Products – Extruded products

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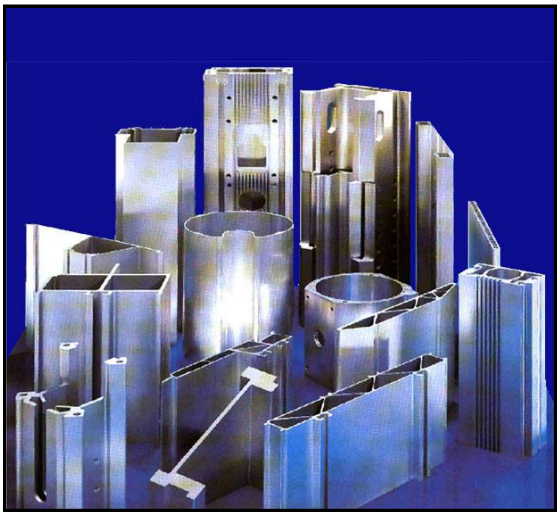
1 Extruded products



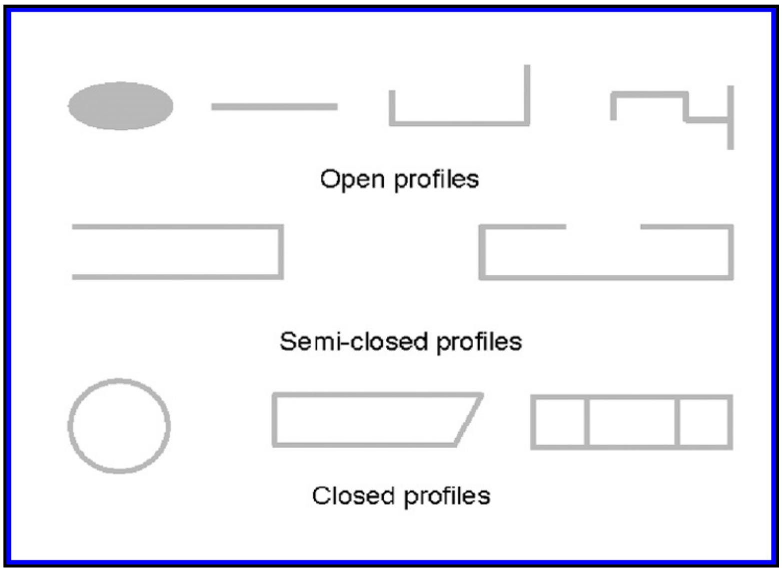
Source: Corus Group

1.1 Basic types of extruded shapes

The figure illustrates basic types of extruded shapes, open, semi-closed and closed. A lot of different shapes are illustrated in different chapters of the manual. Extrusions represent unique design possibilities, clearly differentiating aluminium from steel sheet.
It is said about products from extrusions that only imagination limits the possibilities. It differs from steel profiles in the respect that

- material thickness can differ in the cross section
- inner and outer webs and fins are easily made
- multi chamber hollow profiles are made by standard technology
- several techniques have been developed for joining extrusions mechanically

Moreover, extrusion dies have in general low cost. When complexity increases and talking about dies for hollow sections for hard alloys, die cost increases considerably.



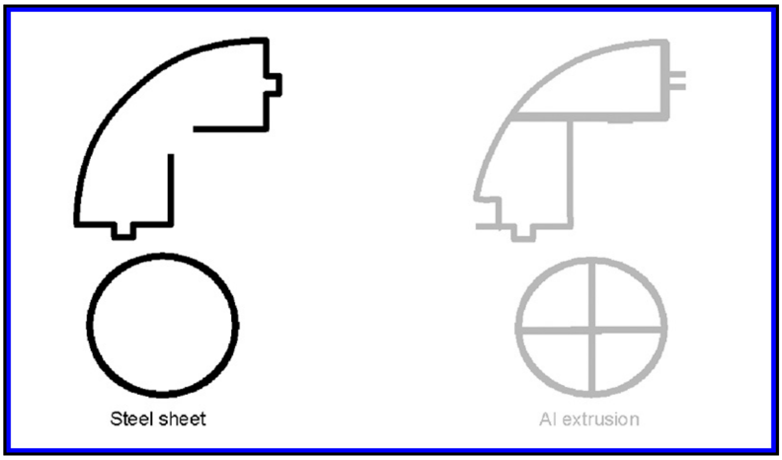
Basic shapes of extrusions - open, semi-closed and closed

1.2 Extruded shapes with webs and brackets

Compared to steel profiles, aluminium extrusions can be made more complex and material can be added where it is needed.

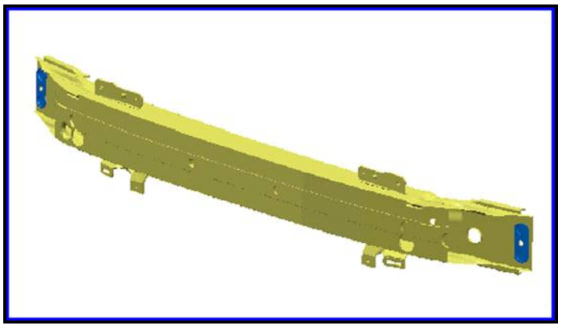
The figure (below) illustrates

- a complex profile made stiffer and with added material where needed.
- tubes – the aluminium tube has improved stability due to inner ribs.

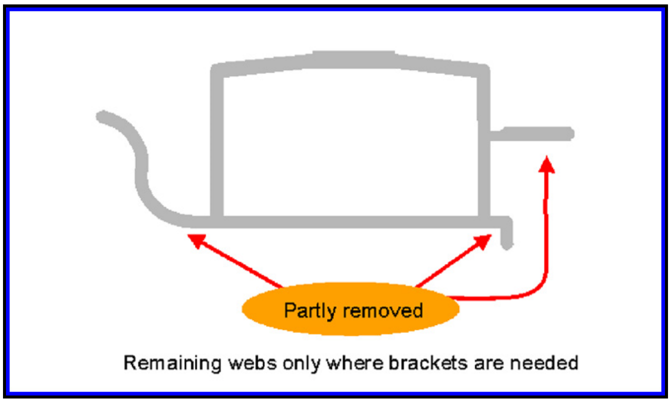


A steel sheet profile compared to an aluminium extrusion for similar purpose

External webs can be used as brackets. Areas where the webs are not necessary can be removed. See bumper beam below.



A bumper beam, a formed hollow extrusion where webs are cut away in areas not necessary



Profile cut of the bumper beam

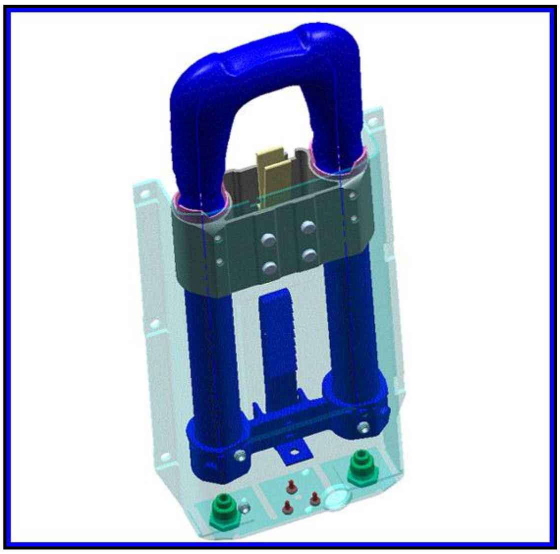
1.3 Pedals, door hinges - multi-function shaped extrusions

It should be noticed that extrusions are not used as long components only. Many application cases are found where extrusions are cut to pieces, and without more reworking there is a finished product. Figures illustrate pedals for Lotus Elise.

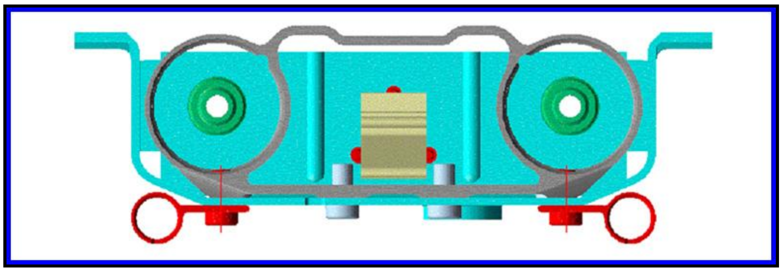
Pedal box - Lotus Elise

Pedals for Lotus Elise

The casing of a roll over protection bar shown in the figure, illustrates how a number of functions may be integrated already in the basic shape of the extrusion – a spectacle shape.



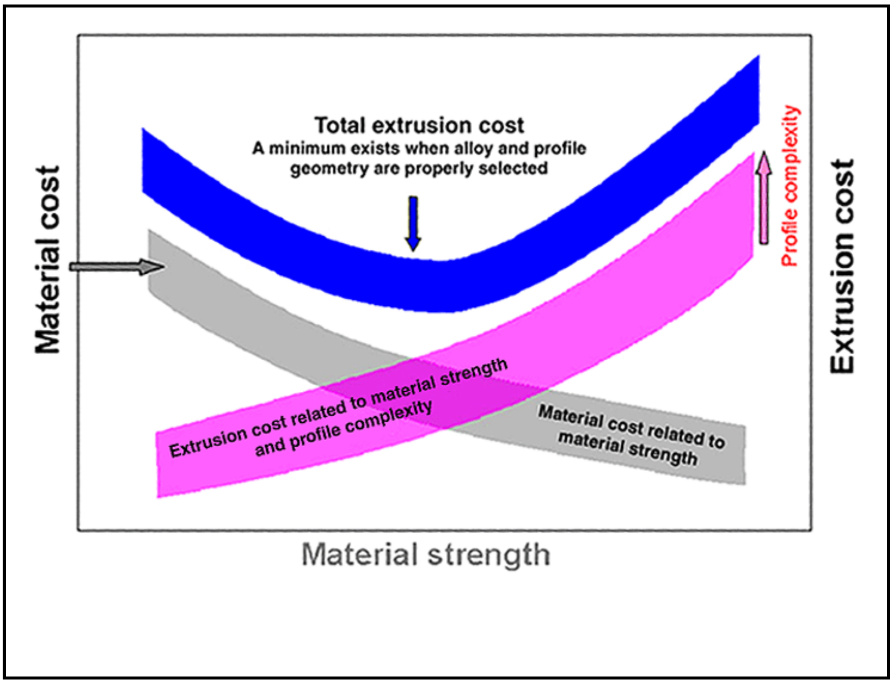
Roll over bar assembly for cabriolet



A spectacle shaped extrusion

1.4 Cost considerations

The graph below seeks to illustrate relations between cost, material strength and profile complexity. When more high strength material is applied, the cross-section may be down-gauged and material cost may be saved. On the other hand, extrudability is reduced and thus extrusion cost will increase.



Total cost of an extruded product related to material strength and material cost, and profile complexity

Increased profile complexity may increase integration of functions, and reduce weight. However, it too reduces extrusion speed and thus increases cost. All together, finding cost optimum is an intricate, but doable affair, requiring the experience developed in the aluminium industry over many years.

1.5 Alloys

1.5.1 Extrusion alloys and typical applications

On principle, all wrought alloys (and even casting alloys) can be extruded to profile shapes. However, the metal flow through the die cavities at high extrusion temperatures demands special flow characteristics in order to fill the die openings uniformly at high flow rates and to achieve desired microstructures, properties and optimum surface quality. It is for these reasons that extrusion alloys have been specially optimised to suit the process and application requirements.

Beside the brief overview on automotive extrusion alloys (see below) more details on selected automotive extrusion alloys and their typical applications are presented in the following subchapters.

Besides those presented there are numerous varieties and variations of extrusion alloys. The user is referred to the suppliers for recommendations.
The unalloyed, the **1xxx-series** is used for **non-structural application** and are the best extrudable among the alloys.

Liquid lines have over years been made in **EN AW-3103**.

As **space frames** and other structural body parts are increasing in volume, more and more medium to high strength **6xxx-series** alloys are applied.

In general, the alloys **6060 and 6063** are the **high volume alloys**. Each extruder/ supplier offers his own family of alloys within each of these basic alloys.

A major part of extrusion based products supplied to the automotive field has over the years been **bumper beams** in special **7xxx-series** alloys (different from aerospace 7xxx alloys).

1.5.2 Composition

Extrusion alloys in automotive applications

See also:
- AAM – Materials – 3 Designation system > Wrought alloys > International designation systems for wrought alloys
- AAM – Products – 2 Extruded products > Tempers and mechanical properties
- AAM – Products – 2 Extruded products > Fabrication properties
- AAM – Products – 2 Extruded products > Corrosion resistance
- AAM – Manufacturing – 3 Forming > Bending

The following table contains some typical extrusion alloys for automotive applications:

Designation	Chemical composition (mass %), remainder Al								Remarks	Others		Al min. %
	Si	Fe	Cu	Mn	Mg	Cr	Zn	Ti		Each	Total	
1050	0.25	0.40	0.05	0.05	0.05	-	0.05	0.03	0.05 V	0.03		99.50
3103	0.50	0.7	0.10	0.9-1.5	0.30	0.10	0.20		0.10 Zr+Ti	0.05	0.15	Rest
5049	0.40	0.50	0.10	0.50-1.1	1.6-2.5	0.30	0.20	0.10	-	0.05	0.15	Rest
6005	0.6-0.9	0.35	0.10	0.10	0.40-0.6	0.10	0.10	0.10	-	0.05	0.15	Rest
6060	0.30-0.6	0.10-0.30	0.10	0.10	0.35-0.6	0.05	0.15	0.10	-	0.05	0.15	Rest
6061	0.40-0.8	0.7	0.15-0.40	0.15	0.8-1.2	0.04-0.35	0.25	0.15	-	0.05	0.15	Rest
6063	0.20-0.6	0.35	0.10	0.10	0.45-0.9	0.10	0.10	0.10	-	0.05	0.15	Rest
6082	0.7-1.3	0.50	0.10	0.10-0.45	0.6-1.2	0.10	0.20	0.15	-	0.05	0.15	Rest
6351	0.7-1.3	0.50	0.10	0.40-0.8	0.40-0.8	-	0.20	0.20	-	0.05	0.15	Rest
7108	0.10	0.10	0.05	0.05	0.7-1.4	-	4.5-5.5	0.05	0.12-0.25 Zr	0.05	0.15	Rest

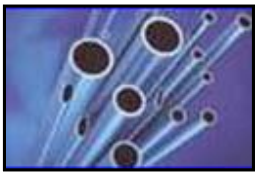
Other alloys which also are in use are: EN AW-1100, 2024, 2618, 3003, 3007, 3102, 4010, 5005, 6005, 6012, 6014, 6101, 6106, 6262, 7003, 7005, 7029, 7046, 7021 and 7075. For a specific selection a contact with suppliers is recommended.

1.5.3 Typical applications areas

Typical application examples

See also:

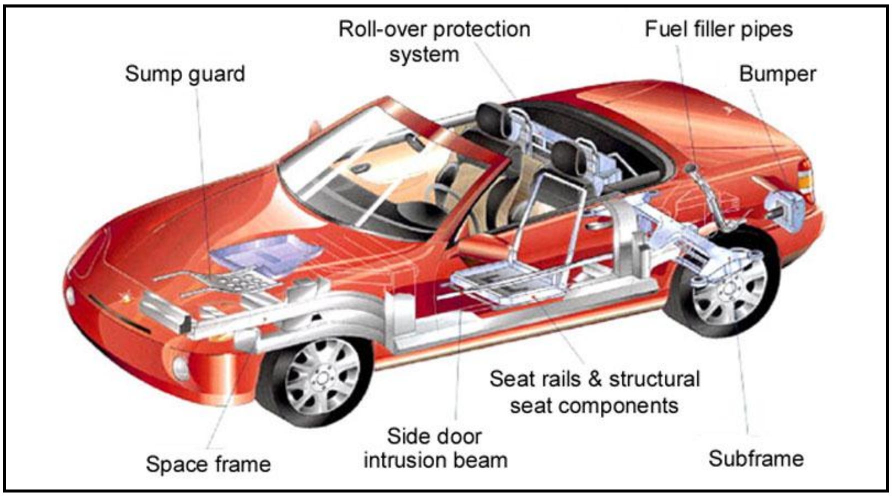
- AAM – Products – 3 Automotive tubes

Typical extruded products are:

1. Extruded and drawn tubing
2. Extruded, drawn and polyamide coated tubing
3. Multi Port tubing
4. A selection of profiles used in automotive structural application:
   - Bumper beams
   - Dash board carrier
   - Crash boxes
   - Cant rails
   - Sub-frames
   - A- and B-post
   - Complete space frames
   - Seats and seat rails
   - Wind shield frames

The car (fig. below) is a virtual car, where frequently used extrusion based components have been drawn in.



Application characteristics of alloy 1xxx series

Alloy 1000 Series

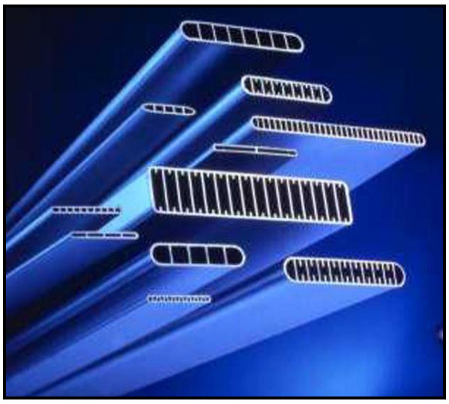
Al

Characteristics:

- High electrical and thermal conductivity
- High corrosion resistance
- Poor machinability
- Excellent finish capability and formability
- Excellent extrudability
- Low strength

Pure aluminium is often chosen in products where good corrosion resistance is necessary and where excellent formability is desired, such as:

- tubes,
- thin walled multiport extrusions,
- equipment for electrical components, heat exchangers, heat shields



Application characteristics of alloy 3xxx series

See also:
- AAM – Applications – 1 Power train > Heat exchangers
- AAM – Products – 3 Automotive tubes > Available forms and thicknesses > Extruded

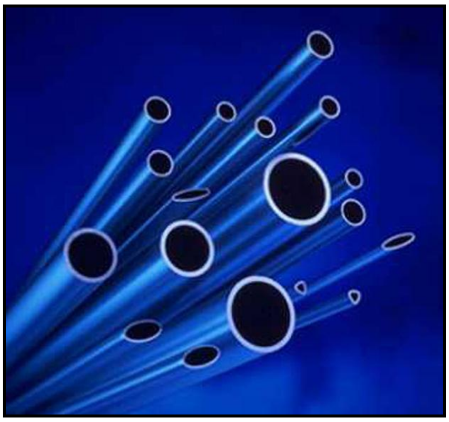
Alloy 3000 Series

Al + Mn

Characteristics:

- Excellent thermal conductivity
- Good weldability
- Good corrosion resistance
- Good extrudability
- Good formability
- Poor machinability
- Low to medium strength

The corrosion properties of these alloys are excellent and so is the formability, and the alloys are often used in:
- Extruded and drawn tubes
- Automotive heat exchangers such as radiators, heater cores, air condition coolers and evaporators



Application characteristics of alloy 5xxx series

Alloy 5000 Series

Al + Mg

Characteristics:

- Medium to high strength
- Low extrudability
- Good corrosion resistance
- Good weldability
- Good machinability and formability

The 5000 alloys combine a wide range of strength, good forming and welding characteristics, and high resistance to general corrosion. Alloys with 1% Mg can be extruded at normal rates, but with higher Mg-content the extrusion speed will be very low. Examples of applications are:

- LNG-tanks (liquid natural gas tanks)
- Decorative alloys with a wide range of strength and bright surface finish capabilities are also characteristic of the AlMg alloy system

Application characteristics of alloy 6xxx series

See also:
- AAM – Applications – 3 Car body > Bumpers
- AAM – Applications – 3 Car body > BIW
- AAM – Applications – 3 Car body > Seats
- AAM – Design – 2 Performance > Crash

Alloy 6000 Series

Al+Mg+Si

Characteristics:

- Medium to high strength
- Good extrudability
- Good corrosion resistance
- Good weldability
- Good machinability and formability
- Excellent finish capability
- The most widely used extrusion alloy group

Typical applications:

- Crash box
- Side impact beams
- Seat components
- Bumper beams
- Engine cradle
- Space frame
- Sub frame

Windshield frame BMW Z8

Source: BMW AG and Hydro Automotive

BMW Z8 sub assembly front

Source: BMW AG and Hydro Automotive

Application characteristics of alloy 7xxx series

See also:

- AAM – Applications – 3 Car body > Bumpers

Alloy 7000 Series

Al+Zn+(Mg)

Characteristics:

- High strength
- Low to medium extrudability
- Low to good corrosion resistance
- Variable weldability
- Good machinability
- Good cold formability

Typical applications are sections for structural purposes where high strength is required.: e.g. bumper beams

Typical applications of extrusion alloys

See also:

- AAM – Materials – 3 Designation system > Wrought alloys > T-Tempers for heat-treatable wrought alloys (EN 515)

Alloy	Temper [1])	Typical Automotive Applications
1050	soft	tubes, heat exchangers, finning tubes
3003	soft	radiator, air condition coolers
3007	soft	heat exchangers with low wall thickness
3103	soft	corrosion resistance, bending
5005	soft	corrosion resistance in maritime environments
5049	H112	housings for coolers
6005	T6	link ambushing, transport profile, 6005A: space frame and seat components, suspension parts
6008	T6	turn over protection AUDI TT, space frame AudiA2
6014	T6	space frame Audi A2
6060	T6	bumper, engine cradle, space frame,severely bent parts i.e. door frame, Audi A 2 window frames
6061	T6	seat tracks, bumper beams, sub frame, ABS Body valve extr.
6063	T6	crash box, space frame, sub frame
6082	T6	side impact bar, door beam, crash box, space frame, bumper beams
6106	T6	space frame components, energy absorption parts
6351	T6	door reinforcement, seat rails, air condition connecting parts
7003	T6	bumper beams, pump body
7046	T6	bumper beams
7108	T6	bumper beams

General:

Tabled applications were collected in a survey from the participating companies. Note that this is only informational. For details concerning your design please contact your supplier.

Remarks:

Temper "soft" in this table applies to non-heat treatable alloys and means states F = as fabricated and O = annealed.
Hard tempers of heat treatable alloys are labelled T6 = solution treated and artificially aged (for max. strength).

1.6 Extruded shapes

1.6.1 Infinite variety of shapes

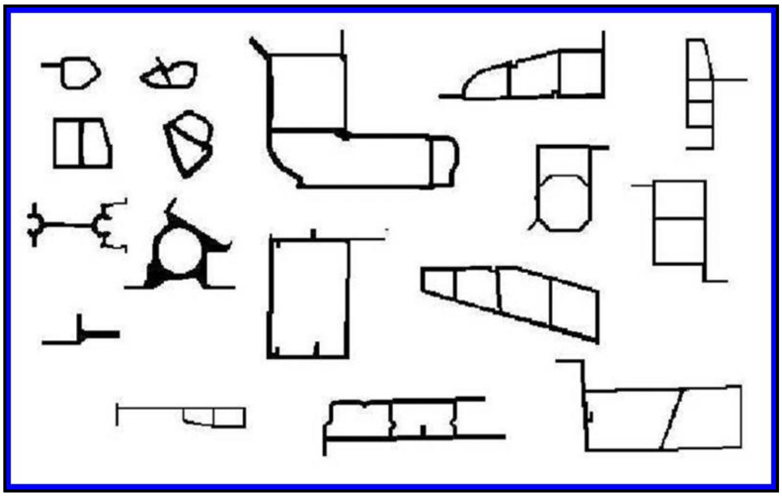
See also:

- AAM – Products – 2 Extruded products > Profile dimensions > Design guidelines

An infinite number of shapes are available. The difficulty of extruding, and thus extrusion cost, depends on shape, size and alloy.

Section categories are presented next page.

Below, the figure exhibits shape examples used in modern car space frames. Many of those are multi-chamber profiles and many include details facilitating subsequent assembly.



Profile examples used in modern car space frame

1.6.2 Section classification

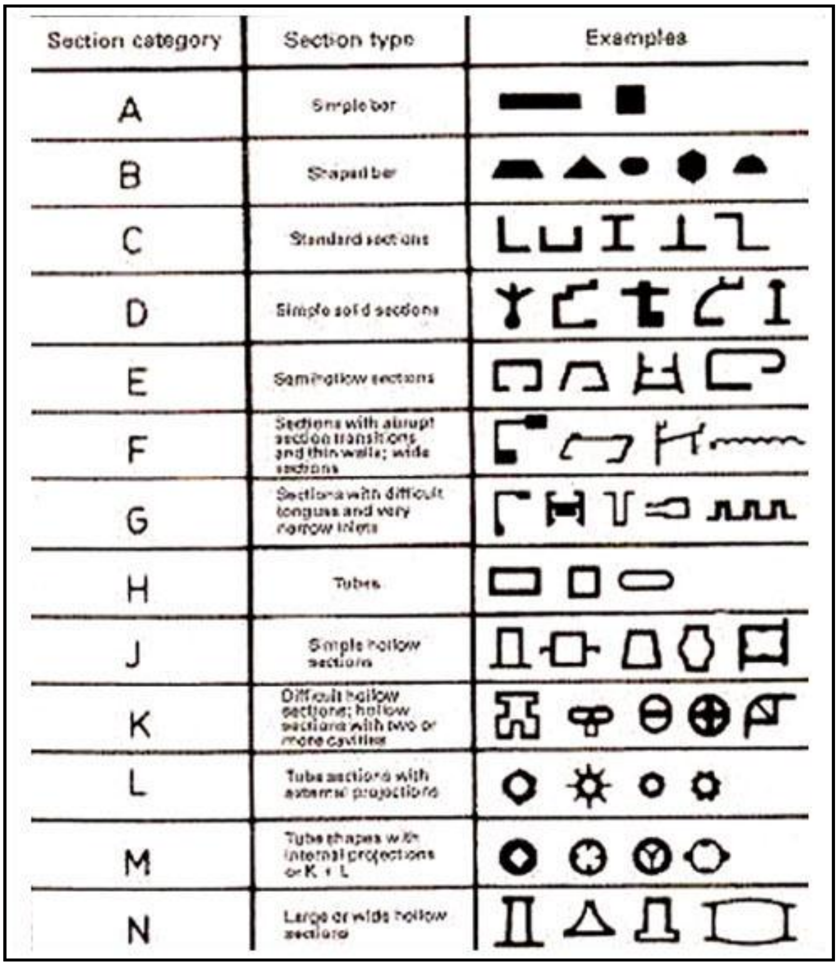
See also:

- AAM – Applications – 3 Car body > Bumpers
- AAM – Design – 2 Performance > Crash

Literature:

- Laue, K., Stenger, H.: Extrusion, American Society for Metals, 1981.

Extruded profiles have been classified according to degree of difficulty. The table (below) lists section categories A through N in increasing order of extrusion difficulty. Categories are illustrated by some sections.



Section category	Section type	Examples
A	Simple bar	
B	Shaped bar	
C	Standard sections	
D	Simple solid sections	
E	Semi-hollow sections	
F	Sections with abrupt section transitions and thin walls; wide sections	
G	Sections with difficult tongues and very narrow inlets	
H	Tubes	
J	Simple hollow sections	
K	Difficult hollow sections; hollow sections with two or more cavities	
L	Tube sections with external projections	
M	Tube shapes with internal projections or K + L	
N	Large or wide hollow sections	

Classification according to degree of difficulty

Ref. K Laue and H Stenger, Extrusion, American Society for Metals, ISBN: 0-87170-094-8

The most clearly extrudable are simple and shaped bars, followed by standard extrusions and simple solid section, semi-hollow sections, section with difficult tongues, tubes, simple hollow sections, difficult hollow sections and the most difficult are wide hollow sections. A major part of sections used in automotive are in the categories D through K.

Extrusion cost is strongly related to extrudability and thus section category. However, multi-functional sections will open for more efficient solutions, a higher extrusion cost may frequently be acceptable.

1.7 Profile dimensions

1.7.1 General

When designing extrusion-based products, one should note certain limitations and special characteristics with extrusions.
In the following, you will find subject like:

- Minimum wall thickness
- Tolerances
- Size limitations
- Design guidelines

There is a considerable cost impact on doing good design. A close dialog with the extruder is therefore recommended to obtain the best possible design. Please note also that some extruders have specialised in certain directions.

1.7.2 Minimum wall thickness

What factors determine minimal wall thickness?

Literature:

- R. Cobden: Aluminium: Physical Properties, Characteristics and Alloys. TALAT lecture 1501, EAA, 1994

General
Extrusion is a plastic flow process where the material flow speed through the die must be equal at all points of the cross section. The process window is determined by a number of factors that interact and where wall thickness is one parameter. Alloy, and relation between cross section area and billet diameter, are other factors that affect the process.

What factors determine minimal wall thickness?

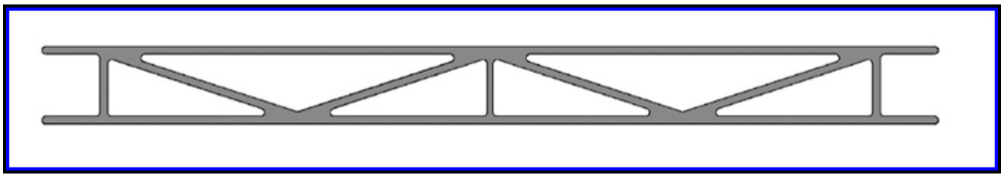
Heat generation is a key factor. Pushing aluminium through the die produces heat. The larger the degree of forming, the more heat is generated. High temperature creates problems on the extrusion surface in the form of pick ups and cracks

Tolerances are strongly related to wall thickness. If the thickness is too small it will be difficult to ensure proper flow characteristics and therefore small tolerances.

Choice of alloy affects the minimum achievable wall thickness. Alloys with a high content of alloying elements are harder to extrude than those with low content, thus requiring thicker walls.

Cross section complexity is an influential factor.

In general it is easier to produce thin walls in simple sections as compared to those in complex sections. In hollow sections with several channels it can be difficult to fill the cavities between mandrels with metal, c.f. figure below, which in turn may call for increasing wall thickness.



Multi-channel extrusion with thin walls

Getting metal into the thin, inner walls may be quite a challenge

Freedom of design is one of the extrusion processes' true strengths, especially the possibility of putting the material where it is best used.

Still, when designing a thin walled section it is favourable to consider **symmetry** and **constant wall thickness**, as these properties contribute to better flow characteristics.

It is easier to make thin walls in small extrusions than in large ones. Also, an extrusion press with **high specific pressure** (ratio between press force and container cross-section) is in general better suited for producing thin walled extrusions.

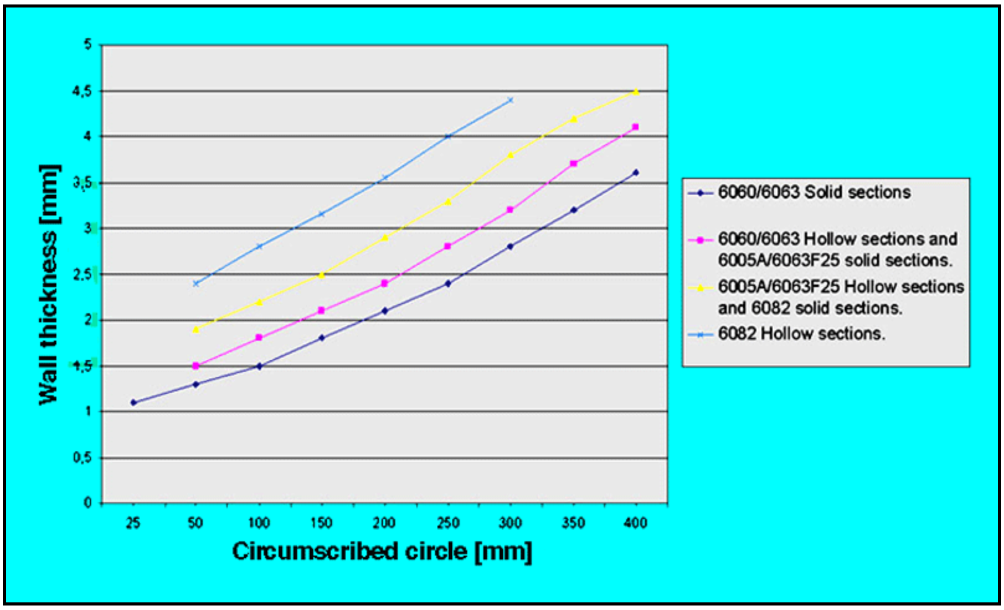
Recommended minimal wall thickness

See also:
- AAM – Applications – 3 Car body > Bumpers
- AAM – Design – 2 Performance > Crash

Recommendations

The best way to design a thin walled extrusion is by **cooperating with an extruder**. Each press has its own characteristics and the extruder knows what his press is capable of.

The diagram provides a picture of what is possible in terms of wall thickness in relation to circumscribed diameter. These curves will vary for each extrusion press.



Recommended minimal wall thickness for various alloys and section types

Source: SAPA

1.7.3 Tolerances

Rule of Thumb

Rule of thumb for tolerances is:

Linear dimensions: ± 1% of nominal value
Wall thickness: ± 5–10 %, thinner walls → higher percentage
Angular geometry: ± 2 degrees

Factors influencing tolerances are:

- Cross section complexity
- Cross section area
- Alloy
- Wall thickness

The harder an alloy is to extrude, the more difficult it is to meet dimensional requirements. Tubes can be drawn to closer tolerances, but in general extrusions cannot be drawn.

Wide hollow thin-walled extrusions which are difficult to fill with metal, are the most difficult to meet on tolerance requirements.

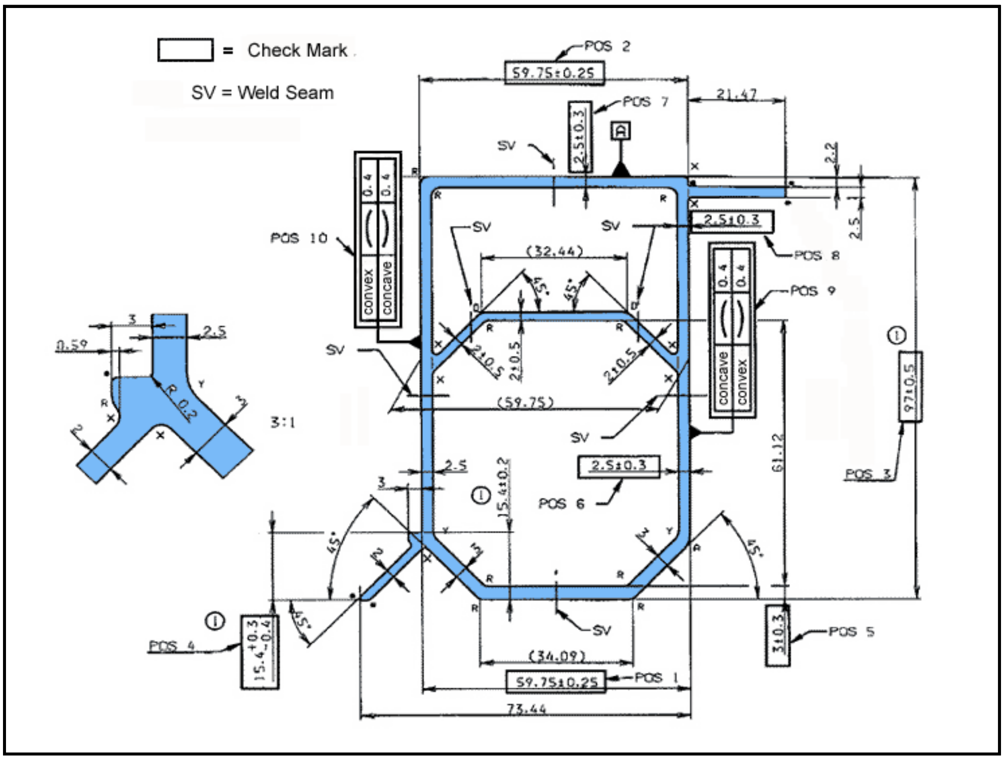
Extrusion tolerances are given in prEN-755-9. Tolerances affect the productivity and thereby the price. Most tolerances are quoted as plus or minus deviation of datum value but, if required, uni-tolerances can be obtained, either all positive or all negative.

It is essential, however, to agree this requirement before the die manufacture commences, as the dimensional datum of the die must be altered.

Most important tolerance measures

The most important tolerance measures are:

1. Wall thickness
2. Gap dimensions / Width
3. Rectangular tubes
4. Round tubes
5. Straightness
6. Angularity
7. Flatness (straightness)
8. Corner radii
9. Twist in section
10. Cutting length and angle



Source: Hydro Aluminium

1.7.4 Size limitations

Maximum cross-section

See also:
- AAM – Materials – 5 Wrought materials production > Extrusion

Maximum cross section area is related to billet size / container diameter, which again is related to each specific extrusion press. This corresponds to the green circle in the figure, and maximum theoretical dimension of a quadratic shaped profile is given by the yellow profile. However, in practice an open profile can be produced according to a circumscribed circle of 80 –85 % of the green circle and closed sections 75 – 80 %.

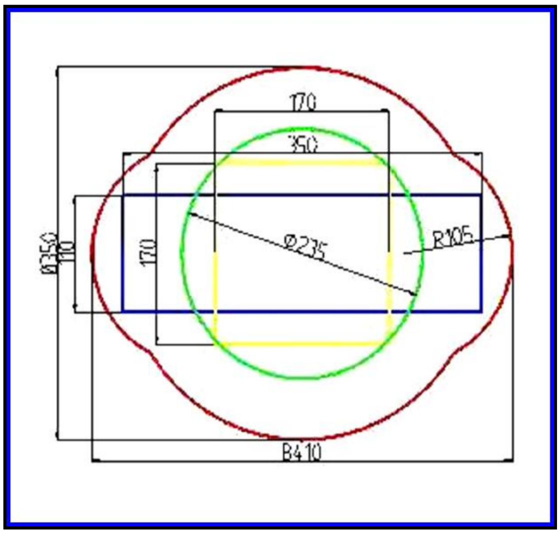


Illustration of possible profile dimensions applying

1. Standard technique and

2. Spreading technique

Some extruders apply a spreading technique, which increases the possible profile dimensions. The red circle indicates the new artificial billet dimension, which in reality is the opening of the pressure ring. The blue rectangular profile indicates maximum possible dimension of open sections, while maximum possible closed sections are somewhat smaller.

While most presses have cylindrical billets, some few have rectangular ones for production of wide shallow sections. The maximum size of a profile is also depending of alloy, wall-thickness, cross section complexity and tolerances. Each press has its own possibilities for extrusion width (max. circumference). Typically, the presses dedicated for automotive extrusions range from 1600 tons press force to 6500, and container diameter ranging from 185 mm to 340 mm.

1.7.5 Design guidelines

See also:

- AAM – Materials – 5 Wrought materials production > Extrusion

Literature:

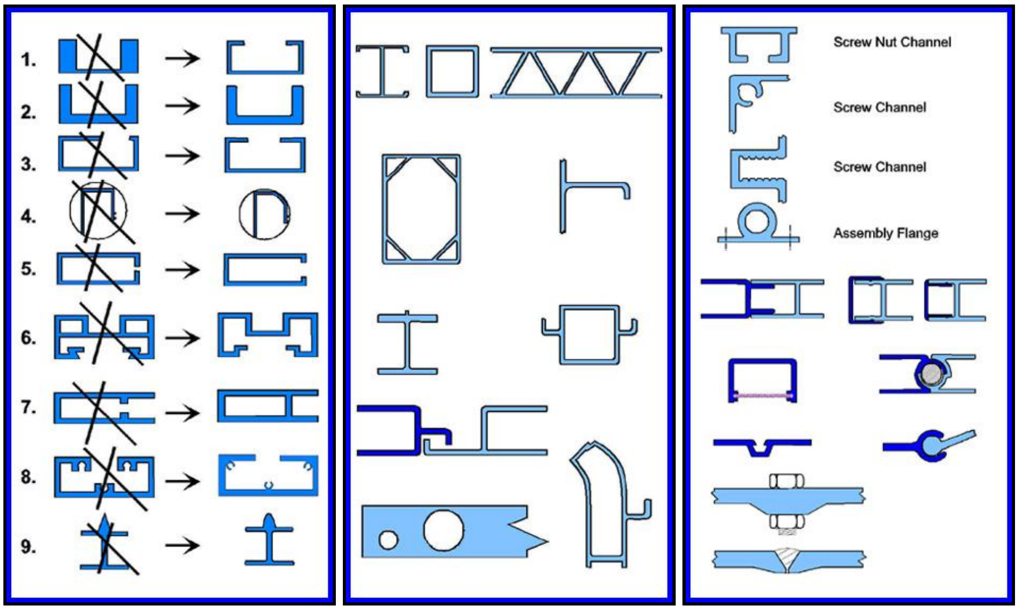
- Laue, K., Stenger, H.: Extrusion, American Society for Metals, 1981.
- Ostermann, F., Anwendungstechnologie Aluminium, Berlin, Heidelberg, London, New York, Tokyo: Springer-Verlag, 1998, ISBN 3-540-62706-5 — [Lit. 1]

The three figures below illustrate some guidelines and practical hints:

1. Design guidelines for improved extrudability and thus reduced cost.

2. Some design hints improving assembly and making attachments to the profile easier.

Some typical extrusion designs improving structural stability and some other details improving functionality. Remember also the use of inner and outer fins when stiffness is demanded.



Design recommendations

Source: SAPA

1.8 Tempers and mechanical properties

Tempers and static properties

See also:
- AAM – Materials – 3 Designation system > Wrought alloys > Temper designation system for wrought alloys (EN 515)
- AAM – Products – 3 Automotive tubes > Mechanical properties

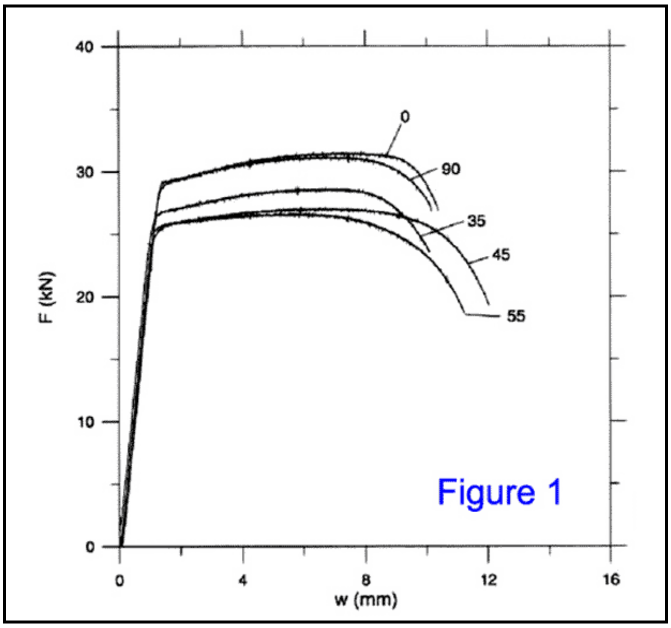
Extrusion tempers:
Non heat treatable alloys, 1xxx-, 3xxx- and 5xxx-series, are mostly delivered in temper F. 6xxx-series alloys are normally delivered in temper T5.
7xxx-alloys are usually solution heat treated before artificial ageing and are therefore delivered in temper T6 and in some cases T7, which is an over-aged temper improving toughness.

Static properties:
Static properties in the following table are given as **typical** only. Min. values are given in EN 755-2. Several suppliers of extrusions offer their own alloy(s) within the standard alloy, and also their own property limits.
Statistics on open versus closed sections of alloy 7108 show that closed sections of equal thickness are about 10 MPa lower in tensile and yield strength, and approx. 3% higher in elongation (A5).

Alloy EN-AW	Temper	Typical Mechanical Properties		
		Yield Strength (MPa)	Ultimate Tensile Strength (MPa)	Elongation A (%)
1050	F	40	74	23
3003	F	>70	>120	>15
3103	F	>40	>100	>15
5049	F	120	215	18
6005	T5	255	280	10.5
6060	T5	190	225	12
6061	T5	275	310	11.5
6063	T5	210	240	18
6082	T5	295	330	11.5
6351	T5	280	315	10.5
7108	T6	360	400	10

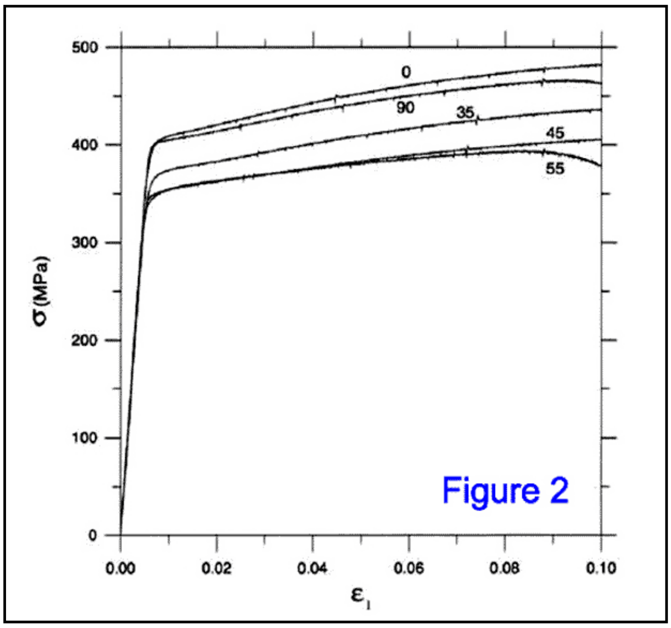
Source: Hydro

Static properties differ in various directions of the profile. In general static properties are given in the longitudinal direction of the extrusion.



Load-elongation curves for alloy 7108-T5

Source: Hydro Aluminium

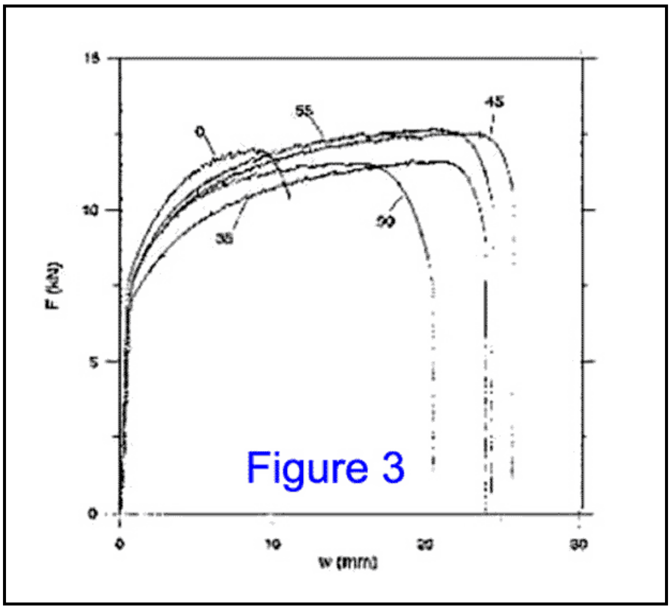


Stress-strain curves for alloy 7108-T5

Source: Hydro Aluminium

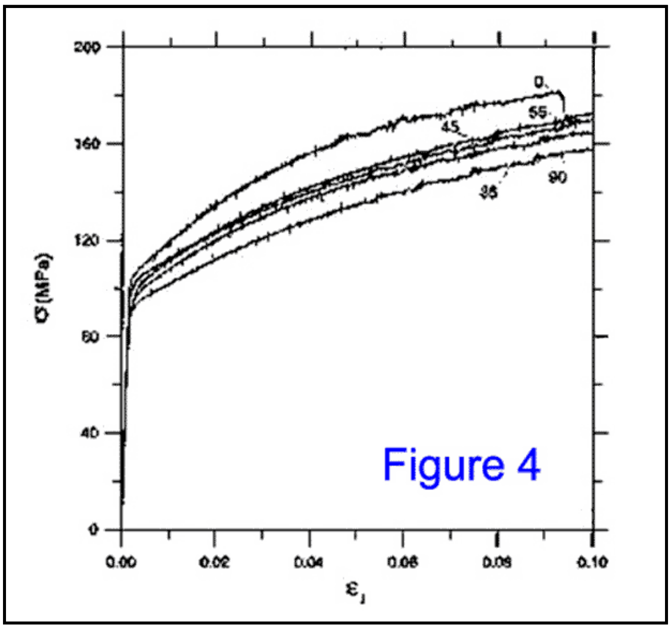
Fig. 1 and 2 show representative tensile tests in various directions for alloy 7108-T5 in which the grains are fibrous non-recrystallised.

The tensile properties of a recrystallised profile are somewhat different.



Load-elongation curves for 6063-T5

Source: Hydro Aluminium



Stress-strain curves for 6063-T5

Source: Hydro Aluminium

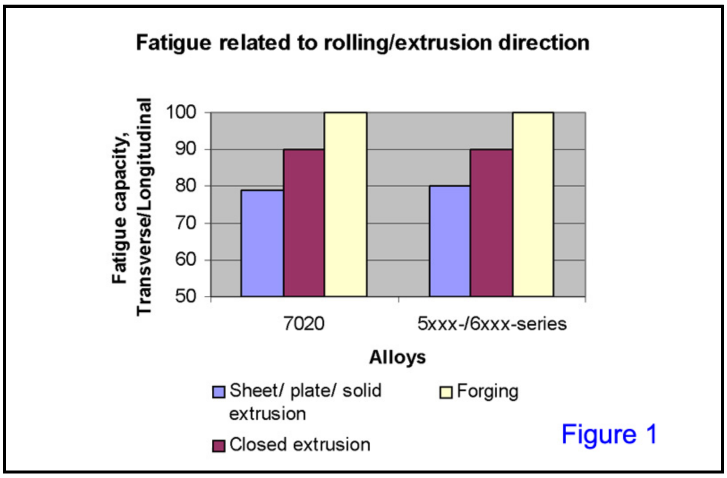
Fig. 3 and 4 for alloy 6063-T1 demonstrate some difference from figs. 1-2. Strain to fracture is lower in L and T direction than in 45° and much more evident in the recrystallised 6063. It should be noticed that in temper T1 the strength level is lower than in T5, but the principal shape of each curve is equal. The effect demonstrated above is texture effects and applies also to sheet material.

Other static properties of relevance may be creep, compression, bearing, shear, creep and properties at elevated and low temperatures. For those, see *Materials (general)* and *Talat.*

Dynamic properties (fatigue)

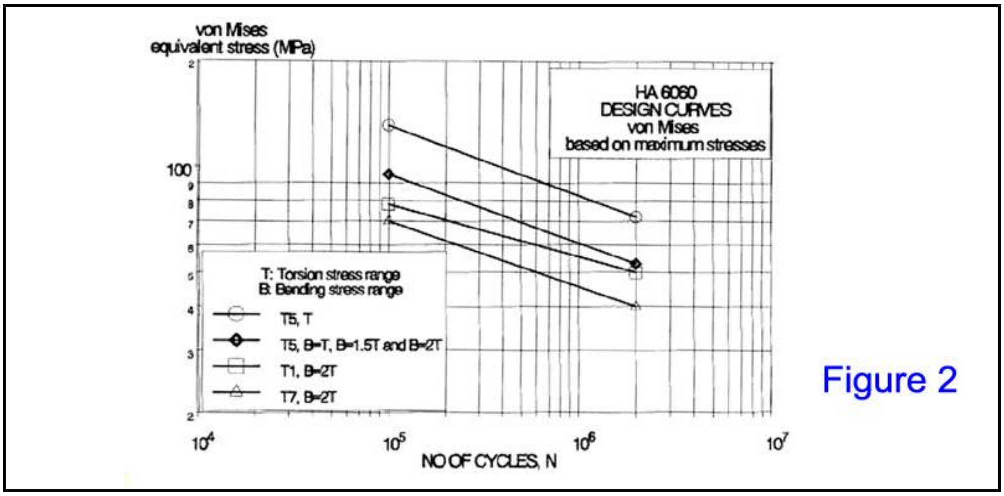
Fatigue data does not differ much between the different wrought products, sheet, extrusions and forgings. All these product types differ in properties related to material flow direction, Longitudinal (L) and Transverse (T), and so do also fatigue properties depend on material flow direction. In most cases fatigue strength in the L-direction is demanded and more favourable than in transverse direction.

In fig.1 fatigue capacity related to loading direction is indicated. In fig. 2, SN-curves of von Mises equivalent stress fitted by regression is indicated for a hollow rectangular extrusion including bending as well as torsional loading. Tensile strength seems to have very limited influence on bi-axial fatigue.



Fatigue capacity related to material direction

Source: Eurocode 9



SN-curve, von Mises eq. Stress, fitted by regression

Bending and torsion loading of hollow extrusion

Source: Hydro and Sintef

However, in car structures as in many others, highest stress is most probably found in joints like welds. Therefore, design and performance of welds and other joints are more important considering than the base material itself.

Moreover, it is recommended to see TALAT lectures 2401, 2402 and 2405.

1.9 Fabrication properties

1.9.1 Qualitative fabrication properties of extrusion alloys

Forming, Machining, Welding and Surface Treatment [0 = very bad; 5 = excellent] [2])

Alloy	Temper [1])	Cold Formability	Machinability	Weldability	Anodizing	Painting
6005	T4	3	3	3	2	3
6005	T6	2	3	3	3	4
6008	T4	4	2	4	4	5
6008	T6	2	3	4	4	5
6014	T4	5	2	5	4	5
6014	T6	3	3	5	4	5
6060	T4	4	2	4	4	4
6060	T6	3	3	4	4	4
6061	T4	4	3	5	-	-
6061	T6	3	3	4	3	3
6063	T4	4	2	4	4	4
6063	T6	3	3	4	4	4
6082	T4	3	3	3	3	3
6082	T6	2	3	4	2	3
6101	T4	3	2	3	4	4
6101	T6	3	3	3	4	4
6106	T4	3	3	3	1	2
6106	T6	3	3	3	1	2
6351	T4	3	1	3	2	3
6351	T6	3	4	4	3	3
7003	T4	3	2	4	3	3
7003	T6	3	2	4	3	3
7005	T6	3	2	2	-	3
7029	T6	3	2	0	3	3
7046	T6	2	3	3	-	-
7108	T6	3	3	2	-	3

Data contained in this table are of qualitative nature and not guaranteed

General:

All properties were collected in a survey from the participating companies. Note that the properties have informational character. For guaranties on certain minimum properties for your design please contact your supplier.

Remarks:

1) Temper "soft" in this table applies to non-heat treatable alloys and means states F = as-fabricated and O = annealed. Heat treatable alloys in soft state are designated as T4 = solution heat treated and naturally aged.
Hard tempers of heat treatable alloys are labelled T6 = solution treated and artificially aged (to maximize strength).

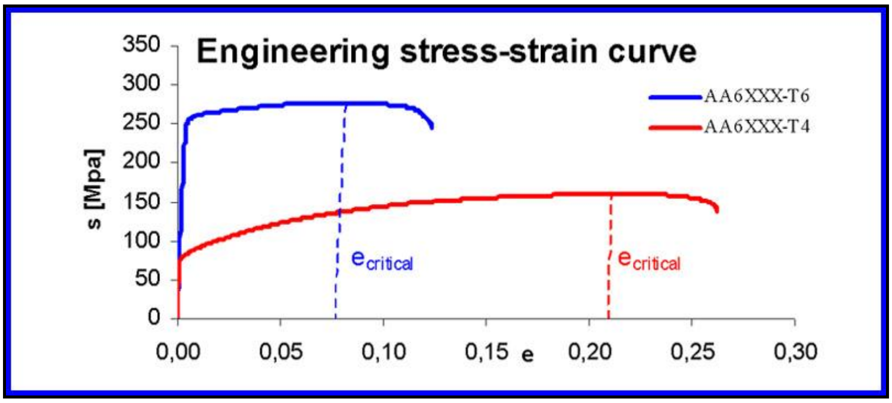
2) Ratings based on results from the survey. Feedback was averaged and rounded

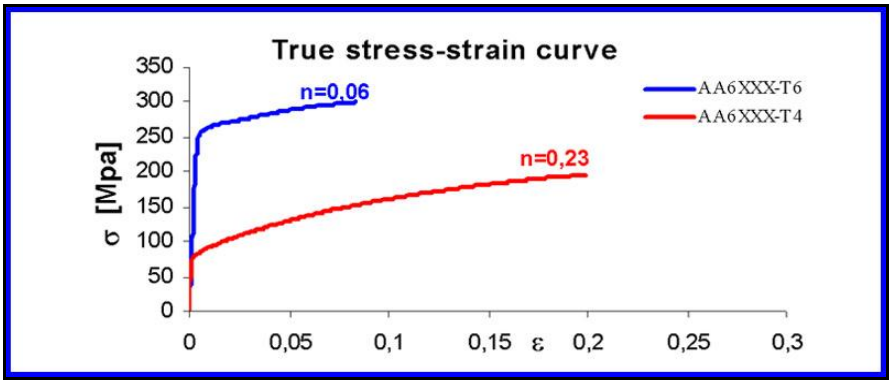
1.10 Flow curve, formability data

Flow curve

See also:

- AAM – Products – 1 Rolled products > Flow curve, formability data





The flow curve, related to the true cross section area, can be described by Ludwik's law:

$$\sigma = K\varepsilon^n$$

where K is the flow resistance (constant), and n is the strain-hardening coefficient. The flow curve usually depends on orientation w.r.t. extrusion direction (anisotropy, press effect).

Formability of extrusions is depending on:

- the ductility, ε critical, where necking occurs.
- the strain hardening, n-value, which influence the ability to distribute the strain.
- the anisotropy, influencing the deformation in different orientations.

Formability – Profile bending

The **formability of extruded profiles** may be defined as a section's ability to be bent into a specific shape (Figure 1-3)

....without exceeding the materials formability (Figure 1)
i.e. by

- necking,
- thinning,
- fracture.

This depends on the flow curve, as described above. See also chapter on sheet forming, since there is reason to believe that parts of this can be applied to profile bending.

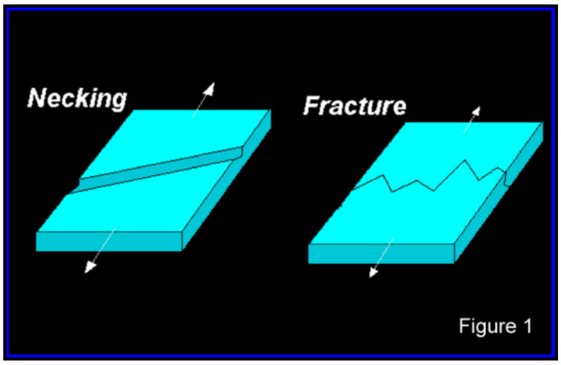


Figure 1

....with minimum distortions of cross sectional members (Figure 2)
i.e. by

- sagging,
- local buckling,
- volume conservation.

This depends mainly on profile's cross-section geometry. A low profile-width to thickness ratio (high compactness) and large bending radii will be beneficial. Also high strain hardening can be beneficial to the buckling resistance for compact profiles. Using mandrels the cross sectional distortions will be minimised.

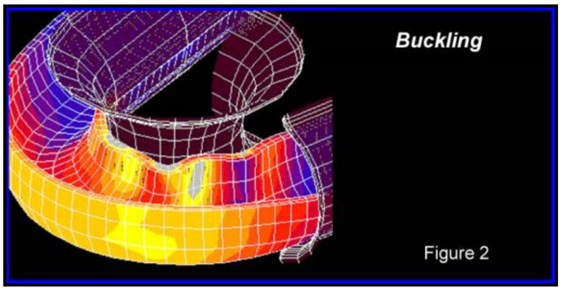
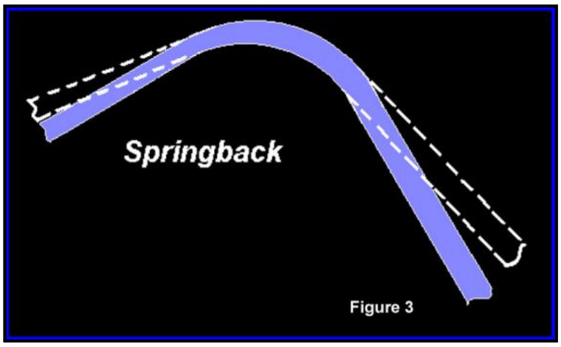


Figure 2

....within the overall dimensional tolerances specified (Figure 3)
i.e. by

- elastic springback.

When the deformed section is unloaded, springback occurs due to elastic recovery. The phenomenon increases with increased yield strength, decreased bending stiffness (E×I), increased bending angle and reduced radius.


Springback
Figure 3

1.11 Microstructure and surface

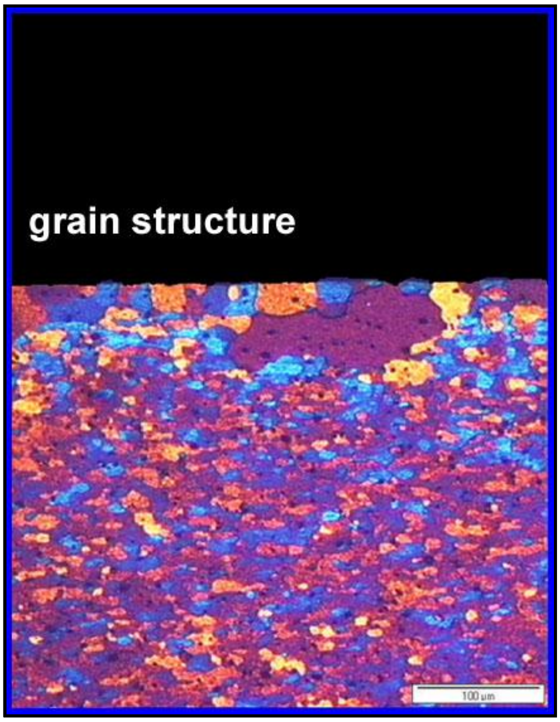
1.11.1 Factors affecting microstructure and surface quality

The **microstructure** of an extruded product is mainly characterized by two parameters:
- the grain structure (size, geometry)
- the second phase particles, which can be classified in several families depending on size and composition

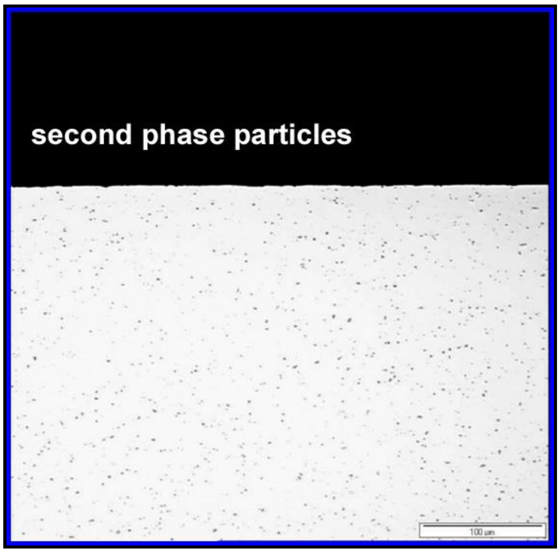
Examples are given on next pages.

The microstructure depends on the alloy composition and on the manufacturing process conditions.

It has a strong effect on most properties of the extruded product: mechanical properties, formability, corrosion, weldability...



Grain structure of a 6082 extrusion; micrograph is perpendicular to extrusion direction (anodic etching)



Particle distribution in a 6082 extrusion, perpendicular to extrusion direction

The **surface quality** of an extruded product depends mainly on the **extrusion process conditions**, but also on **alloy composition** and on **handling** / **transport** / **storage conditions**.

The surface quality requirements depend on the final application: are there visible parts? Is there a surface treatment? … These questions should be clarified early between the producer and the customer since they can impact the extrusion process conditions.

Several kinds of **surface defects** can be encountered on extruded products.

Examples are given next pages.

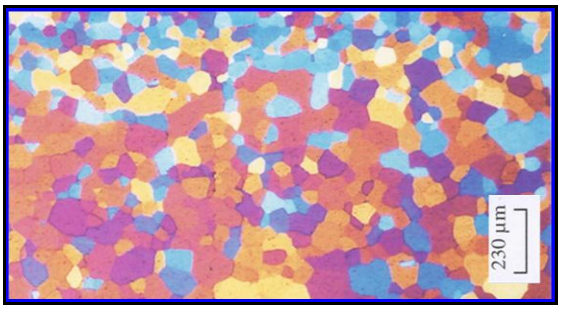
6060 extrusion of an automotive door frame

Example of visible extrusion parts (door frames) on a prototype car (Matra)

1.11.2 Grain structure

Recrystallised grain structure

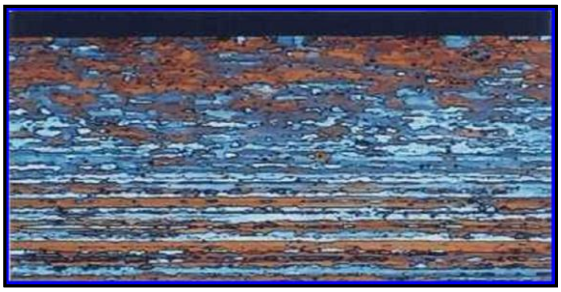
- most frequent type of microstructure: occurs naturally, if the alloy is not specifically designed to remain fibrous.
- grain size usually ranges between 50 and 300 microns.
- maximum grain size should be controlled; large grain size may be detrimental to formability.



Example of a recrystallized grain structure in a 6060 extruded product

Fibrous grain structure

- usually observed in higher strength alloys with specific addition elements (like Mn, Cr, Zr).
- induces an increase in mechanical properties along extrusion direction (called "press effect").
- ductility may be reduced compared to a recrystallised grain structure.



Example of a fibrous grain structure in a 7xxx extruded product

Mixed grain structure (fibrous / recrystallised)

- depending on extrusion process conditions, fully fibrous structure may be difficult to achieve; surface recrystallises first.
- may be detrimental (ductility, mechanical properties) if recrystallised grains are too large or if recrystallised layer is too thick.

Example of a mixed grain structure in a 7xxx extruded product: recrystallization has occured near the surface

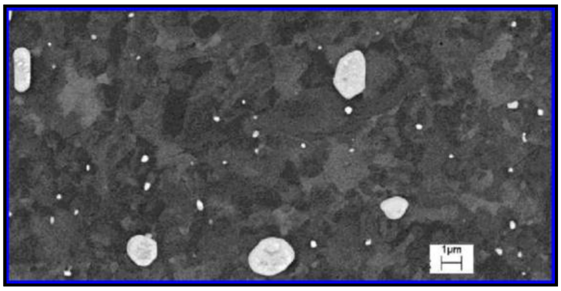
1.11.3 Second phase particles

Typical size range: 1 to 20 microns
The particles found in this range are:

- **Fe and Si intermetallic phases** which are always present in the microstructure.
- Large **Mg_2Si precipitates** which may be present if process conditions did not allow their complete dissolution.

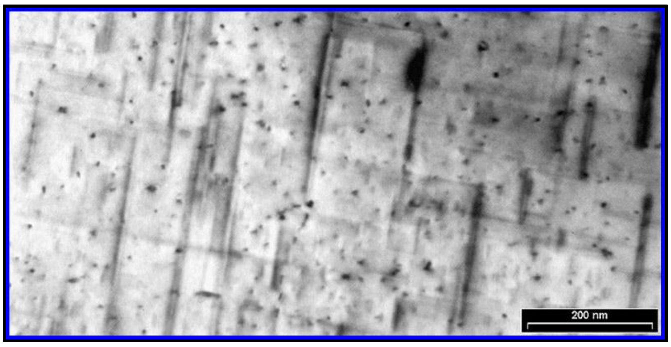
AlFeSi intermetallic phases (light grey) and undissolved Mg2Si precipitates (black) in a 6082 extrusion (optical microscope)

Typical size range: 0.1 to 1 µm.
When addition elements like Mn or Cr are present, they form small particles called **dispersoïds**. These particles are used to control recrystallized grain size or to obtain a fibrous grain structure. They are smaller and denser than the intermetallic phases.



Fine AlMn dispersoïds and large AlFeSi intermetallic phases in a 3103 extrusion (scanning electron microscope)

Typical size range: 0.01 to 0.2 µm.
In age hardening alloys, addition elements precipitate during final thermal treatment to form **hardening precipitates**. They strongly increase the mechanical properties of the product. Automotive extrusions made of 6xxx or 7xxx series in the T4 and T6 temper will contain such hardening particles.



Hardening needle-like Mg2Si precipitates in a 6xxx alloy

1.11.4 Surface quality

Several kinds of surface defects can form on extruded products. They do not necessarily affect the structural properties, but they can be unacceptable for aesthetic reasons, depending on the final application of the product. For most structural applications in automotive, this is of very limited concern.
Two common surface defects are:

die lines (figure 1) – scratches in the extrusion direction, always present to some degree; they are caused by the friction between the metal and the extrusion die.

pick up (figure 2) – local tearing of metal or oxide particles during extrusion.

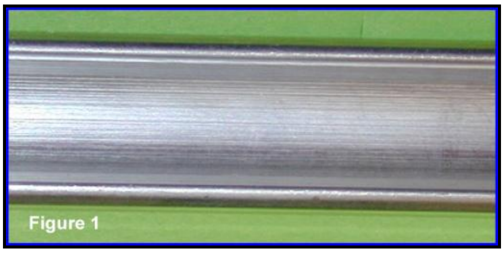


Figure 1

The requirements for surface quality should be precisely defined with the producer since they can affect the design of the extrusion die. Three levels of requirements are usually defined: high, medium, low. An extruded product for a structural automotive application with no visible part may have only low surface quality requirements.

For high surface quality requirements, special care is necessary: choice of the alloy, manufacturing process conditions, special care for handling and storage, individual protection for transport,...

1.11.5 Surface treatment – Reason and methods

Reason:

- Aesthetical and decorative reasons
- Improved corrosion resistance
- Improved mechanical and/or physical properties
- Improved solderability and/or brazeability

Methods:

- Mechanical surface treatment (treated elsewhere)
- Electrolytic and chemical polishing
- Anodising
- Organic coating (powder coating, wet painting, foiling and screen printing)
- Metal plating

1.11.6 Electrolytic and chemical polishing

These two polishing methods are used very often prior to anodising in order to obtain a bright surface appearance. In this case the process is called bright anodising. Chemical polishing is used more often than electrolytic polishing. The methods are especially suitable for complex profile geometry where mechanical polishing is difficult. Sometimes mechanical polishing is used prior to electrolytic / chemical polishing when mirror gloss appearance is required. Example of electrolytic polishing is the "Brytal" process. Examples of chemical polishing are Acid-cleaning, Glossing, buffing, Chromating and Phosphatising.

Electrolytic polishing:
Electrolytic polishing is carried out by means of current, special chemicals end high temperature. The "Brytal" process is one of the commercial electrolytic polishing processes, and with this process it is possible to obtain mirror finishes on large flat areas. The profiles should be carefully polishes by mechanical means before treatment.

Chemical polishing:
Chemical polishing is carried out by means of special chemicals (like Phosphoric Acid, Nitric Acid and Sulphuric Acid) and high temperature. Mirror-like surfaces are generally produced in mixtures of Phosphoric and Nitric Acids to which numerous other additions can be made to secure a higher levelling action. Sulphuric Acid is very often added to the mixture to remove or minimise the die lines.

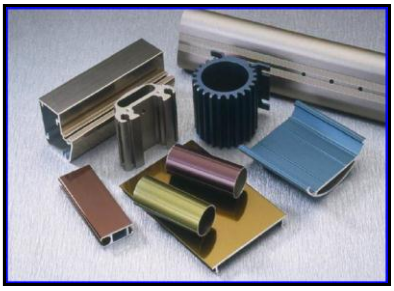
1.11.7 Anodising

Preface

Anodising is an artificial re-building of the oxide layer by use of current and an electrolyte (normally Sulphuric Acid).

The thickness of the layer is dependant on the service-conditions. For indoor (automotive?) use the thickness is typically from 3-15 μm, and for outdoor (automotive?) use the layer should be between 15-20 μm or even thicker depending on required service life.

The anodic oxide coating improves some major properties of aluminium.



Properties and process

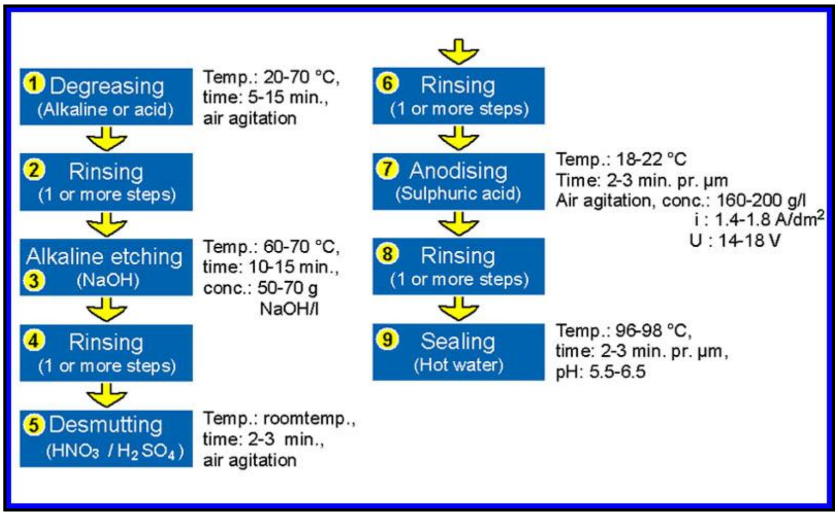
Response to colouring. Mainly brown shade colours suitable for outdoor use. Many colours available for indoor use. Generally, all colours are heat sensitive by fading

Corrosion resistance. A low porosity oxide film has a good resistance against pitting corrosion. Chloride ions have little effect on a uniform layer.

Wear resistance. Anodising improves wear resistance. Especially hard anodising increases the abrasion properties, but also normal architectural anodising gives better wear resistance.

Surface hardness. Normal architectural anodising increase the surface hardness from 60-130 HV to 200-350 HV.

Electrical resistance. The anodic oxide layer has high electrical resistance. Anodised aluminium is suitable for electrical components, e.g. transformers and capacitors.



Usual process for colour anodising

Parameters

To obtain high standards of surface finish it is necessary to control the following parameters:

- Control of surface finish and metallurgical structure of aluminium alloys used for anodising.
- Control of pretreatment, anodising and, when required, colouring and finally sealing of the coating.

Methods of pretreatment used prior to anodising are available that can mask or eliminate many of the surface irregularities of the aluminium alloys, but the metallurgical condition of the alloy cannot be controlled by the anodiser and is dependent on the processing at the casting and extrusion stages of fabrication.

Alloys (AAXXXX)	Protective anodising	Anodising and dyeing	Bright anodising	Hard anodising	Electro-plating
1080	E	E	E	E	-
1060	E	VG	VG	E	VG
1200	VG	VG	VG	E	VG
2011	M-G	M-G*	U	G	-
2014	M	M*	U	G	VG
2031	M	M*	U	G	VG
3103	G	G	M	G	G
3105	G	G	M	G	-
4043	G	M*	U	G	X
5005	E	VG	G	E	-
5056	G	G	M	E	X
5083	G	G	M	G	X
5154	VG	VG	G	E	X
5251	VG	VG	G	E	X
5454	VG	VG	G	E	-
6061	VG	G	M	VG	X
6063	E	VG	G	E	X
6082	G	G	M	G	X
6463	VG	VG	VG	VG	-
7020	G	G	M	G	-

E = Excellent
VG = Very Good
G = Good
M = Moderate
U = Unsuitable

** = Only suitable for dark colours*

X = A modified etching technique prior to plating is essential

1.11.8 Organic coating

Overview

Organic coating is mainly powder coating and wet painting. Powder coating is applied either by electrostatic or tribostatic charging of the powder particles. Wet painting is applied by spray (incl. electrostatic spraying) or electrophoretic painting.

Reasons for using organic coating

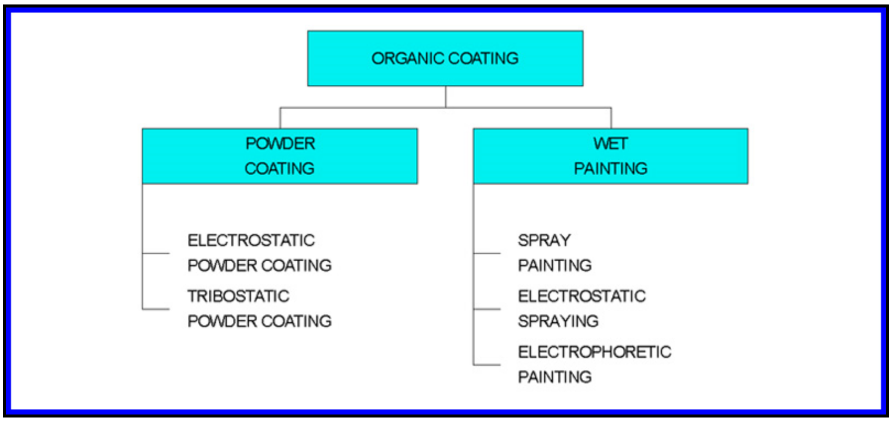
Aesthetic and decorative purposes: a wide range of colours is available and the coating will mask irregularities in the suitable (proper) pre-treatment (conversion coating).

Weather resistance: most of the organic coatings for outdoor use have a very good gloss and color stability. However, epoxy coatings are not suitable for exterior automotive ?? use. The epoxy resin is broken down by the UV-light.

Wear resistance: some special powder coatings (polyamides) have superior abrasion resistance. Abrasion tests have shown that such coatings are 600 times superior to conventional powder coatings. (See also page 8).

Friction: some special powder coatings (polyamides) have a low friction coefficient in relation to conventional powder coatings.

Picture of powder coated profiles or process



Organic coating of extrusions - main methods

1.11.9 Metal plating

Metal plating is deposition of a metal layer on another metal or plastic substrate. The precipitation occurs usually from a solution which contains ions of the metal used for the coating. Plating could either be carried out by means of electro- deposition, electroless deposition or mechanical deposition of a metal.

The main reasons for plating on aluminium are:

- Formation of an attractive finish,
- Increased corrosion resistance,
- Increased surface hardness,
- Increased solder ability / braze ability.

1.11.10 Surface treatment – Comparison of methods

Method	Advantages	Disadvantages
Anodising	• Retention of metallic appearance • Gives good weather and corrosion resistance	• White colouring of the oxide layer is not possible • Possibility for uneven colour • Reveals material and process defects • Limited colour selection for exterior application
Organic coating	• A wide range of colours is available • Gives a good weather and corrosion resistance • Masks irregularities in the material	• The metallic aluminium appearance is hidden
Metal plating	Comparing to bare metal: • Improvement of decorative appearance • Improvement of wear, corrosion resistance and hardness • Improvement of solderability/brazability	• More expensive than organic coating and anodising • Most metal plated coatings are cathodic compared to aluminium

Application to alloys:

6060: Suitable for decorative and protective anodising, organic coating and metal plating

6005 and **6082:** Suitable for protective anodising and organic coating. Less suitable for decorative anodising and decorative metal plating due to a gray (black) appearance. Surface appearance may be improved by proper desmutting after alkaline etching. However, a modified etching technique prior to metal plating is essential. Suitable for functional (not decorative) metal plating.

1.12 Corrosion resistance

1.12.1 General survey of corrosion resistance of automotive extrusions

See also:
- AAM – Materials – 4 Microstructure and properties > Corrosion behaviour > Protective oxide film

Corrosion of extrusions does not differ much from corrosion of rolled products. However, some aspects is worth mentioning.
- Pitting corrosion may occur in lines along the extrusion direction as a result of iron-containing particles broken up and lined during extrusion.
- Abrupt changes in grain size as a result of high strain rate differences may cause galvanic effects and cause galvanic corrosion in shape end surfaces and drilled and punched holes.
- Part of the heat affected zone of some welded 7xxx-series alloys is a preferred corrosion zone.
- Several alloys of the 7xxx-series are susceptible to stress corrosion. Welding creates residual stresses and welding of these alloys should be thoroughly evaluated with regard to environment and loading

See also more detailed information on corrosion of aluminium alloys in **Materials (general)**

Relative ratings of resistance to general corrosion of some common extrusion alloys for automotive applications ("5" is best)

Alloy	Temper	Corrosion resistance rating	Remarks
3003 3101	soft soft	4 5	Alloys of the 3xxx series have very high corrosion resistance.
6005 6060 6082 6082 6106 6351 6351	T4, T6 T4, T6 T4 T6 T4, T6 T4 T6	3 4 3 4 3 3 4	Alloys of the 6xxx series have good to very good corrosion resistance. Copper additions, usually added to increase strength, may have a detrimental effect on corrosion and are therefore limited to small amounts. Alloys with Silicon in excess may show susceptibility to intergranular corrosion.
7003 7029 7108	T4, T6 T6 T6	3 2 3	Copper-free 7xxx series alloys have good corrosion resistance, approaching that of the 3xxx and 6xxx alloys. Addition of Copper may reduce corrosion resistance

1.13 Thermal stability

1.13.1 Brief summary of thermal stability of extrusions

See also:

- AAM – Products – 1 Rolled products > Thermal stability

Thermal stability of extrusions is very similar to rolled products.

Briefly summarised:

Age hardening alloys in temper T4 will increase strength over time, and the rate of hardening increases with increasing temperature. At room temperature, the hardening should be considered completed after about 2 years. Alloys containing more alloying elements will increase in strength more and faster than those lower alloyed. 7xxx-alloys age harden faster than 6xxx-alloys.

In all tempers, extrusions will loose strength when exposed to elevated temperatures. At temperatures as low as 100 deg. C, yield strength is as low as about 90 % of RT strength. From temperatures of about 140 deg. C and above, increased exposure time decreases strength. After 1000 h exposure at 250 deg. C, YS is about 20 % of the unexposed YS at RT.

1.14 Crashworthiness

See also:

- AAM – Applications – 3 Car body > Bumpers
- AAM – Design – 2 Performance > Crash

Information will be provided in 2nd Edition of the Manual.

1.15 Fatigue

1.15.1 Main factors affecting fatigue performance

See also:

- AAM – Materials – 4 Microstructure and properties > Mechanical properties > Fatigue
- AAM – Materials – 4 Microstructure and properties > Corrosion behaviour > Corrosion fatigue
- AAM – Design – 2 Performance > Fatigue > Investigation of service failures in aluminium products

Literature:

- Lahaye, C.T.W.: An empirical method to predict paint appearance starting with substrate roughness data. Proc. IBEC96, (1996)

Fatigue fracture in automotive extrusions is rarely experienced as dimensioning usually is done for peak loads as crash, but some extrusion characteristics should be noticed w.r.t. fatigue.

In general, fatigue properties of extrusions do not differ much from those of sheet. The most important factors are notch effects created by joints of various types, by surface topography, internal defects of various size (inclusions, extrusion welds,...), and changes in microstructure (recrystallised coarse grained surface layer and fibrous inner grains).
Closed sections contain pressure welds, i.e. during the extrusion process the material has been divided into several „rivers", passing the bearing bridges of the mandrel, and then being press-welded behind the bridges. This is an important quality measure of a hollow extrusion.

If these welds are not properly closed/ press welded, defects occur and tensile and fatigue properties in the transverse direction will be influenced. Moreover, design of the extrusion will also influence on fatigue, again by notch effects from the shape. Influencing factors are sharp corners and sharp changes in profile thickness.
Corrosion will also influence fatigue by way of creating notches. Surface effects may create lined pitting corrosion attacks and thus make stress raisers in the transverse direction.
Local abrupt changes in grain size may also cause notch effects and thus influence fatigue performance.
From the figure shown in *Materials > Microstructure and properties > Mechanical properties > Fatigue*, it can be seen that fatigue strength in general is about 1/3 of tensile strength while notch fatigue properties are almost independent of alloy and static strength.

1.16 Joining of extrusions

1.16.1 Introduction

See also:
- AAM – Materials – 2 Alloy constitution > Heat treatment > Retrogression heat treatment
- AAM – Joining – 1 Fusion welding
- AAM – Joining – 2 Resistance welding
- AAM – Joining – 3 Friction stir welding
- AAM – Joining – 5 Mechanical joining
- AAM – Joining – 6 Adhesive bonding
- AAM – Manufacturing – 3 Forming > Impact forming

Extrusions can be joined by several methods:
- Fusion welding (MIG and TIG and laser)
- Hybrid laser technique (laser/MIG)
- Friction Stir Welding
- Spot welding
- Blind rivets
- Self piercing rivets
- Clinching bolting and
- Adhesive bonding
- Compression Fit Joint

All these methods are described in section Manufacturing > Joining. In this section those methods that have special relevance for extrusions will be described.

1.16.2 Fusion welding

See also:
- AAM – Joining – 1 Fusion welding

MIG welding is commonly used and can be applied within the whole range of extrusion thicknesses of practical interest. In cases like T- and K-joints welding is the only well developed joining technique. The method is well suited for automation and is therefore an attractive candidate for high-volume production. Proper choice of filler material reduces the risk of solidification cracking. Other advantages include high productivity and robustness.

TIG welding is an alternative method particularly in welding of thin walled extrusions where close control of penetration and quality is crucial.

Laser welding (CO_2, YAG and diode) gives high heat intensity causing a correspondingly narrow heat affected zone and low distortions. However, the method requires very tight fit-up of the parts to be welded, and can usually not accept gaps larger than about 0.2mm, which means that the method requires tight tolerances.

The **hybrid laser technique,** which combines a laser and a MIG heat source, utilises the advantages of both methods and can therefore accept larger gaps than the laser method alone. Due to the high heat input, the method offers very high travel speeds.

Plasma-arc welding is another highly efficient joining method which yields a very confined local heating due to an intensively heated plasma arc.

1.16.3 Welding simulation

Thermally induced **deformations** are unavoidable in fusion welding and may represent a challenge to overcome due to tight geometrical tolerance limits. Another phenomena is degradation of the base material due to **softening** of the HAZ.

Recent advances in development of numerical weld simulation tools can now significantly reduce these problems, since such tools can be applied to optimise the welding parameters, as well the fixture and clamping system. The right hand figure shows an example of output from a typical weld simulation applying the toolbox WELDSIM *). The component is a corner of a windshield frame and the colours represent different yield stress levels. (The red colour corresponds to unaffected base material while the dark blue colour symbolises severe softening).

Several software programs calculating distortions are commercially available.

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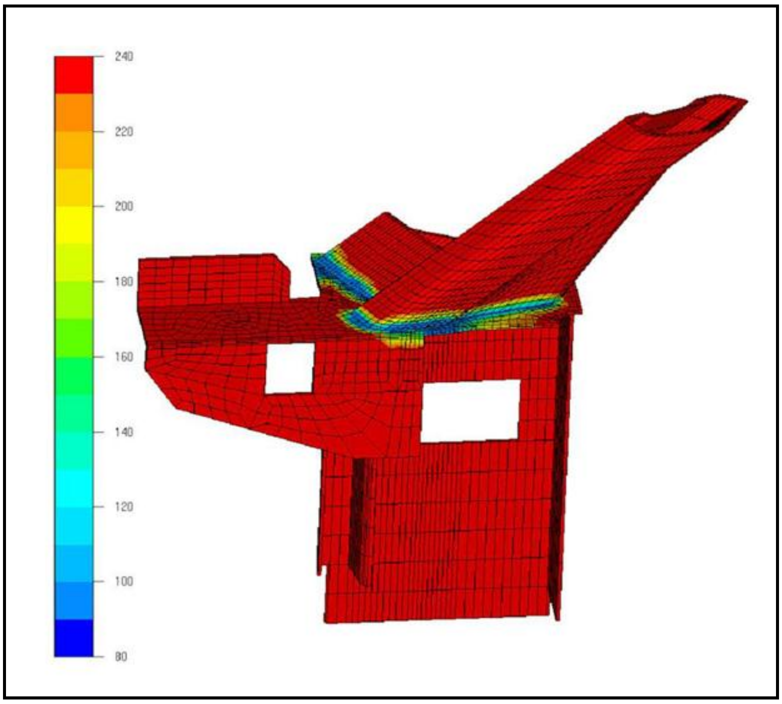
*) Not commercially available yet, for information, contact Hydro Automotive Structures.



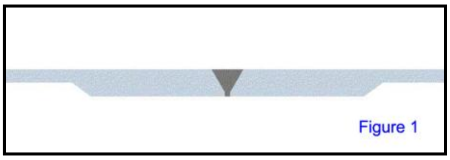
Simulated yield stress after welding of a windshield frame

Source: Hydro

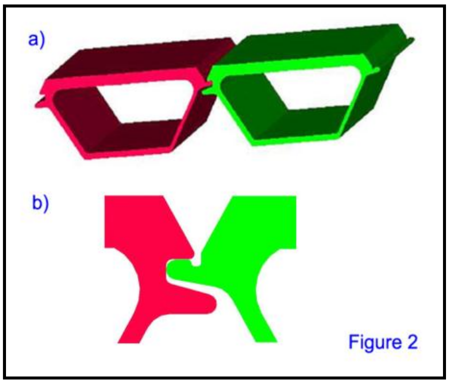
1.16.4 Welding techniques related to extrusions

Various techniques are available to improve weld quality of extrusions.

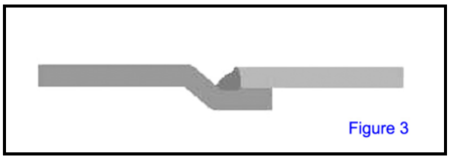
- Strength reduction in HAZ can be compensated for by local thickness increase, fig.1.
- Welding groves are included in the extrusion design, fig. 1 and 2a and 2b.
- Lap joints, fig. 3 allow some variations in overlap contrary to butt joints and can thus help on dimensional adjustment. Transverse loads create a bending moment in the weld and may contribute to bending fatigue.
- Big profiles can be made by welding together two or more sections which are prepared for welding by tongue and groove, fig. 4.



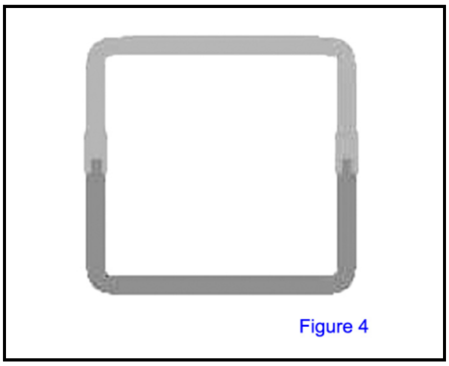
Increased thickness compensates for reduced strength



Welding grooves and backing support are included in the extrusion



Lap joints



Example making big profiles out of smaller when there is size limitation in the press

1.16.5 Adhesive bonding

See also:
- AAM – Joining – 6 Adhesive bonding

The experience with adhesive bonding of automotive structures is rather limited. The only known space frame structure currently in production applying adhesive bonding are the Lotus Elise (since 1996) and the Aston Martin Vanquish.

When bonding, in general the design must match the fact that bonding surfaces need to be much larger than those used when welding. The forces working on the bonded material should be shear loads, and peel load should be avoided, fig. 1.

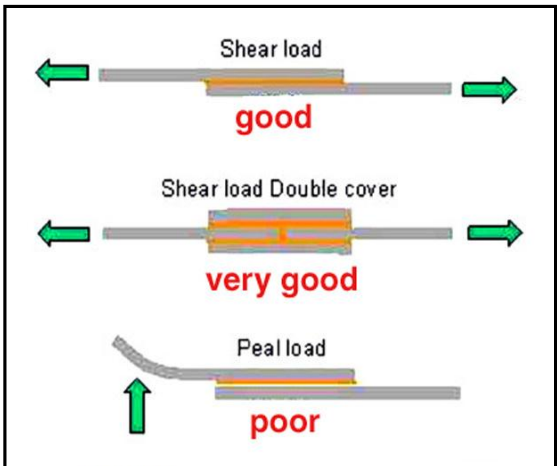


Figure 1

Longitudinal joining of extrusions or sheet to extrusion by adhesive bonding is excellent, but T-joints and similar joints can also be made when proper design is used, fig. 2.

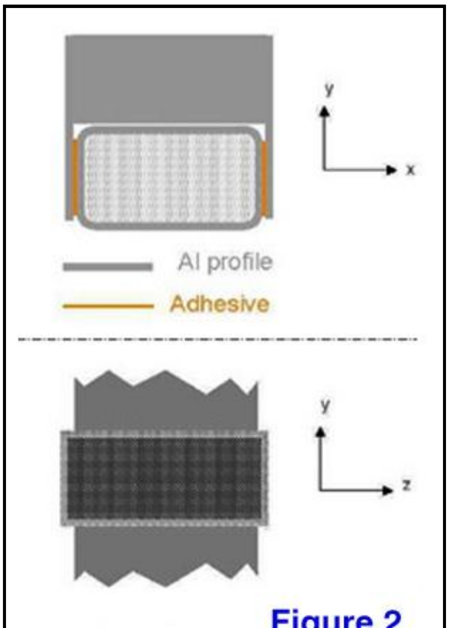
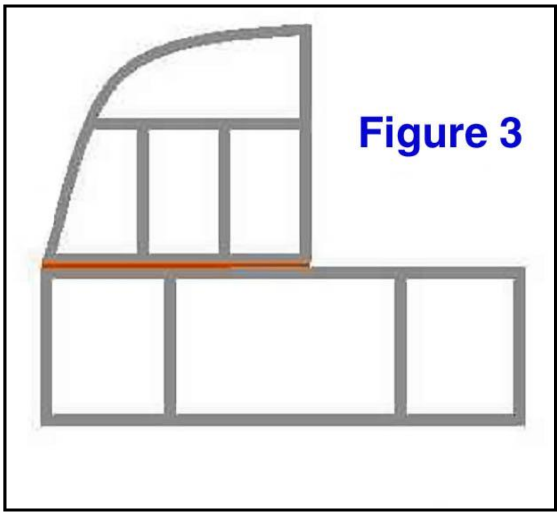


Figure 2

Example of a T-joint design

Adhesive bonding makes no thermal distortion and no changes in material characteristics. When two large closed sections are to be joined longitudinally and access from inside is very limited, adhesive bonding should be considered, fig. 3.



Normally extrusions are thin-walled, which means welding need more attention