (Sorting)
1502.03.02	Demands on Material Properties
1502.03.03	Sources of Material Specification
1502.03.04	Steps in Material Specification
1502.03.05	Relation between Specification and Materials Properties
1502.03.06	Examples of Technological Properties
1502.03.07	Discriminating Property Values for Technological Properties
1502.03.08	Example: Requirements for Car Bumper in Aluminium
1502.03.09	Example: Self-Supported Electric Transmission Cable
1502.03.10	Limits to Optimum Material Selection
1502.04.01	Maximizing Weighted Property Values
1502.04.02	Choice of Reference Values
1502.04.03	Material Optimisation: Example for a Beam Subjected to Bending
1502.04.04	Solution Principle for the Beam Subjected to Bending
1502.04.05	Used Material Data and Merit Parameters for the Example (Bending of Beams)
1502.04.06	Optimisation Parameters for the Example (Bending of Beams)
1502.04.07	Reduced Set of Optimisation Parameters for the Example
1502.04.08	Advantage of Using Merit Parameters and Factors Controlling Their Forms
1502.04.09	Using Merit Parameters: Value of Weight Savings
1502.04.10	Relative Merit Parameters: Value of Weight Savings
1502.04.11	Material Selection Based on Linear Strength
1502.04.12	Material Selection Based on Square Root of Strength