Design of Aluminium Structures: Selection of Structural Alloys

Structural Design according to Eurocode 9: Essential Properties of Materials and Background Information

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Paper presented at the workshop in Brussels: **EUROCODES - Background and Applications**-
Session EN 1999-Eurocode 9: Design of Aluminium structures; 20. February 2008[**)]

Summary

Aluminium has in fact proved itself as a suitable material for load bearing structures for more than one hundred years. However certain knowledge of aluminium is necessary to design structures. In combination with the materials and material provisions of EUROCODE 9: EN 1999, the task of this paper is to cover the most important aspects needed to design in aluminium. It covers the important differences in physical properties compared to steel which need to be understood to design aluminium structures. It covers the influence of heat on the mechanical properties of aluminium. The essential metallurgical aspects are explained to enable understanding of aluminium's nomenclature system for alloys and their temper designations. It deals with the alloys, listed in EUROCODE 9, gives background information and advice for their selection and application for structures. In particular the topic design of extruded profiles and material selection combined with this is treated in a special section. In Annex C fields of application are listed where the Eurocode 9 is the (legal!) basis for the design or where the code is commonly used or can be used for the design.

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**) Corrected and amended in august 2008

1. Introduction

Engineers familiar with steel charged with designing an aluminium structure are faced with two particularities. The first is the large number of alloys combined with the different so called tempers which are available. The second, and this may be a problem, is the fact, that as either sheet or standard section only a limited range of alloys are available from stock. An adherent problem is the fact that the range of sections available from stock is very limited and confined to small shapes although a few stockists also have a few medium sized sections. The reason for this is that the processes for producing steel sections usually involves rolling whereas in contrast aluminium sections are usually manufactured by warm extrusion. Rolling is characterized by high roll die costs in combination with considerable changeover times and therefore needs large production quantities for economic manufacture of one section. Aluminium extrusion die costs vary between low for small sections and moderate for the large shapes. The quantities to economically produce an aluminium section are relatively small and lie between 200 kg and 3000 kg, depending on size of section. The consequence is that many engineers and companies design their own sections which are specific for the structure and are designed often with a high functionality. Ninety percent of all sections produced by aluminium extruders are individually designed and are therefore only available for the use by the designer/purchaser of the section. This explains the special stock situation which applies to aluminium sections and why no standards for so called standard sections (FLUTZ) exist.

For the experienced engineer the choice of alloy and temper is not very difficult, especially after the clarification of the following points:

- Which level of strength is needed?
- Is high welding strength really necessary? (Or: Is it possible to avoid welding at distinct locations, e.g. may depend on size of sheet available)
- Which form of semi product is needed: sheet/plate/extrusions?
- What are the quantities needed – are they available from stock?
- Are individually designed sections of quantities sufficient for production?
- Are filigreed/multi-hollow sections of advantage or needed?
- Is there a need for high ductility material?
- Is bendability/formability of sections needed?
- Is foldability/formability for sheet material required?
- Is decorative anodisability necessary?
- Is exceptionally good corrosion behaviour required (for special applications)?
- Are there special requirements with respect to elevated temperatures?

Last but not least, what will be the materials cost? There are considerable differences between the various alloys and the semi products and often the engineer is forced to change the design to make cost compromises.

This may explain why the engineer designing in aluminium needs to know much more about the material aluminium itself especially when compared to the steel designing process. This also concerns some physical properties which are different for aluminium than for steel. The paper deals with all these questions and also gives background knowledge of rules and provisions given in EC9 concerning material. In EN 1999-1-1 in Annex C some information about material questions is already given, these chapters help but are not really enough.

2. Hardening of aluminium

2.1 General

Pure aluminium itself is a metal with relatively low strength. Aluminium in its purest form has a tensile strength of around 40 N/mm² and a proof strength of about 10 N/mm². For most technical applications this is too low. Aluminium alloys however have been developed with mechanical properties far in excess of those of the base material.

In all solid metals plastic flow in the individual crystals of the material occurs along specific slip planes. These slip planes offer the lowest resistance to internal shear stresses and at the atomic level shear movement occurs along these planes without any separation of the material. If a metal is strained over its elastic limit it begins to flow and permanent plastic deformation occurs. When subjected to loads above the material's elastic limit tensile test specimens become longer and thinner. In the material many of such shear planes appear. Since the commercial alloys, when considered macroscopically, are generally fine grained and relatively isotropic, the shear planes are inclined at approx. ±45° correspon ding to the plane with the highest shear stress.

For the engineer, thinking in mechanical terms, it is easy to appreciate that an improvement of the shear strength should also improve the general mechanical strength of the metal. The idea that this can be achieved by use of structures which act like shear dowels is not so very wrong and is a help in understanding the various differing methods of hardening aluminium. The basic principle is that all types of lattice imperfection can cause an increase in shear strength.

2.2 Alloy hardening

A very efficient means of producing lattice imperfections is to introduce suitable foreign elements into the aluminium matrix. To a certain degree their efficacy depends on the difference in atomic radii between the foreign element and aluminium. The relationship between the content of added foreign element and the hardening effect is not linear, as can be seen from **Fig. 1**.

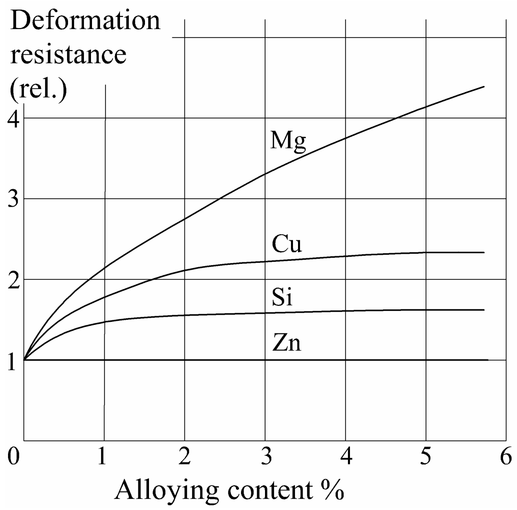

Figure 1: Hardening effect as a function of the content of alloying element

One of the elements which best suits the requirement to improve strength is magnesium. Therefore aluminium-magnesium alloys were the predominant choice for structural aluminium applications 100 years ago and were still so many years later. High strength values in alloys with up to 10 percent magnesium were available.

However, problems when hot and cold working these alloys and the less than optimum corrosion behaviour of the alloys with very high magnesium levels, led to the gradual adoption of alloys with lower amounts of magnesium but with additions of manganese.

In **Fig. 1** the curve for the frequently used alloying element, manganese, is not shown. Manganese itself as a single alloying addition has only a limited importance with respect to hardening. In combination with magnesium, however, it is much more effective. In addition corrosion behaviour is improved.

2.3 Work hardening

Plastic deformation produces imperfections in the lattice by markedly increasing the numbers of so called "dislocations" particularly along the slip-planes. With increasing load and deformation, additional slip planes continuously develop so that, with the resulting increase in dislocation density, the material develops increased mechanical strength. Parallel to this increase in strength, ductility decreases until ultimately the deformation process has to be stopped. When cold rolling, this so called "work hardening or "strain hardening" continues until the material begins to develop cracks, usually at the edges of the strip. This phenomenon can be easily demonstrated with a paper clip. Bending to and fro shows an immediate increase in resistance and finally a breaking of the wire. However this hardening process can be reversed by the use of heat. Depending on temperature and time at temperature the gain in material strength can be reversed and returned to its starting level before cold working. The material also returns to its original ductility. This thermal process to arrive at a so called "O temper"*) material is described as annealing. From this soft 'O' state the cold working processes can be restarted. In industrial production the procedure may be repeated several times to produce very thin material from what was originally a thick slab of metal.

Fig. 2 shows the process of cold working and annealing, here as a function of time at constant temperature. In the literature you may also find diagrams which show annealing as a function of the level of the applied temperature. It is typical for the cold working effect that the first stages of cold working have the greatest effect on material strength.

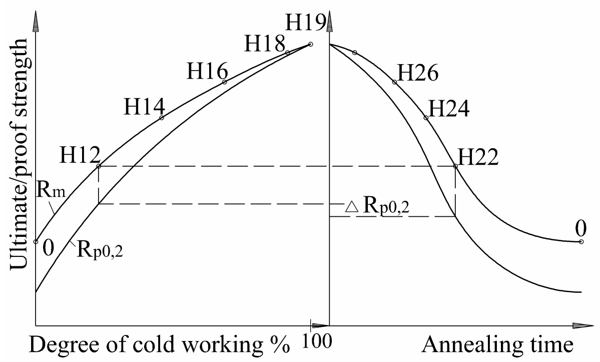

Figure 2: Strength as a function of the degree of cold work and annealing temperature respectively

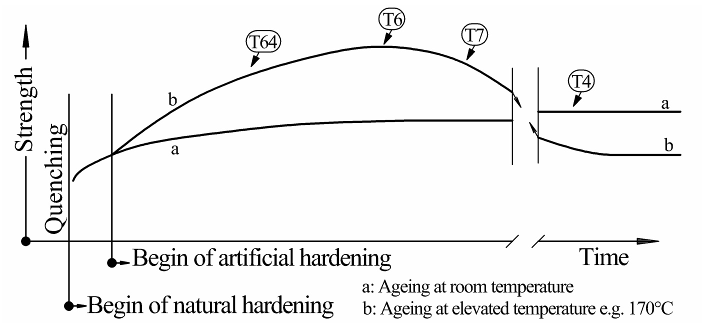

Figure 3: Strength in function of time at ambient and elevated temperature

2.4 Precipitation hardening

The effect of precipitation hardening was first discovered and used practically by Wilm in 1906. The effect is caused by the fact, that one or more suitable elements are able to form particles, so called intermetallic compounds, with each other or together with the matrix material aluminium. They also constitute lattice imperfections and depending on the size of these particles and their uniform distribution they cause a remarkable increase of strength. The whole process begins with a solution heat-treatment i.e. all alloying elements are in solution (solid solution), after that a quenching is necessary to also get a uniform distribution of all elements at ambient temperature. After that the elements involved begin to move in the aluminium matrix, they unify to intermetallic compounds and grow. This happens at room temperature but with more efficiency

*) Temper "O", not 0 (=zero)

at elevated temperatures (natural ageing and artificial ageing). It is important to know that the hardening effects due to precipitations can also decrease if too high temperatures are acting for a short time on the material or more moderate temperatures for a longer period.

Fig. 3 shows the process of ageing. It is typical that natural ageing begins immediately after quenching with a relatively high speed but degressive and then asymptotically approaches an upper limit (T4). Depending on the alloy this may need weeks, but for most alloys the process may be regarded as finished after one week. After a certain time, (hours, few days) mostly depending on manufacturing conditions, the material to be artificially aged is placed in a furnace, whereby the ageing can be executed under really different temperature conditions. Typical for all temperatures is a quick hardening degressively going to a summit (T6), which, depending on temperature, may be very flat. If the temperature acts for a longer time, the effect of the precipitations on strength decreases and we get an over-aged temper (T7). In this stage the material shows some improved physical properties: better ductility, corrosion resistance (some copper and/or zinc containing alloys) and better electrical conductivity. It must be said that there is deliberately no scale on the diagram and the abscissa shall not be seen linear. The duration of the different phases may be very different depending on the alloy and thermal conditions.

Here it must be emphasised that today precipitation hardening alloys are dominating in many areas (e.g. extruded sections). They show in the (warm) working processes a significant lower deformation resistance and gain their often remarkable strength later by the precipitation hardening process.

3. Alloys

3.1 General

In practice only a few elements have proven to be really suitable as alloying additions in aluminium wrought and cast materials for structural applications. These are:

Magnesium (Mg); Silicon (Si); Manganese (Mn); Copper (Cu); Zinc (Zn)

They can be used as single elements and also in combinations. The very limited series of alloy families which result are shown in **Table** 1 for wrought alloys and **Table 2** for casting alloys, where different alloy families are important.

Working with aluminium it is necessary to know the nomenclature used with this material. This refers to the designation of the alloys in use and also to the temper states in which they are supplied to the market.

	Mn	**Mg**	**Si**	**Zn**
Mn	AlMn 3xxx			
Mg	AlMgMn 5xxx	AlMg 5xxx	AlMgSi 6xxx	
Si		AlSiMg 6xxx	AlSi 4xxx	
Zn		AlZnMg AlZnMgCu 7xxx		
Cu		AlCuMg 2xxx		

Table 1 Wrought alloy families

	Mn	**Mg**	**Si**	**Zn**	**Cu**
Mn					
Mg		AlMg 5xxxx			
Si		AlSiMg 4xxxx	AlSi 44xxx		AlSiCu 4xxxx
Zn		AlZnMg 7xxxx			
Cu					AlCu 2xxxx

Table 2 Casting alloy families

3.2 Designation of wrought alloys

The system of designation of the Aluminium Association (AA) in the USA is today the most generally used system. The European standards also follow this nomenclature. It makes use of a 4 digit number for the designation of an alloy, in special cases the 4 digits can be followed by a letter (A, B, C,..). The family or the most important alloying element is characterised by the first digit. **Table 1** shows under the chemical symbol the corresponding numerical designation.

The families not listed in the table are the 1xxx, 8xxx and 9xxx series of alloys:

The 1xxx series designation concerns unalloyed aluminium materials which are distinguished according to their degree of purity.

The 8xxx series designations are for miscellaneous types of alloys (i.e. Fe alloys) which cannot be grouped in the other families.

9xxx series designations are not used.

The first digit gives basic information about the principal alloying element(s):

2xxx: Copper

3xxx Manganese

4xxx Silicon

5xxx Magnesium

6xxx Magnesium and silicon

7xxx Zinc

The designation system also says something about the hardening of the alloys belonging to a family.

The 1xxx, 3xxx and 5xxx series are so called non-heat-treatable alloys; they gain their strength by alloying (e.g. increasing content of Mg) and work hardening.

The 2xxx, 6xxx and 7xxx series are heat-treatable alloys, which gain their strength by alloying but make use of precipitation hardening as the main mechanism. Work hardening in normal production is not used.

The 4xxx and 8xxx series of alloys cannot be characterised so easily. All three methods of hardening may be found in these groups depending on the alloy type.

3.3 Designation of casting alloys

For cast products quite different alloys are preferred. Casters prefer type 4xxxx alloys with high silicon content, since with these alloys good quality is easily produced.

Casting alloy designations have the prefix "EN AC-" to distinguish them from wrought alloys and have 5 digits in total. The system originated in Europe and not in the USA.

The first digit means the same as for wrought alloys, i.e. it defines the principal alloying element. There is however a difference concerning casting alloys with magnesium and silicon additions made to develop hardening effects and hence higher mechanical properties, through controlled precipitation of the magnesium silicide phase. In casting alloys higher levels of silicon are of benefit in reducing the tendency to shrinkage cracking. Therefore, even in the magnesium silicide phase hardening casting alloys, silicon is well in excess of other elements. The logic of the designation system therefore requires that these alloys have a "4" as first digit in contrast to the magnesium silicide hardening wrought alloys which have a "6" as first digit.

In the 4xxxx series we find mainly heat-treatable alloys with subgroup 44xxx which are non-heat-treatable alloys, because they only have silicon as the main alloying element. A second group of non-heat-treatable alloys is the group with Mg as single main alloying element, designated the 5xxxx group. Work hardening for casting is not relevant.

3.4 Numerical and chemical designation of alloys

In former times the standards of many countries did use designations based on chemical symbols. For the engineer unfamiliar with aluminium alloys this was an advantage. He could judge an alloy with such a designation much more easily in terms of its strength, dominating methods of hardening, weldability and behaviour under different atmospheric conditions.

Numerical designation	Chemical designation			
EN AW-	**EN AW-**	**sheet**	**extrusions**	**forgings**
3004	AlMn1Mg1	X		
3005	AlMn1Mg0,5	X		
3103	AlMn1	X		
5005/5005A	AlMg1(B)/(C)	X		
5049	AlMg2Mn0,8	X		
5052	AlMg2,5	X		
5083	AlMg4,5Mn0,7	X	X	X
5454	AlMg3Mn	X	X	
5754	AlMg3	X	X	X
6060	AlMgSi		X	
6061	AlMg1SiCu	X	X	
6063	AlMg0,7Si		X	
6005A	AlSiMg(A)		X	
6082	AlSi1MgMn	X	X	X
6106	AlMgSiMn		X	
7020	AlZn4,5Mg1	X	X	
8011A	AlFeSi	X		

Table 3a: Wrought alloys listed in EN 1999-1-1 and the form of standardised semi products (tables 3.2a-c)

EN AW-	EN AW_
3003	AlMn1Cu
3004 *	AlMn1Mg1
3005 *	AlMn1Mg0,5
3103 *	AlMn1
3105	AlMn0,5Mg0,5
5005 *	AlMg1(B)
5052 *	AlMg2,5
5251	AlMg2

Table 3.b Wrought aluminium alloys listed in EN 1999-1-4, (table 3.1
(* : alloy also listed in EN 1999-1-1)

EN AC-	EN AC-
42100	AlSi7Mg0,3
42200	AlSi7Mg0,6
43000	AlSi10Mg(a)
43300	AlSi9Mg
44200	AlSi12(a)
51300	AlMg5

Table 3c: Casting aluminium alloys listed in EN 1999-1-1, (table 3.3)

This is the reason why the European Aluminium Standards still use two principles for aluminium alloy designation: numerical and with chemical symbols.

Table 3a shows the alloys which are foreseen for use for structural applications in EN 1999-1-1.

In Table 3b are listed the alloys for structural thin sheeting: EN 1999-1-4, and in **Table 3c** the alloys suitable for structural castings.

The figures in the chemical designation stand for the typical content of the alloying element in the alloy. The correct designation according to the European standards always includes the prefix EN AW-. This prefix is often not used when talking about the alloys but in written texts, e.g. in orders, it may be important, since still other 4 digit designation systems exist in different areas of the world, especially in aluminium companies

4. Tempers and designation of tempers

4.1 General

It is very typical for aluminium and a new experience for the structural engineer who only uses steel that the materials are available with different mechanical properties, that is to say in different tempers. In practice the highest strength level may not be the best for a particular application. If material is required for specific forming applications e.g. folding or for structures which will be subjected to impact loads, lower strength material may often be an advantage.

The designations of tempers for castings are basically the same. Since no work hardening of castings is performed H- and O-temper designations are not used.

The so called temper F is a peculiarity. According to EN 515 it means "*as fabricated, no mechanical property limits specified*" and insofar it is a state of material preferably destined for subsequent processing and not for direct use in structures. For extrusions this state is the state after the first production step and therefore the resulting semi products can also be used in this state (temper). This is a question of economy especially for non-heat-treatable alloys. These cannot be age-hardened anyway and after extruding are in a metallurgical state close to temper O. This material can therefore be used for structures, even if the standardised strength values which are provided are only for information. For sheet in temper F this conclusion is not allowed. According to the definition, temper F can be a very hard material in this case and therefore not generally suitable for use.

With respect to castings, we have another situation. Temper "F" means only "*as cast*" i.e. a state/temper with no subsequent thermal treatment. In spite of this EN 1706 defines binding technological values for such a material (heat-treatable or non-heat-treatable).

4.2 Tempers of non-heat-treatable alloys

For many years and in many countries, the system used to characterise the condition, i.e. temper, with which non-heat-treatable materials were characterised, used terms such as: soft, 1/4 hard, 1/2 hard. These designations were very easy to understand and to remember. But this "system" has been abandoned. Looking at **Fig. 2** the system now in use can be explained. With increasing degree of cold working, ultimate strength and proof strength also increase. The hardest normally produced state has the designation temper H18 and the former condition ½ hard the designation temper H14. Temper H16 and H12 lie on either side of the H14 temper. Speaking of non-heat-treatable alloys this is not completely accurate[*)] since a controlled thermal treatment gives advantages both technically and economically by annealing the material from the cold rolled temper H18 into a softer state. This is daily practice in rolling mills. Thus, material in a hard rolled temper that is not the hardest temper possible (i.e. H19=extra hard), is commercially available in two different tempers, H1x and H2x, (e.g. H14 and H24). The two tempers have the same ultimate strength, but H2x material has a slightly lower proof strength but higher elongation. The situation is similar with H3x tempers. These tempers are characterized by a (gradual) work hardening followed by a stabilizing heat treatment. Residual stresses in this material are then less than in H1x tempers. The H4x temper range has been introduced for materials which are work hardened and then subjected to some partial annealing during a subsequent paint baking or lacquering operation. The technological values of the H4x tempers need not be identical with the H2x/H3x tempers. Depending on the alloy variant, slight differences can exist.

Additional digits indicate material properties which are mostly of less interest for the structural engineer. **Table 4** gives examples of the definitions of tempers for non-heat-treatable material.

Symbol	**Description**
O	Annealed (soft)
H 111	Annealed and slightly strain-hardened (less than H11) during subsequent operations such as stretching or levelling
H12	Strain-hardened, 1/4 hard
H22	Strain-hardened and partially annealed, 1/4 hard
H32	Strain-hardened and stabilized, 1/4 hard
H42	Strain-hardened and painted or lacquered -1/4 hard
H 14	Strain-hardened, 1/2 hard
H18	Strain-hardened, 4/4 hard (fully hardened)

Table 4: Tempers in use for structural application of work hardened semi products
(typical examples to explain the system)

4.3 Tempers of heat-treatable alloys

The complete heat-treatment consists of a solution heat-treatment, a quenching process and subsequent ageing, where the actual hardening occurs. It must be said that, unlike steel, aluminium alloys are definitely not hard after quenching.

[*)] This is the reason why the terms age-hardening alloys and non-age-hardening alloys are being used more and more.

To get the highest strength values it is important to keep the material for sufficient time at the correct solution heat temperature and to follow the correct quenching procedure. Depending on the alloy this may be carried out using water or moving air*). Quenching with water produces distortion and residual stresses. Alloys quenchable with air have some technical and economical advantages, but most high strength alloys need to be water quenched. If the solution heat-treatment or the quenching process is not properly executed this will result in lower values with respect to mechanical strength and elongation (ductility).

Heat-treatable alloys are produced in many tempers. For structural engineering only a limited number is important and listed in **Table 5**. The wording "solution heat-treated" in **Table 5** generally includes quenching. The ageing process should become easily understandable in combination with **Fig. 3**, whereby the T5 condition is not shown. T5 is a special temper which does not lie between T4 and T6 as most people would think. It is characterised by the fact that the material is not fully solution heat-treated (e.g. temperature too low) and also that the quenching may not be optimum**). The result is lower strength values than T6 and lower values for elongation (poor formability). T6 characterises an artificially aging up to the maximum strength. For T66 see the remarks in Chapter A.1.3

Symbol	Description
T4	Solution heat-treated and then naturally aged
T5	Cooled from an elevated temperature shaping process and then artificially aged
T6	Solution heat-treated and then artificially aged
T61 T64	Solution heat-treated and then artificially aged in underageing conditions in order to improve formability (T64 between T61 and T6)
T66	Solution heat-treated and then artificially aged – mechanical property level higher than T6 achieved through special control of the process 6000 series alloys
T7	Solution heat-treated and artificially over-aged
Tx51 Tx510 Tx511	These suffixes stand for a controlled stretching to relieve internal stresses coming from manufacturing (the fourth digit characterises only variants – no influence on characteristic values!)

Table 5: The main tempers in use for structural application of precipitation hardened semi products (T7 only listed to explain the system)

5. Alloys and tempers of alloys listed in EC 9

5.1 General

In EN 755-2 (extrusions), EN 485-2 (sheet), EN 586-2 (forgings) and EN 1706 (castings) a great number of alloys are listed. Many of them are only used for very special applications. A reason for the great number of alloys is that "Inventing" a so called "new aluminium alloy" is not difficult and frequently only involves adjustment of accompanying elements of an existing composition. The advantages often gained are the perfect adaptation of an alloy for a special use by optimisation, for example of mechanical properties, hardening behaviour, ductility, surface etc. Since the quantity to be cast as pre-material for the working process is also relatively limited, it is not surprising that so many alloys exist. In EN 755-2 (issued in 2008) 57 alloys are listed, in EN 485-2 (issued in 2007) 47, in EN 586-2 (issued in 1997) 6 and in EN 1706 (issued in 1998) 37 alloys are listed.

In addition to the common extruded products in Table 3.2b of EN 1999-1-1, drawn tubes are also listed, for which in some cases different technological values may be valid and for which a separate standard exists, EN 754 (cold drawn rod/bar and tube). The number of alloys listed in this standard is 32 and significantly smaller than the number of alloys in EN 755. But for technological reasons, all these alloys also have to be listed in EN 755.

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*) EN AW 7020: quenching with water not allowed, exception large wall thicknesses
**) Note the difference between "solution heat-treated" and "cooled from elevated temperature".

It makes no sense to offer so many possibilities for structural applications. The design engineer will not be able to readily select the best alloy from a technical standpoint. The second important question concerning economic availability in the marketplace is also difficult for him to answer. There are also a range of technical aspects which pose problems e.g. weldability, the effective strength values of the HAZ to be assumed for the design, corrosion behaviour in practice, etc. Therefore it was clear that only a limited number of alloys and tempers proven over the years in practice should be listed in EC 9. It was also clear that the number would be greater than the list of alloys available in an individual country, since to a certain degree in different lands different alloys and tempers have been historically preferred and are in use. Some alloys however are in general use in most of the countries. This fact has facilitated the task of selection which alloys and tempers should be listed in EC 9. Generally alloys with poor corrosion behaviour e.g. with high copper content were not regarded as applicable for structural works.

The situation with casting alloys was easier, since hitherto the most structural standards of European countries had no design rules for castings.

To discuss the properties of the listed materials and the provisions with background information it seemed better to concentrate this in an annex. So the main part of this paper deals with more generally interesting questions with respect to the selection of alloys.

5.2 Wrought alloys

In the ENV[*)] 1999-1-1, issued in 1998, 11 alloys were listed and apparently this has been well accepted. There were only few comments referring to this topic and only three "structural" alloys have been added: EN AW-5049 (AlMg2Mn0,8), EN AW-6106 (AlMgSiMn) and EN AW-8011A (AlFeSi(A)). The number has increased in spite of this to 17 in total, the reason being the new part of EUROCODE 9, the EN 1999-1-4, dealing with thin walled sheeting, which required for its special purpose a series of suitable alloys to be listed. Three of them have been adopted in EN 1999-1-1, since they can also be used for other applications. Three others have stayed listed only in Part 4 and there was no need to transfer them to Part 1 for general application. These are: EN AW-3003 (AlMn1Cu), -3105 (AlMn0,5Mg0,5), -5251 (AlMg2). There may be doubts whether there is a need for so many alloys from a technical standpoint. The explanation is that there are many long established products in the marketplace which have approvals by a range of authorities. Changing these alloys would involve much effort and cause many problems.

A similar situation to that covered in the previous paragraph concerning the listing of alloys applies to the tempers of the alloys. Allowing all possible tempers would bring the designer in a similar situation as allowing too many alloys. Therefore only the tempers which were most frequently used in the past are listed. In addition to the O/H111 temper these are the tempers H12, H14 and their corresponding partially annealed tempers for work hardened materials. Higher strength tempers such as H16 and H18 were avoided, since good forming behaviour is often desired. Temper H16/H26/H36 is only found with alloys preferably destined for thin walled sheeting.

The design rules for thin walled sheeting require basically that sheet material with a proof strength >165 N/mm² is needed. This means for many alloys listed in EN 1999-1-4 that a temper H18 or a corresponding H28/H38/H48 is required. Since such a hard material cannot be generally recommended, these tempers are not listed in EN 1999-1-1. (There are no problems to list such hard material in EN 1999-1-4, since the machines capable of producing such shapes, e.g. trapezoidal sheeting, are working without damaging the material.)

In this context it has to be mentioned that alloys exist for which the technological values are standardized only for sheet and plate or for extruded products respectively. Therefore in EC 9 there are only a limited number of alloys which are standardised for both sheet and extrusions and which also have been regarded as useful for structural application in both forms. These alloys are EN AW-5454, EN AW-5754, EN AW-5083, EN AW-6061, EN AW-6082 and EN AW-

[*)] ENV = European prestandard for subsequent conversion into EN

7020 (6 of 17 alloys in total). Since the formability during the extrusion process of EN AW-5083, -5454 and -5754 is very limited and allows only basic solid and no multi-hollow sections, the number of "universal" alloys drops to three. Anyway in the most cases it is not necessary to use only one alloy for a structure. Aluminium multi-alloy structures are normal in practice.

After all EN 1999-1-1 now offers a wide pallet of alloys and tempers to be used for structural applications. The range of strength in the sense of proof strength $R_{p0,2}$ (f_o) runs from EN AW-5005 O with 35 N/mm² up to EN AW-7020 T6 with 290 N/mm². The low strength qualities are normally not important for structural engineering applications but could be used when specially formed structural elements are required. With mechanical strength values of 290 N/mm² for EN AW-7020, 260 N/mm² for EN AW-6082 and 280 N/mm² for EN AW-5083, some structural aluminium alloys lie over the proof strength of mild steel S235. Important for designers are the values for EN AW-6060/6063. These are the most common extrusion alloys because they are very cost effective. The characteristic values of the proof strength i.e.140 - 160 N/mm² seem to be low, but under most design conditions they are sufficient for structures.

The question why EN 1999-1-1 does not list well known high strength alloys such as EN AW-7075 (AlZn5,5MgCu) or EN AW-2024 (AlCu4Mg1) with 560 N/mm² and 450 N/mm² for $R_{p0,2}$ as used for aircraft can be answered very simply: EN 1999 is principally a design code for buildings even if this standard can also be used for many other applications. In many countries it will become part of legal regulations and therefore other aspects have had to be taken into consideration e.g. the durability and the fact that not all buildings and structures are regularly inspected and maintained. The corrosion susceptibility of the high strength alloys, specifically those containing copper as an alloying element, means that they cannot be allowed for general use.

A look at table 3.1a in EN 1999-1-1 shows that, with one exception with respect to the durability rating, all alloys belong to class A and B. The exception is EN AW-7020 and here it is necessary to comment on corrosion resistance. Long time corrosion tests (Heligoland) and also experience have shown that EN AW-7020 and similar alloys have a corrosion behaviour which, with respect to the appearance of the surface, is at least as good as that of AlMgSi-alloys. If in this table EN AW-7020 is downgraded, the reason is that as a result of welding exfoliation corrosion could be provoked, depending on the environmental conditions and the design of structural details (absence of water pockets etc.). This good surface behaviour is not shown by other 7xxx-alloys and also is not present in the 2xxx- alloys due to their high copper content.

.A similar situation as for EN AW-7020 is given in practice also for EN AW-5083, which may have in some tempers or gets under unfavourable thermal conditions a certain susceptibility to intergranular corrosion. Therefore we find in table 3.1a of EN 1999-1-1 a footnote referring to clause C.2.2.2(2) in Annex C of the Code, where further information is given. But in the case of EN AW-5083 the durability rating was not downgraded to B or C as in the case of EN AW-7020.

For structural engineering the most commonly used alloys are:

EN AW-6082, EN AW-6061 and EN AW-7020 (less frequently)
for structures and components from sheet and extrusions of the same alloy

EN AW-5083 and EN AW-5754
for structures and components from sheet
(also in structures mixed with sections of other alloys)

EN AW-6060 and EN AW-6063
for structures and components from extrusions
(also in structures mixed with sheet of other alloys)

Now in detail:

EN AW-6082 and -6061 are the classic alloys corresponding in their proof stress to normal mild steel and therefore preferred by engineers for structures resembling conventional steel work. Semi products are standardised both for sheet and extrusions. EN AW-6082 is the European variant, EN AW-6061 is preferred in America and its sphere of influence. EN AW-6061 contains more copper; this may influence the appearance and the weldability, depending on the actual copper content of a batch.

EN AW-7020 is also standardised for sheet and extrusions. It has the highest strength values of the alloys listed in EN 1999-1-1. Since the necessary quenching rate is low, the alloy shows better strength after welding by natural hardening. Semi products from this alloy are relatively higher priced. The alloy is often used for military bridges and also for cranes and cherry pickers. Depending on the application a second artificial hardening process is recommended after welding.

EN AW-6060 and the similar EN AW-6063 are the typical alloys for extrusion. Sheet in these alloys are not standardised and are also not produced. They show medium strength values and are anodisable for decorative applications. They allow the production of filigree and very complex extruded sections at moderate cost, since high extrusion speeds and air quenching are typical in production. EN AW-6060 is practically unknown in America and it's sphere of influence. In Europe both alloys are available. EN AW-6106 also belongs to this type of alloy but has better welding strength. With this alloy, decorative aspect concerning anodising cannot be guaranteed.

EN AW-5083 and EN AW-5754 are the common alloys for the design of conventional structures from sheet. Extrusions in these alloys are standardised but scarcely on the market. The high hot forming resistance of these alloys allows only simple sections with greater wall thicknesses and no hollow sections using port-hole dies. But seamless tubes are possible and available on the market.

EN AW-5049, -5052, -5454 and EN AW-6005A are not very frequently used for structural works. Their use is confined to special applications and products/manufacturers. The three 5xxx- alloys combine strength with good corrosion resistance, EN AW-6005 combines strength with good extrudability and this is the reason why this alloy is in very common use for railway carriages.

The alloys EN AW-3004, -3005, -3103, -5005 and -8011 are typical alloys for structural sheeting. They are used with low thicknesses and as roll formed products used for roofing and cladding. Often alloys of this group are also used for special façades (anodised, organic coatings). If adopted normally greater quantities of material are needed and the decision as to the best and most economic alloy should be made together with the manufacturer.

5.3 Casting alloys

In the ENV-version issued in 1998 only 5 alloys were listed and apparently this was well received. There were some objections against EN AC-43200 due to the relatively high contents of iron with 0,65% and of copper with 0,35% which is allowed. It was replaced in the EN version by EN AC-43300, an alloy with the same alloying elements but a reduced content of these two elements (with higher strength and better ductility/elongation). Also EN AC-44100 was replaced by EN AC-44200 for similar reasons: iron and especially copper content are lower with this alloy. EN AC-43000, a very economical and therefore often used alloy, was additionally listed in temper F.

Only casting methods (sand or permanent mould) in combination with temper were listed which enable the requirement of 2% elongation (measured on the standard A_5 gauge length) to be easily achieved by the cast house.

Concerning the applicability of castings for structural works the prestandard ENV 1999-1-1 had different provisions compared to the revised and now valid EN 1999-1-1. For details see A.2.1.

6. Practical viewpoints for the selection of materials

6.1 Sheet, plate and extrusions

When designing in steel the design engineer does not worry about the availability of the steel semi products he intends to use. He can be sure that as long as he uses normal steels such as S235 or S355, no problems in procurement will exist since most stockists have a wide pallet of sheet and sections according to steel section standards on stock.

With aluminium the situation is really different. Sheet in small and mid sized formats up to 1500x3000 mm is easy to obtain but the availability of more complex alloys and tempers is limited. EN AW-5083, -5754 and -6082 are common. Some stockists specialised as suppliers for shipyards may also have larger dimensions on stock. However most other materials or special formats have to be ordered and therefore will have a delivery time. For the aforementioned common alloys orders of minimum 10 t for one thickness are usually necessary. Sheet of alloys which are not so commonly used need orders with quantities of 30 to 50 tons (question of casting lot).

The situation with sections is different. The reason for this lies in the fact that aluminium sections are extruded and steel sections (mostly) hot rolled. Aluminium sections however are extruded and die costs are modest. Die changing needs only short times and therefore ordered lots may be small, depending on size of the section, between 200 and 3000 kg. This leads to the situation, that most engineers design their own sections optimally adapting them to the special requirements of each application. This brings considerable advantages: cost i.e. weight is reduced, the section is given its optimised form in terms of functionality and often machining costs are also saved.

This individualism due to the special process of extruding has given aluminium tremendous advantages but also a certain disadvantage. The pallet of sections offered by stockists is very limited and reduced to simple and mostly small sections. The alloys offered are usually EN AW-6060 and sometimes -6082. A few stockists also offer larger profiles. With tubes the pallet offered by stockists is much better. Every engineer therefore, beginning his first design in aluminium, is well advised to study which semi products are available from stock. He should especially investigate the possibilities and requirements needed to create and to order his own sections.

For structural engineering it is often very important to know what the geometric limits are for the existing production facilities for the semi-products.

Sheet and plate can be produced with widths of more than 3 m and lengths of up to 22 m. The exact limits may depend on thickness and alloy. For lengths under 10 m and with widths up to approximately 2 m there are more manufacturers. When designing in sheet it is also important to know that folding presses with working widths up to 16 m are not so common but facilities with more than 20 m do also exist.

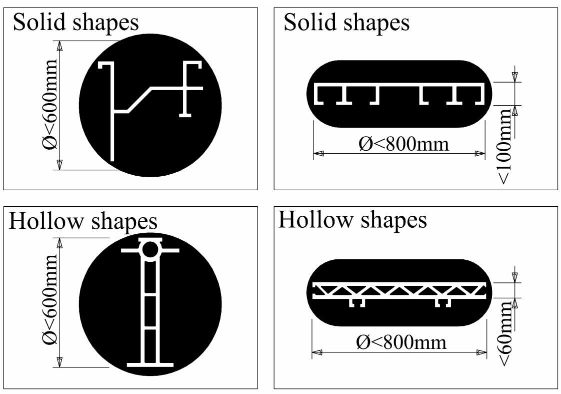

Figure 4: Limits for the design of large extrusions (Europe)

The limits for the length of extrusions are 30 m, if they have the necessary stiffness of the section to allow proper transportation. Normal lengths lie between 6 and 10 m. Normal stock length is 6 m. The limits for the cross sections are shown in **Fig. 4**. These are the geometric limits of the largest European extrusion press.

As already mentioned it is very common that the design engineer creates his own individual profiles. Therefore it is important that he knows some rules about this and also which alloys are recommended with respect to costs and feasibility. Since the main part of this paper deals with questions of more general interest with respect to the selection of alloys, more detailed information is given in Annex B. In this context the cross sectional tolerances play an important role. Since with extrusions they are much smaller than with rolled profiles, the engineer often designs individually drafted sections not only with respect to bearing capacity but also with respect to additional functionality of the section. Then tight tolerances are often needed and for such requirements a special standard exists: EN 12020 which deals with tighter tolerances for sections in EN AW-6060 and -6063 compared to EN 755-9 for sections in the other alloys. But often also special tolerances are agreed between design engineer and semis manufacturer.

6.2 Cast and drop forged parts

Cast and forged parts are always individually designed parts and ordered directly from the manufacturer (if they are not part of a system distributed via stockists). If no special experience exists, it is recommended that the engineer contacts and collaborates closely with the manufacturer to determine the best design in combination with the alloy.

To give an idea of the number of pieces which are needed for economic manufacture by forging shops, the number 1000 may be quoted as the minimum size of a production lot. If the often high die costs are accepted some manufacturers may produce lots with a lower number of pieces, but it may be a problem for the forging shop to get the pre-material from the semi product manufacturer in the form or quantity needed. The alloys themselves listed in EN 1999-1-1 are all common.

A similar situation applies to cast parts. Depending upon alloy, foundry and size of the casting the usual minimum quantity is 500-1000 but in special circumstances it may possible to obtain somewhat smaller amounts. Sand cast parts are possible in much lower quantities, depending on size and alloy. Production lots of 10 or 50 are not unusual. The procurement of the casting alloys listed in EN 1999-1-1 is no problem for the foundry, and small quantities can be supplied. The most frequently used alloys are EN AC-42100, -43000 and -44200. The alloys preferred by the foundries due to their good castability are EN AC-43000, -43300 and -44200. The alloy EN AC-51000 (AlMg5) is difficult to cast and therefore not popular with foundries and is therefore used relatively seldom despite the fact that engineers like to make use of it due to its bright surface and anodisability (other alloys are more or less greyish, especially when anodised).

7. Physical properties essential for design

7.1 General physical properties

The most important property of aluminium is its density, which is with 2,7 g/cm³ and thus only about a third of the density of steel.

The second most important property is the good corrosion resistance of aluminium, though aluminium as such is not a very noble metal. This is due the fact that aluminium and aluminium alloys react with oxygen and water vapour in the air to produce a thin, compact oxide film which protects the underlying metal from further attack. So aluminium and most of the copper free alloys prove to be very corrosion resistant if the pH-value of any contact liquid lies between 5 and 8; with this range the most existing atmospheric/environmental conditions are covered.

The linear thermal expansion is $24 \times 10^{-6}/°C$ and thus twice as large as that of steel. This has to be taken into account for many structures, where free thermal expansion is necessary. Where expansion is restricted the resulting stresses are due to the smaller E-modulus only 2/3 compared to steel.

The elastic modulus of aluminium is 70 000 N/mm² and thus only a third of the modulus of steel. This has essential consequences for the geometry of the design, since deflections of beams, bearing capacity of columns, i.e. lateral buckling and local buckling directly depend on the elastic modulus. In many cases of structural design the stiffness of a section is the crucial criterion. If a steel section is to be replaced by aluminium and the stiffness is to be kept at the same level, a thickening of all parts by the factor 3 is not very efficient, since the relation of the specific weight of the two materials is also approximately 3 to 1. But saving weight by using aluminium is the normal intention, for physical and also for economical reasons. For the design of beams a practical and proved rule says: increase all dimensions with exception of width by the factor 1,4 and you will arrive at a cross section with a moment of inertia about three times as large and hence a section of the same stiffness (E × I) and you will save about 50% in weight.

With this rule you have also compensated to a certain degree for a loss of stiffness with respect to local buckling. Experience also says that following such a rule leads to very useful cross sections. Often steel sections are not optimal, since standardized sections have to be used. With an individual design in aluminium often we save more than 50%. This is also shown in **Fig. 5**. If we have no restrictions in height and local buckling is not the design criterion we can also save up to 60%. If stiffness of a component is not the criterion and the strength of steel lies within given values of aluminium then a saving of 70% may be possible. However this is seldom the case and is the top limit.

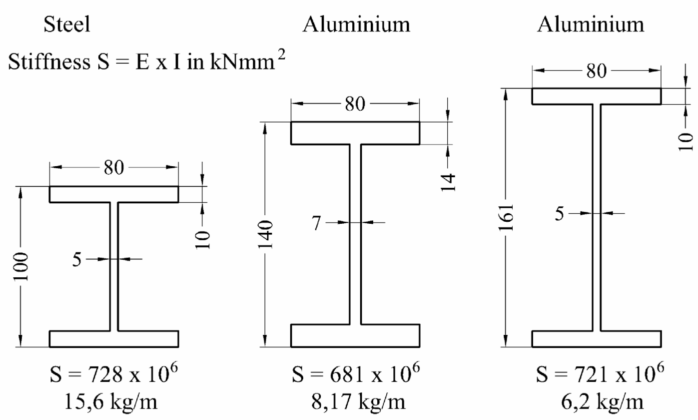

Figure 5: Comparison of stiffness and weight per m of steel and aluminium section

These considerations lead us to a second important fact. If we increase the moment of inertia by a factor of three and increase the height only by the factor 1,4 then the section modulus (moment of resistance) increases by 2,14, i.e. the stresses in the substitute aluminium section are as a result less than half the steel stresses. Now we understand why the structural engineer should not look in the first instance for alloys with the highest strength and this explains why the lesser alloyed AlMgSi types EN AW-6060, -6063 are so successful.

7.2 Influence of heat

As with other materials the strength of aluminium decreases with increasing temperature. Up to certain temperatures this phenomenon is reversible, i.e. after cooling down the material has the same properties as before. With temperatures up to 80 ℃ the drop in strength is negligible for all alloys and tempers. Over 80 ℃ some design situ ations could require creep effects to be considered. Heat-treatable alloys begin to loose strength at temperatures over 110 ℃ depending on time. Non-heat-treatable alloys in work hardened tempers begin to loose strength at temperatures over 150 ℃ – whereby the loss of strengt h also depends on time. In 'O temper' non-heat-treatable alloys no permanent loss in strength occurs.

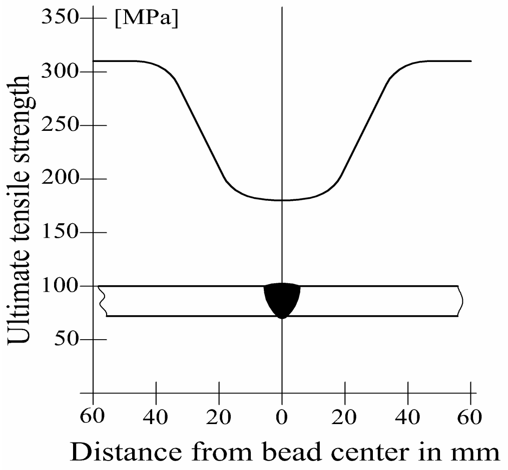

Figure 6: Reduction of strength in the heat affected zone (HAZ) (typical for EN AW-6082)

A short heating as used for baking of paints is possible without severe change in properties. For exact thermal conditions ask the semis manufacturer, since certain alloys may be somewhat more susceptible (e.g. EN AW-7020).

Much more severe is the loss of strength on welding. Here the temperatures are so high because of local melting that a fall in the strength in the vicinity of the weld must be taken in account and often forms an important aspect of the verification of the design of a structure, see Fig. 6. The non-heat-treatable alloys loose all strength gained by work hardening and return to the 'O temper'.

The heat-treatable alloys in temper T6 have a loss of approximately 40% of their strength with the single exception of the alloy EN AW-7020, which looses only 20%. All these alloys do not go to a fully annealed temper since a certain quenching effect is unavoidable. Therefore standardised strength values for the heat affected zone are based on tests.

8. Application of aluminium in the future

With a proportion of 8% aluminium is, after oxygen and silicon, the third most abundant element in the earth's crust. Today aluminium is exclusively extracted from bauxite but it exists in many other minerals. However today's known reserves of bauxite are sufficient for more than 1000 years at the present exploitation rate. Aluminium is a material of excellent recyclability. The weight losses when remelted and also the degrading of quality in the recycling process are very low. Aluminium has also a high recycling rate. All this will lead one day to a reduction of the exploitation of bauxite, though the quantity of aluminium in use will increase. There are practically no limitations to the availability of aluminium.

Many people complain about the high consumption of energy needed to produce a kg of aluminium. This is true but only one side of the coin. Quite apart from the fact that the energy to produce one kg aluminium has been halved in the last 50 years, aluminium saves energy in our modern technology dominated world. The lowering of weight of modern railway coaches, cars and other transport systems by using aluminium reduces their fuel consumption so that not only the (sometimes higher) purchasing costs but also the relatively high consumption of energy needed to first produce the aluminium are compensated. Taking into account the very small quantity of energy needed for remelting aluminium, its often cited disadvantages do not exist.

In structural engineering the light weight is not the main reason for the use the aluminium, even if there are many examples where the light weight is advantageous:

- Cranes, where energy may be saved or a cheaper substructure is possible or when a crane with higher capacity needs to be installed;

- Marquees, where the light weight facilitates the erecting process and helps to reduce the danger of accidents;
- Structures to be erected in remote areas, where only air transport is possible;
- Structures such as scaffolding, where the low weight allows loading more material on one vehicle or where installation is quicker.

The main reason for the use of aluminium for buildings and in structural engineering is still its good corrosion behaviour. No coating is necessary under most atmospheric conditions. And the costs and environmental problems which exist when renewing organic coatings are still underestimated. This is being recognised more and more by municipalities and explains the great number of pedestrian bridges installed in the recent years in Germany – with an increasing tendency.

Besides the above we also have many structural applications, where, due to the functionality given by the use of extruded sections, the structure is economically competitive.

Annex A

Comments and explanations to material properties and material provisions given in EC 9 *)

A.1 Wrought alloys

A1.1 General

The most material properties given in table 3.2a, 3.2b and 3.2c of EN 1999-1-1 are characteristic values and therefore the basis for the design of an aluminium structure.

A.1.2 Tabled values for sheet materials, table 3.2.a of EC 9

f_u and f_o are values taken directly from EN 485-2 , where as R_m and $R_{p0,2}$ they are defined as the lower limit of ultimate strength and 0,2% proof strength to be achieved and confirmed by the manufacturer of sheet and plate. They are often only valid up to a certain thickness or for a certain thickness range, which may be different for different tempers of a material. The reason for this lies in the production conditions. The general question is what can be done if thicker material is needed, but technological values are not specified. This can be answered as follows: materials with low thickness limits are typically used and developed for thin-walled sheeting and usually there is no need for thicker material. Materials which are used for heavier structures usually have standardised thickness range limits, which are sufficient for most applications. If a manufacturer has to produce thicker material there should be no problem for use in accordance with EN 1090-3 if the manufacturer confirms the technological values of the adjacent standardized thickness range. If this is not possible, it will be a question of the legal situation existing locally, e.g. if building authorities have to give their approval.

Here in table 3.2.a of EC9 the value for A (= minimum elongation of the tensile specimen) is mostly given as the A_{50} value. This means that the gauge length is constant and independent of the cross section area of the tensile test specimen. The measuring of the fracture elongation with constant gauge length results in the fact that, depending on the thickness relations, the fracture elongation of thin material may be much lower than that of thicker material. This is due to the definition. Therefore EN 485 defines, for different material thicknesses, different elongation values. EN has taken over the lowest, for not overloading the tables. The resulting figures may cause some irritation for the design engineer, even if A is not a binding characteristic value for the design. But sometimes the engineer is looking for a ductile material. If the engineer is interested in knowing the real plastic behaviour he should examine the original EN 485-2 and take the A value, i.e. the value for a measurement with proportional gauge length. With this value he can make a comparison with other materials and tempers.

With **Table A.1** and **Table A.2** the situation may be explained using EN AW-5454 (AlMg3Mn) as an example. Up to a thickness value of 12,5 mm the A_{50} value is given and increases with increasing thickness. For thicknesses greater than 12,5 mm the test is executed with round test specimens with proportional gauge length for which the A value is valid, which is for the most alloys/tempers equal or slightly smaller than the defined A_{50} value for the thickness range up to 12,5 m. The A value is the value for the elongation measured with proportional gauge length i.e. A= $A_{5,65\sqrt{A0}}$ = A_5 value. The width of the 50 mm gauge specimens is always 12,5 mm (independent of the thickness). With a wall thickness of 6,28 mm*) according to the definition the length of 50 mm is identical with the proportional gauge length, this means that with a thickness of 6,28 mm (i.e. practically 6 mm) we can expect that A_{50} should be (theoretically) identical with A_5. With increasing thicknesses above this value the A_{50} values become increasingly greater than the

*) The provisions concerning material in EN 1999-1-4 are much less comprehensive compared to those of the main part of EC9, EN 1999-1-1. In EN 1999-1-4, table 3 gives only mechanical values for the parent material, since for the applications of structural sheeting welding is not foreseen. Furthermore the column for BC does not exist. The explanations given in the clause A.1.2 apply correspondingly also for the materials listed in EN 1999-1-4.

*) $=(50/5,65)^2/12,5$

A5-values. Since in EN 485-2 the elongation values are defined for defined thickness ranges, for the range from 6 mm to 12,5 mm the (fictive minimum) A_{50} value for a thickness of 6 mm is consequently valid for the whole range and should be identical with the generally valid A_5 value. But since the relations between round and rectangular cross sections for the test specimens concerning elongation are in reality not so easy as formulated by the definition, the A_5 values for the most alloys/tempers are fixed slightly under the A_{50} value for 6 mm thickness.

In case of weldments the values for $f_{o,haz}$ and $f_{u,haz}$ are characteristic values for the resistance of the heat affected zone (HAZ). For precipitation hardening alloys the values are based on measurements, where a gauge length of 100 mm was used. For work hardening alloys the ultimate strength values correspond with the value of the temper O (fully annealed). For the work hardened and the partially annealed tempers the yield strength $f_{o,haz}$ is based on a convention. It is 1,25-times the value of temper O. Due to the fact that the yield strength of partially hardened material is always considerably higher than the yield strength of (fully) annealed material, only the limited material in the heat affected zone deforms, the rest of the material remains unaffected. Therefore this yield strength value becomes independent of the temper of the partially work hardened or partially annealed material. For strain hardening material in Temper O no HAZ can exist and the HAZ-values are identical with those of Temper O.

The column for the HAZ factor is only a help for the designer, since the values are directly calculated from the values in the columns on the left of the table by dividing $f_{u,haz}$ by f_u etc.. If the thickness of welded materials exceeds the limits defined in the footnote 2) the reduction values $\rho_{o,haz}$ and $\rho_{u,haz}$ have to be calculated for each individual case.

The buckling class characterizes "B" materials/tempers with a low proportional strength limit and "A" materials with a high proportional strength limit. The distinction has to be made for lateral flexural buckling, for the calculation of the effective thickness (width) for Class 4 parts according to clause 6.1.5 of EN 1999-1-1. All materials with a standardised f_o-value of 230 N/mm² and less were classified as "B", with exception of precipitation hardening materials in tempers T6x. These were classified as A materials such as the other materials with f_o >230 N/mm².

n_p is a value needed for calculations in the plastic range of the material taking into account a certain strain hardening due to plastic deformation. The values are (as is required in design standards) conservative but due to the great scatter they cannot regarded as typical values, especially not for calculations of hardening for other purposes. This explains also the text of the footnote 5), that n_p may only be used with the given values of the yield strength.

Concerning footnote 2 of Table A.1, i.e. Table 3.2.a of EN 1999-1-1 a special remark is necessary. The text says that for greater wall thicknesses the ultimate strength value for the HAZ has to be factored down by 0,9 also for the work hardened alloys. Seen from a metallurgical standpoint this does not seem reasonable, since for all work hardened or partially annealed tempers the ultimate strength value is identical with the value of temper O. This provision is thus in conflict with the last sentence of the footnote too. The same also applies to the identical footnote 4) of Table 3.2.b of EN 1999-1-1.

Alloy EN-AW	Temper 1)	Thick-ness mm 1)	f_o 1)	f_u	A_{50} 1) 6)	$f_{o,haz}$ 2)	$f_{u,haz}$ 2)	HAZ-factor 2)		BC 4)	n_p 1), 5)
			N/mm²		%	N/mm²		$\rho_{o,haz}$ 1)	$\rho_{u,haz}$		
3004	H14 | 24/H34	≤ 6 | 3	180 | 170	220	1 | 3	75	155	0,42 | 0,44	0,70	B	23 | 18
	H16 | 26/H36	≤ 4 | 3	200 | 190	240	1 | 3			0,38 | 0,39	0,65	B	25 | 20
5005/ 5005A	O/H111	≤ 50	35	100	15	35	100	1	1	B	5
	H12 | 22/H32	≤ 12,5	95 | 80	125	2 | 4	44	100	0,46 | 0,55	0,80	B	18 | 11
	H14 | 24/H34	≤ 12,5	120 | 110	145	2 | 3			0,37 | 0,40	0,69	B	25 | 17
5454	O/H111	≤ 80	85	215	12	85	215	1	1	B	5
	H14|H24/H34	≤ 25	220 | 200	270	2 | 4	105	215	0,48 | 0,53	0,80	B	22 | 15
6082	T4 / T451	≤ 12,5	110	205	12	100	160	0,91	0,78	B	8
	T61/T6151	≤12,5	205	280	10	125	185	0,61	0,66	A	15
	T6151	12,5<t≤100	200	275	12 3)			0,63	0,67	A	14
	T6/T651	≤ 6	260	310	6			0,48	0,60	A	25
		6<t≤12,5	255	300	9			0,49	0,62	A	27
	T651	12,5<t≤100	240	295	7 3)			0,52	0,63	A	21

1) If two (three) tempers are specified in one line, tempers separated by "|" have different technological values but separated by "/" have same values. (The tempers show differences for f_o , A and n_p.).

2) The HAZ-values are valid for MIG welding and thickness up to 15mm. For TIG welding strain hardening alloys (3xxx, 5xxx and 8011A) up to 6 mm the same values apply, but for TIG welding precipitation hardening alloys (6xxx and 7xxx) and thickness up to 6 mm the HAZ values have to be multiplied by a factor 0,8 and so the ρ-factors. For higher thickness – unless other data are available – the HAZ values and ρ-factors have to be further reduced by a factor 0,8 for the precipitation hardening alloys (6xxx and 7xxx) and by a factor 0,9 for the strain hardening alloys (3xxx, 5xxx and 8011A). These reductions do not apply in temper O.

3) Based on A $\left(= A_{5,65\sqrt{A_o}}\right)$, not A_{50}.

4) BC = buckling class, see 6.1.4.4, 6.1.5 and 6.3.1.

5) n-value in Ramberg-Osgood expression for plastic analysis. It applies only in connection with the listed f_o-value.

6) The minimum elongation values indicated do not apply across the whole range of thickness given, but mostly to the thinner materials. In detail see EN 485-2.

Table A.1: Excerpt from table 3.2a of EN 1999-1-1:*Characteristic values of 0,2% proof strength f_o, ultimate tensile strength f_u (unwelded and for HAZ), min elongation A, reduction factors $\rho_{o,haz}$ and $\rho_{u,haz}$ in HAZ, buckling class and exponent n_p for wrought aluminium alloys – sheet,. strip and plate*

Temper	**Specified thickness**		**R_m**	**$R_{p0,2}$**	**Elongation min**	
	over	**up to**	**min**	**min**	**A_{50}**	**A**
O/H111	0,2	0,5	215	85	12	--
	0,5	1,5	215	85	13	--
	1,5	3,0	215	85	15	--
	3,0	6,0	215	85	17	--
	6,0	12,5	215	85	18	--
	12,5	80,0	215	85	--	16
H14	0,2	0,5	270	220	2	
	0,5	1,5	270	220	3	
	1,5	3,0	270	220	3	
	3,0	6,0	270	220	4	
	6,0	12,5	270	220	5	
	12,5	25	270	220	--	4
H24/H34	0,2	0,5	270	200	4	
	0,5	1,5	270	200	5	
	1,5	3,0	270	200	6	
	3,0	6,0	270	200	7	
	6,0	12,5	270	200	8	
	12,5	25,0	270	200	--	7

Table A.2 : Excerpt from table 35 EN 485-2: EN AW-5454 [AlMg3Mn] (the columns for bending radii, hardness HBW and max values for R_m and $R_{p0,2}$ are not shown).

A1.3 Tabled values for extrusion materials: table 3.2.b of EC 9

Most of the annotations to table 3.2a of EC9 are also valid, but some differences exist between the two tables, i.e. the two kinds of semi products (profiles and sheet, two different committees!).

f_u and f_o the values are taken directly from EN 755-2 or EN 754-2 for drawn tube , where they are defined as R_m and $R_{p0,2}$, the lower limit of ultimate strength and 0,2% yield strength, to be kept and confirmed by the manufacturer of the extrusions. The differentiation of the values with respect to thickness, product form (round and rectangular tube, bar, open or hollow section) is much more characteristic for extrusions than for sheet and plate. To copy directly all the figures of EN 755-2 would have resulted in tables being unreadable. The solution was to insert bold figures. A bold figure as a thickness limit means that this range is the smallest range that is valid for all forms of extrusions (bar, tube, open or hollow sections) but there may be special extrusion forms for which the defined technological properties are valid for greater thicknesses. A bold figure for a strength value means, that there may be other forms of extrusions for which higher strength values are valid for the same or greater thickness ranges. If the design engineer wants to use the whole field he will find the actual limits in EN 755-2 or EN 754-2 resp.[*)]. These facts can be studied for example for EN AW-6060 by comparing the figures in **Table A.3** with those of **Table A.4.**

In this connection it is important to know that the term "tube" does not only refer to round tubes. Therefore the definition for the term "tube" according to EN 755-1 referring to EN 12258-1 may be repeated: "*Hollow wrought product of uniform cross section with only one enclosed void along its whole length, and with a uniform wall thickness…… Cross sections are in the shape of circles, ovals, squares, rectangles, equilateral triangles or regular polygons and can have corners rounded* ….".

EN 755-2 has a further provision, which may be a trap for the design engineer: For the alloys listed in EC 9 EN AW-6005A, -6060, -6061, -6063 and -6082 the following applies (footnote 3): *"If a profile cross section is comprised of different thicknesses which fall in more than one set of specified mechanical property values, the lowest specified value shall be considered as valid for the whole profile cross section.*"

The problem is now that the engineer in the drafting stage is unsure about the strength value he should assume for the design, since at this stage he does not know which shape (i.e. thickness of a detail) the section will ultimately have. If the draft is practically complete and he adds a tiny element for his individually drafted section, then this could also change the technological values to be confirmed by the manufacturer and have an influence on his static calculations. To avoid these problems the footnote has been completed with the following text: "*Exception is possible and the highest value given may be used, provided the manufacturer can support the value by an appropriate quality assurance certificate."* In practice to confirm such a statement is no problem for most manufacturers.

As can be seen, for sheet and extrusions, strength values normally drop with increasing thickness. This is related to the quality of quenching and/or the degree of working. For EN AW- 6082 we see the opposite. This is not a printing error. It has to do with an extrusion effect that thinner parts of an extrusion may easily develop a coarser grain structure and this may be combined with slightly lower strength and elongation values.

[*)] In this case the ρ-values have to be individually calculated, see footnote 1).

Alloy EN-AW	Product form	Temper	Thick-ness t mm 1) 3)	f_o 1)	f_u 1)	A 5) 2)	$f_{o,haz}$ 4)	$f_{u,haz}$ 4)	HAZ-factor 4)		BC 6)	n_p 7)
				N/mm²		%	N/mm²		$\rho_{o,haz}$	$\rho_{u,haz}$		
5083	ET, EP,ER/B	O / H111, F, H112	$t \leq 200$	**110**	**270**	12	110	270	1	1	B	5
	DT	H12/22/32	$t \leq 10$	200	280	6	135	270	0,68	0,96	B	14
		H14/24/34	$t \leq 5$	235	300	4			0,57	0,90	A	18
6060	EP,ET,ER/B	T5	$t \leq$ **5**	120	160	8	50	80	0,42	0,50	B	17
	EP		$5 < t \leq 25$	100	140	8			0,50	0,57	B	14
	ET,EP,ER/B	T6	$t \leq$ **15**	**140**	**170**	8	60	100	0,43	0,59	A	24
	DT		$t \leq 20$	160	215	12			0,38	0,47	A	16
	EP,ET,ER/B	T64	$t \leq$ **15**	120	180	12	60	100	0,50	0,56	A	12
	EP,ET,ER/B	T66	$t \leq$ **3**	160	215	8	65	110	0,41	0,51	A	16
	EP		$3 < t \leq 25$	150	195	8			0,43	0,56	A	18
6082	EP,ET,ER/B	T4	$t \leq$ **25**	110	205	14	100	160	0,91	0,78	B	8
	EP/O, EP/H	T5	$t \leq 5$	230	270	8	125	185	0,54	0,69	B	28
	EP/O,EP/H ET	T6	$t \leq 5$	250	290	8	125	185	0,50	0,64	A	32
			$5 < t \leq$ **15**	260	310	10			0,48	0,60	A	25
	ER/B	T6	$t \leq 20$	250	295	8			0,50	0,63	A	27
			$20 < t \leq 150$	260	310	8			0,48	0,60	A	25
	DT	T6	$t \leq 5$	255	310	8			0,49	0,60	A	22
			$5 < t \leq 20$	240	310	10			0,52	0,60	A	17

Key: EP - Extruded profiles; EP/O - Extruded open profiles; EP/H - Extruded hollow profiles; ET - Extruded tube; ER/B - Extruded rod and bar; DT - Drawn tube

1): Where values are quoted in **bold** greater thicknesses and/or higher mechanical properties may be permitted in some forms see ENs and prENs listed in 1.2.1.3. In this case the $R_{p0,2}$ and R_m values can be taken as f_o and f_u. If using such higher values the corresponding HAZ-factors ρ have to be calculated acc. to expression (6.13) and (6.14) with the same values for $f_{o,haz}$ and $f_{u,haz}$.

2): Where min. elongation values are given in **bold**, higher minimum values may be given for some forms or thicknesses.

3): According to EN 755-2: following rule applies: *"If a profile cross-section is comprised of different thicknesses which fall in more than one set of specified mechanically property values, the lowest specified value should be considered as valid for the whole profile cross-section."* Exception is possible and the highest value given may be used provided the manufacturer can support the value by an appropriate quality assurance certificate.

Table A.3 : Excerpt from table 3.2b EN 1999-1-1: ***Characteristic values of 0,2% proof strength f_o, ultimate tensile strength f_u (unwelded and for HAZ), min elongation A, reduction factors $\rho_{0,haz}$ and $\rho_{u,haz}$ in HAZ, buckling class and exponent n_p for wrought aluminium alloys – extruded profiles, extruded tube, extruded rod/bar and drawn tube. .*** (the footnotes 4) to 7) are omitted- but see **Table A.1**)

In the table 3.2b of EC9 we also find a temper T66. This is specific to the European standard (it does not exist in the US standard). According to EN 515, T66 is a temper with "*mechanical properties higher than T6 achieved through special control of the process 6000 series alloys*". In fact another route has to be followed. The T66 values can only be reached compared to an alloy composition fit for T6, by a slightly higher content of magnesium and/or silicon. And this is the (hidden) reason, why for EN AW-6060 and EN AW-6063 the HAZ-strength values are slightly higher than for T6. This is important for aluminium design and therefore this fact has also found its expression in the standard.

Concerning the elongation values, EN 755-2 (developed by the extruders) has another view than EN 485 (developed by rolled product manufacturers). Indeed, in the 1997 version of EN 755-2 the A_{50} value is preferred for thicknesses below 12,5 mm, but also gives, parallel for these thicknesses, the A' -value (=$A_{5,65\sqrt{A0}}$). This latter value has been listed in EC 9, since it means more to the design engineer than the A_{50} value. In the revised version of EN 755-2 (issued in 2008) the elongation value A_5 is the preferred value and it shall be applied unless there is a prior agreement between purchaser and manufacturer which allows A_{50} to be used.

Temper	Dimensions mm	R_m MPa	$R_{p0,2}$ MPa	A %	A_{50mm} %
Extruded tube					
T4	≤15	120	60	16	14
T5	≤15	160	120	8	6
T6	≤15	190	150	8	6
T64	≤15	180	120	12	10
T66	≤15	215	160	8	6
Extruded profile					
T4	≤25	120	60	16	14
T5	≤5	160	120	8	6
	5<d≤25	140	100	8	6
T6	≤3	190	150	8	6
	3<d≤25	170	140	8	6
T64	≤15	180	120	12	10
T66	≤3	215	160	8	6
	3<e≤25	195	150	8	6

Table A.4 : Excerpt from table 36 EN 755-2 (2008) : EN AW-6060 [AlMgSi] (the column for the maximum values for hardness HBW is not shown).

The grey background in some boxes is only to explain the "bold value system".

1.4 Tabled values for forging materials: table 3.2.c of EC9

Alloy EN-AW	Temp er	Thickness up to mm	Direction	f_o	f_u	$f_{o,haz}$ 1)	$f_{u,haz}$ 1)	A 3)	Buckling class
				N/mm²				%	
5754	H112	150	Longitudinal (L)	80	180	80	180	15	B
5083	H112	150	Longitudinal (L)	120	270	120	270	12	B
			Transverse (T)	110	260	110	260	10	B
6082	T6	100	Longitudinal (L)	260	310	125 2)	185 2)	6	A
			Transverse (T)	250	290			5	A

1) $\rho_{o,haz}$, $\rho_{u,haz}$ to be calculated according to expression (6.13) and (6.14)
2) For thicknesses over 15 mm (MIG-welding) or 6 mm (TIG-welding) see table 3.2.b, footnote 4).
3) $A=A_{5,65\sqrt{A0}}$

Table A.5 : Copy of table 3.2c EN 1999-1-1: ***Characteristic values of 0,2% proof strength f_o, ultimate tensile strength f_u (unwelded and for HAZ), min elongation A, buckling class for wrought aluminium alloys – forgings***

Compared to the comments for table 3.2a (sheet) and 3.2b (extrusion) of EC9 no further comment is necessary. The characteristic values correspond to the minimum values of EN 586-2 (issued in 1994). The values for the HAZ are identical with the base alloy in the case of EN AW-5754 and -5083. For EN AW-6082 they are identical with those of wrought semi products – see table 3.2a of EN 1999-1-1.

A1.5 Other provisions

In table 3.2a of EN 1999-1-1 we find in the line for EN AW-5005 (AlMg1(B)) also the alloy EN AW 5005A (AlMg1(C)). These two alloys have a very close chemical composition and have the same defined values for strength. The latter is not a must for all alloys differentiated only by another suffix, A or B or C. The reason for listing both in the standard is the lower values allowed for the impurity elements Fe and Cu, where the limits for EN AW-5005A are lower. For this reason the quality of anodic coatings is much improved. This is often required for decorative façade applications.

A.2 Casting alloys

A2.1 General

According to clause 3.2.3.1 EN 1999-1-1 the applicability of EC 9 to castings is very limited. In fact it only exists if the design rules in the informative Annex C of EC 9 are applied or are allowed to be applied respectively. This means that the National Annex has to make them binding. In the prestandard ENV, any design rules were given. The provisions were that castings should only be used if their suitability and resistance could be determined and the quality control procedures were to the satisfaction of the engineer. In table 3.3 casting alloys with different tempers were listed, i.e. more or less recommended. It was soon clear that such a wide provision could not satisfy the stringent requirements of a European design standard with respect to safety and clear application rules. Therefore the relevant paragraphs were basically changed in *"EN 1999-1-1 is not generally applicable to castings*." To now give the design engineer a simple possibility of applying castings as load bearing elements in Annex C of EN 1999-1-1, design rules and rules for quality control were formulated, for details see A.2.3.

Since the casting process is decisive in determining the qualities of a cast part, table 3.3 of EN 1999-1-1 distinguishes between castings produced from permanent moulds and those which are sand cast. Other processes are not seen as generally applicable for structural parts.

A2.2 Tabled values for casting materials, table 3.3 of EC 9

Table 3.3 of EC9 is very easy to survey compared with the tables 3.2a and 3.2b of the Code. No data concerning heat affected zones are included, since welding of cast parts is not foreseen due to the lack of data [*)]. Also no data are given for buckling; it is assumed that cast parts are compact and lateral buckling does not occur. No data are given for n_p, since plastic bending of cast parts could not generally be allowed with respect to the relative poor ductility. The values for f_o and f_u are only 70% of the values listed in EN 1706, since the listed values are those determined by a separately cast test specimen, but the casting itself may only have 70% of this value. A similar situation applies to the elongation values. A test specimen taken out of the casting needs to have only 50% of the elongation value of the separately cast specimen. It is therefore clear that only these reduced values can be taken as characteristic values for design. Concerning the elongation an additional provision has been defined in EN 1999-1-1. Test specimens have to be taken out of the casting and these shall have an elongation of min 2% with a gauge length of $5{,}65\sqrt{A0}$ (=A_5).

Alloy	Casting process	Temper	f_o (f_{oc}) N/mm^2	f_u (f_{uc}) N/mm^2	A_{50} % [1)]
EN AC-42100	Permanent mould	T6	147	203	2,0
	Permanent mould	T64	126	175	4
EN AC-42200	Permanent mould	T6	168	224	1,5
	Permanent mould	T64	147	203	3
EN AC-43000	Permanent mould	F	63	126	1,25
EN AC-43300	Permanent mould	T6	147	203	2,0
	Sand cast	T6	133	161	1,0
	Permanent mould	T64	126	175	3
EN AC-44200	Permanent mould	F	56	119	3
	Sand cast	F	49	105	2,5
EN AC-51300	Permanent mould	F	70	126	2,0
	Sand cast	F	63	112	1,5
1) For elongation requirements for the design of cast components, see C.3.4.2 (1).					

Table A.6 : Copy of table 3.3 EN 1999-1-1: *Characteristic values of 0,2% proof strength f_o, and ultimate tensile strength f_u for cast aluminium alloys – gravity castings*

[*)] This does not mean that casting materials generally are not weldable.

A2.3 Design and quality provisions

The special design rules defined in Annex C of EN 1999-1-1 are based on the following provisions:

• The design has to be based on linear stress analysis; no plastic flow shall be taken in account.

• The proof of sufficient resistance of the base material comprises two criteria: sufficient security against yield strength and sufficient security against ultimate strength. The partial factors may be defined in the National Annex. Proposed is $\gamma_{Mo,c}$ = 1,1 (as for wrought material) and $\gamma_{Mu,c}$=2,0, a much higher value, to minimize the possibility of an unintentional plastic deformation.

• The specification for a cast part shall include information about the zones of the casting concerning the degree of utilization U defined as: design stress/design resistance.

U = more than 70% in tension (areas H)
U = between 70 and 30% in tension (areas M)
U = between 100% and 30% in compression (areas M)
U = less than 30% (areas N).

For quality control the following rules are to be followed

• The location of the maximum stress shall be indicated and also the direction in which the test sample has to be cut.

• The quality requirements depend on the degree of utilization, i.e. the marked zone designation. Required is a 100% test of each cast part. This requirement seems to be very hard, but is in line with respect to the practice for automotive parts, where 100% tests are normal and do not lead to excessive costs.

The reason for all these special provisions is to the fact that the ductility of castings is very limited, and the quality e.g. porosity can vary in wide ranges also inside a production lot, depending on the performance of the casting, the casting method and the casting equipment in the foundry.

Annex B

Drafting extrusion profiles and choice of alloy

B.1 General rules for the design of sections

In principle, extrusion functions like squeezing paste out of a tube (**Fig. B.1**), a process we are accustomed to doing daily. With aluminium only the temperature and the forces must be much higher, and you need a relatively complicated machine to do it: an extrusion press.

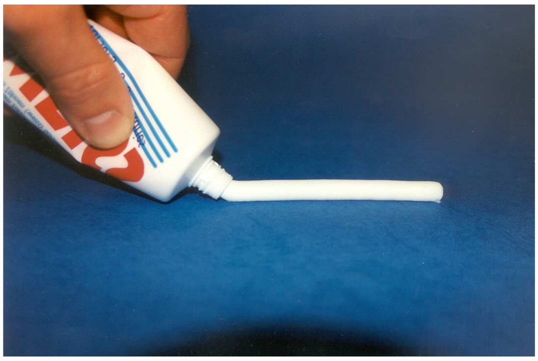

Figure B.1: Extruding tooth paste

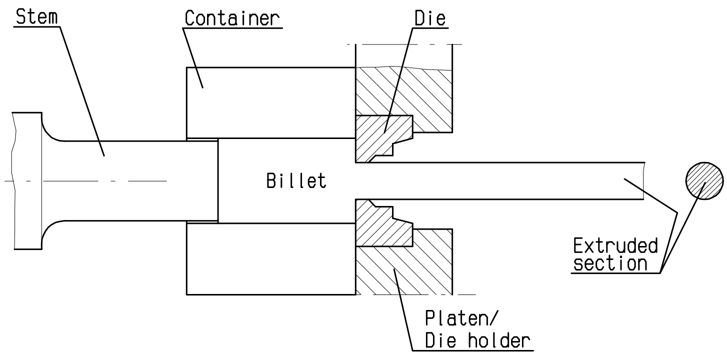

Figure B.2: Extruding an aluminium bar

The process itself is easy to explain. A preheated billet of aluminium (400 to 550 ℃, depending on the alloy) is positioned in a preheated container. Under the forces of the stem the material begins to flow through the die and so acquires the form defined by the die.

The die is in reality the most important device in this process. In its simplest form it is a disc with an opening corresponding to the outer contour of the shape of the section (**Fig. B.2**). The function of extrusion dies is not only to form the contour of a section: they are also the bearing structure, to withstand the whole extrusion force and transmit the forces into the supporting elements of the die and the press. Depending on the extrusion press, these forces may be up to 10 000 tons, with pressures up to 8000 bar. The extrusion dies are therefore made from high-strength, heat-resistant tool steel. The stresses in the die increase with the size (diameter) of the die and its complexity. When large dies are used in combination with high-strength alloys, i.e. hard extrudable alloys, we are often confronted with creep effects in the die steel and fracturing in the low-cycle-fatigue range (one billet is one cycle).

Modern dies for complex multi-hollow sections are a confusing mixture of mandrels forming the inner contours, and feeding channels by means of which the material is transported under high pressure. Between all these elements it is necessary to have enough space for the bearing structure with sufficient bearing capacity and stiffness. A lack of bearing strength induces an early breaking of the die; a lack of stiffness has effects on the tolerances of the cross section (elastic deformation of the die). This explains why these items have consequences on the design of a cross section.

It therefore seems impossible to provide someone who is not an expert in extrusion technology with rules for designing sections. However, with **Fig. B.3** an attempt is made using examples to transfer a feeling for a good design from the point of view of the die-maker. Furthermore the examples in **Fig. B.3** serve to give a certain overview of the general possibilities of the extrusion technology.

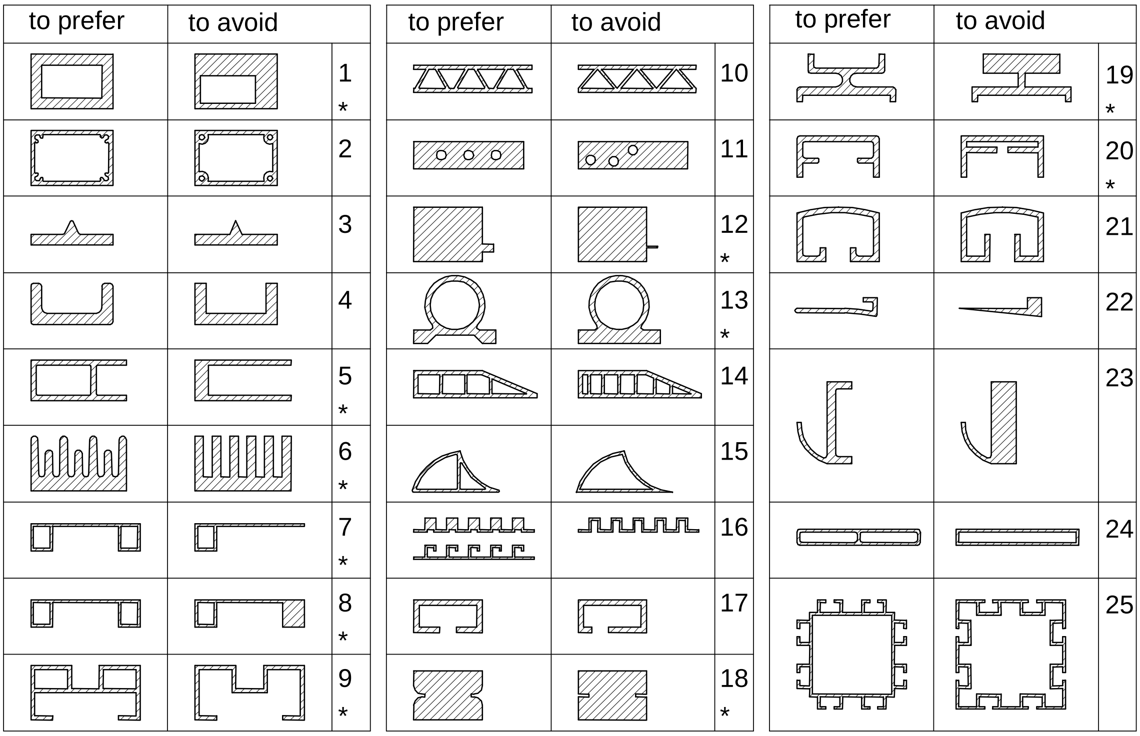

Figure B.3: Examples for basic empiric design rules for extruded sections [1]
*) A remark regarding the asterisked examples: The disadvantages mentioned later or problems are significant only in connection with large extrusions.

Following explanatory remarks are given to Fig. B.3:

1) Arrange hollows (mandrels) symmetrically, if possible.
2) Open screw channels show a better geometrical accuracy in relation to each other and give a longer life to the die.
3) Peaks should be rounded (avoid filling problems; higher extrusion speed).
4) Rounded corners are generally advantageous (longer life of the die).
5) Narrow slits only if unavoidable, otherwise add spacers whereby the tolerances of the opening distance are considerably improved.
6) Alternating long and short cooling ribs improve the life of the die.
7) Contours which are connected with an unfavourable flow of material reduce extrusion speed and induce tolerance problems (for the cross section as well as for straightness and torsion).
8) See 7)
9) The tolerances for polygonal formed open cross sections can be improved considerably by adding stiffeners or by designing a hollow section (disadvantage: higher die costs).
10) In hollow strut plate sections chambers with trapezoidal form (instead of exact triangular form) have the advantage of considerable longer die life.
11) At “borings” the material should flow around in equal thickness.
12) Small appendices in connection with thick parts of a section are hard to fill with metal and sometimes cannot be extruded.
13) Local concentrations of masses should be avoided (influence on form and tolerances).
14) Chambers should be of the same size and spaced at equal distances over the whole section width.
15) “Normal” tolerances are hard to keep for wide and curved contours (problems with respect to “straightening”), fixation of corner points improves the situation considerably.
16) Sections with parts like a squeeze-box are hard to keep within the tolerances.
17) Semi-hollow sections with asymmetric chambers have a shorter die life time and are problematic with respect to tolerances.
18) Too narrow or too deep slits in massive sections should be avoided (the cantilever part in the die may break).

19) The distribution of mass (wall thicknesses) in direction of the general contour should be balanced.
20) Cantilever parts of a die may break when the “inner” areas of semi-hollow sections are too small or too wide.
21) Protruding elements which weaken the bearing capacity of cantilever parts of the dies are to be avoided.
22) Equal flow resistance along the contour of the section is desirable (with small peaks we have filling problems, massive parts may advance and produce tolerance problems).
23) The combination of thick and thin parts in one section should be avoided.
24) Avoid too thin or too wide walls in hollow sections (denting of such elements, especially when made from alloys to be quenched with water; problems with tolerances, increased waste since defect not repairable). Arrange supporting spacers.
25) Avoid squeeze-box effect with hollow sections, walls running straight forward guarantee better tolerances and also a straightening is possible.

B.2 Rules for round tubes and tube-like sections

Round tubes (and similar simple sections) may also be produced as seamless sections (production with mandrel). This is done either because of the requirements of the customer or where for technical reasons this is the only method possible. An overview of the production possibilities is given in **Table B.1**.

In this table you will also find data which are valid for the production of tubes using special dies with seams (porthole dies). This method is the preferred one, since the geometric varieties are much greater and it is more economic.

Type of alloy	Alloys Designation acc. to EN 573		Quenching medium	Wall thicknesses in case of extrusion with mandrel as example for:				Wall thicknesses in case of extrusion with special dies as example for:			
	num. EN AW-	chem. symb. EN AW-		∅a = 200		∅a = 400		∅a = 200		∅a = 400	
				min	max	min	max	min	max	min	max
Medium strength, heat-treatable	7020 6082 6060/6063	AlZn4,5Mg1 AlSi1MgMn AlMgSi/ AlMg0,7Si	air water air	5 5 5	75	8 8 7	160	5 5 3	20 28 30	8 8 7	20 28 30
High alloyed; non-heat-treatable	5083 5754 5454	AlMg4,5Mn AlMg3 AlMg3Mn	no quenching	5 5 5	75	8 10 10	160	--	--	--	--
Low alloyed, non-heat-treatable	5051A *) 3103 1050A *)	AlMg2(B) *) AlMn1 Al99,5 *)	no quenching	5 5 5	75	8 10 12	160	5 5 5	20 22 30	8 10 12	20 22 30

Table: B.1: Feasibility of tubes depending on alloy and extrusion technology [2]. For informative reasons also data for alloys are given which are not listed in EN 1999-1-1 (*) and grey background)

Tubes are not only a means of transporting gases and liquids or an ideal element for structures (**Fig. B.4**). They are often the basis for applications in machinery: tubes are machined or parts are welded to tubes. Here the aluminium section can be a real competitor to steel because a lot of work can be saved and the accuracy of the elements is much higher, due to the complete lack of welding distortion.

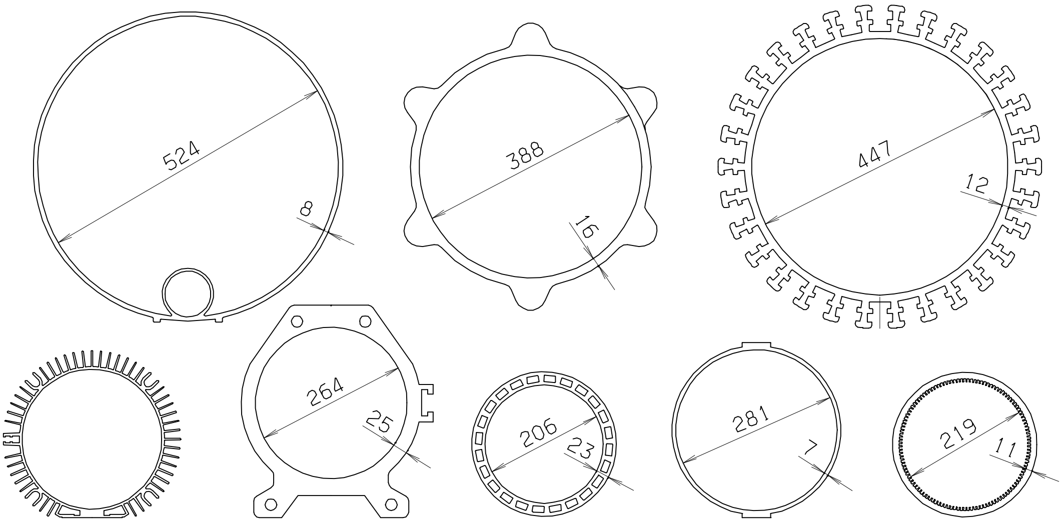

Figure B.4: Tubes with integrated additive elements [1]

B.3 Materials

Following on from the explanations in the previous sections of this paper, this section deals with the choice of the best alloy for the engineer. It covers strength and thermal treatment, the accuracy of form (cross section and the profile itself in the sense of straightness, etc.). It covers requirements in terms of low residual stresses, but also considers economy, i.e. the cost and consequently the price of the extruded section.

Table B.2 gives an overview of the wide range of alloys, but only typical alloys are listed. Besides strength values we find a series of other characteristics of these alloys, such as formability and how easy it is to perform any quenching process. These properties and characteristics are mainly decisive for the choice of an alloy. Generally, the formability resistance increases with increasing strength. As a consequence, the minimum wall thicknesses of the section also increase and the possible complexity of the shape decreases. This is why the small thicknesses that would be allowed for static reasons are often not feasible, and when the engineer is forced to define greater wall thicknesses due to other reasons, it makes no sense to remain with a higher strength alloy.

Comparing the extrusion speed is most interesting since this has an important impact on costs. Here, the low alloyed AlMgSi types (EN AW-6060, EN AW-6063, and EN AW-6106) are generally better than other alloys. Looking further to the feasibility of hollow sections and the formability (this means very thin wall thicknesses), then it is not surprising that this type of alloy dominates in many fields. Furthermore, these alloys have a good corrosion resistance and mostly are excellent for anodisation. The fact that these alloys have only mean strength values is not so critical in practice. Often it is only necessary to choose a higher height of a beam to compensate for the lower strength.

	Designation acc. to EN 573		Temper acc. to EN 755	$R_m/R_{p0,2}$	A_5	Average extru-sion Temp.	Rel. forma-bility resist [1)]	Extru-sion speed	Hollow sections with spe-cial dies	Quench-ing with air
	Numerical designation EN AW-	Chem. Symbolic designation. EN AW-		acc. to EN 755-2 N/mm²	%	°C				
a	6060	AlMgSi	T6	170/140	8	480	0,9	(a)	(a)	(a)
	6063	AlMg0,7Si	T6	215/160	10	480	"1"	(a)	(a)	(a)
	6005A	AlSiMg(A)	T6	270/225	8	510	1,3	(b)	(b)	(b)
	6082	AlSi1MgMn	T6	310/260	10	520	1,6	(c)	(c)	No(c)
	7020	AlZn4,5Mg1	T6	350/290	10	480	2,3	(d)	(e)	(a)
	2017A	AlCu4Mg1	T4	380/260	10	420	3,3	(e)	No	No
	7075	AZn5,5MgCu	T6	530/460	7	420	3,8	(e)	No	No
na	5051(A)	AlMg2(B)	H112	150/60	15	480	2,0	(c)	(e)	n. a.
	5754	AlMg3	H112	180/80	14	460	2,9	(d)	No	
	5083	AlMg4,5Mn0,7	H112	270/125	12	440	3,5	(e)	No	
	1050A	Al99,5	H112	60/20	38	420	0,6	(a)	(b)	

1) k_f-value in relation to k_f of EN AW-6063 ($\varphi = 1\ s^{-1}$);

Remarks:
a: heat treatable alloys; **na**: not heat treatable alloys;

Typ. extrusion speed: (a): very high; (b): high; (c) medium; (d): slow; (e): very slow

Hollow sections with special dies: (a): almost unlimited shape variableness ; (b): hardly limited shape variableness; larger wall thicknesses; (c):limited shape variableness; larger wall thicknesses; (d): like (c) but higher weight per m; (e): clearly limited shape variableness; larger wall thicknesses, higher weight per m; No: special dies not applicable; depending on shape, hollow sections with 1 chamber with mandrel technology

Quenching by air: (a): practically always possible, water only necessary for very thick wall thicknesses
(b): in most cases possible, water only necessary for medium wall thicknesses
No(c): air seldom applicable, only in special cases
No: for full heat treatment water quenching is always necessary
n.a.: not applicable; non age hardening alloys are not heat treated; water only due to processing reasons (quick cooling down)

Table B.2 Technological properties of some aluminium alloys.[1] For informative reasons data for alloys are given which are not listed in EN 1999-1-1 (grey background).

So the engineer always has to make a compromise between strength, wall thickness and cost. In cases where the requirement for light weight is absolutely predominant, it may make sense to extrude high-strength alloys with higher wall thickness and then machine down parts of the section to the required shape and wall thickness.

Besides the above mentioned restrictions on strength and formability resistance, we also have to look at the consequences which may result from the heat treatment. In the last column of **Table B.2** we find details of the quenching conditions. When quenching with water (often unavoidable for metallurgical reasons), we have to accept a higher distortion of the cross section and of the profile itself, and we have to accept higher residual stresses and consequently a higher distortion after machining in cases where utmost accuracy of shape is required. All these are things are aspects which often cannot be ignored in practice.

Annex C

Fields of application for the Eurocode 9

As structural applications of aluminium are much less noticed than structures in concrete, steel or wood, the question often upraises: where and what are the structures for which the Eurocode 9 has been prepared? However there are a great many examples for structural applications where the design has to be done according legal provisions, i.e. in future the Eurocode and examples for structural applications where the design voluntary follows the official standards, since no better or special standards or provisions exist. Especially we find these applications in areas which do not belong to civil engineering but for similar structures which belong to mechanical engineering. It is typical for many applications that they seem to be of low importance, but for which often considerable amounts of aluminium semis are needed, e.g. shuttering, scaffolding.

The following table gives an overview of structural applications of aluminium and fields of structural applications

C	**C + L**	**L**
Storage vessels Lamp columns Profiled roof and wall cladding Support for railway overhead electrification Pedestrian truss bridges Enclosure structures for sewage works Sound barriers Vehicle restraint systems Sewage plant bridges Silos Traffic sign gantries Traffic sign poles Support frames in electric power substations	Bridges Flag poles Aircraft access bridges Transmission towers Bridge inspection gantries Off-shore structures (living quarters, bridges) Tank floating covers	Crane booms Lorry mounted cranes Pit props Military bridges Overhead cranes Mobile inspection gantries Scaffolding systems Ladders Cherry pickers Telescopic platforms Masts for tents
	C + F + L	
	Grating planks/Covers Helidecks	
C + F	**F**	**F + L**
Domes over sewage tanks Marina landing stages Roof access staging Dam logs Curtain walling Overcladding support systems Pedestrian parapets Greenhouses/Glass houses Chicken house structures Wood drying kilns Space structures (domes, etc) Avalanche barriers Exhibition stands Swimming pool roofs Canopies Bus shelters Winter gardens	Complete balconies Conveyor belt structures Monorails Robot support structures Shuttering form work Tunnel shuttering	Access ramps Stages (mobile) Support for shuttering Trackways (temporary) Elevators for building materials Scaffold planks Trench supports Grave digging supports Loading ramps Landing mats for aircraft Access gangways Shuttering support beams Radio masts Shuttering Grand stand structures (temporary) Fabric structure frames

Table C.1: Structural applications of aluminium and fields of application:
Grouping according to principal reasons for the use of aluminium:
C Corrosion reasons L Light weight F Functionality (of extruded sections)

Acknowledgment: I should like to thank Robert Dean, deanlightmetals, for help and corrections to my English text of this paper.

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EN 1999-1-4: Eurocode 9: Design of aluminium structures, Part 1-4 Cold-formed structural sheeting

ENV 1999-1-1: Eurocode 9 issued 1998: Design of aluminium structures – Part 1-1 General rules - General rules and rules for buildings

EN 485-2 Aluminium and aluminium alloys – Sheet, strip and plate – Part 2: Mechanical properties

EN 515 Aluminium and aluminium alloys – Wrought products – Temper designations

EN 754-2 Aluminium and aluminium alloys –Cold drawn rod/bar and tube – Part 2: Mechanical properties.

EN 755-2 Aluminium and aluminium alloys – Extruded rod/bar, tube and profiles – Part 2: Mechanical properties

EN 755-9 Aluminium and aluminium alloys - Extruded rod/bar, tube and profiles – Part 9: Profiles, tolerances on dimension and form

EN 573-1 Aluminium and aluminium alloys – Chemical composition and form of wrought products - Part 1: Numerical designation system

EN 573-2 Aluminium and aluminium alloys - Chemical composition and form of wrought products - Part 2: Chemical symbol based designation system

EN 586-2 Aluminium and aluminium alloys – Forgings – Part 2: Mechanical properties and additional property requirements

EN 1090-3 Execution of steel structures and aluminium structures – Part 3: Technical requirements for aluminium structures

EN 1706 Aluminium and aluminium alloys – Castings – Chemical composition and mechanical properties

EN 12020-2 Aluminium and aluminium alloys –Extruded precision profiles in alloys EN AW-6060 and EN AW-6063 – Part 2: Tolerances on dimensions and form.

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