TALAT Lecture 1302

Aluminium Extrusion: Alloys, Shapes and Properties

16 pages, 23 figures

Basic Level

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Objectives:

- to provide sufficient information on the extrusion of aluminum and the performance of extruded products to ensure that students, users and potential users of those products can understand the fabrication features that affect properties and ecomomics.
- to show how in consequence alloy choice for any end application depends not only on the characteristics required for that end use but also on production requirements.

Prerequisites:

- General knowledge in materials engineering
- Some knowledge about aluminium alloy constitution and heat treatment

Date of Issue: 1994

1302 Aluminium Extrusion: Alloys, Shapes and Properties

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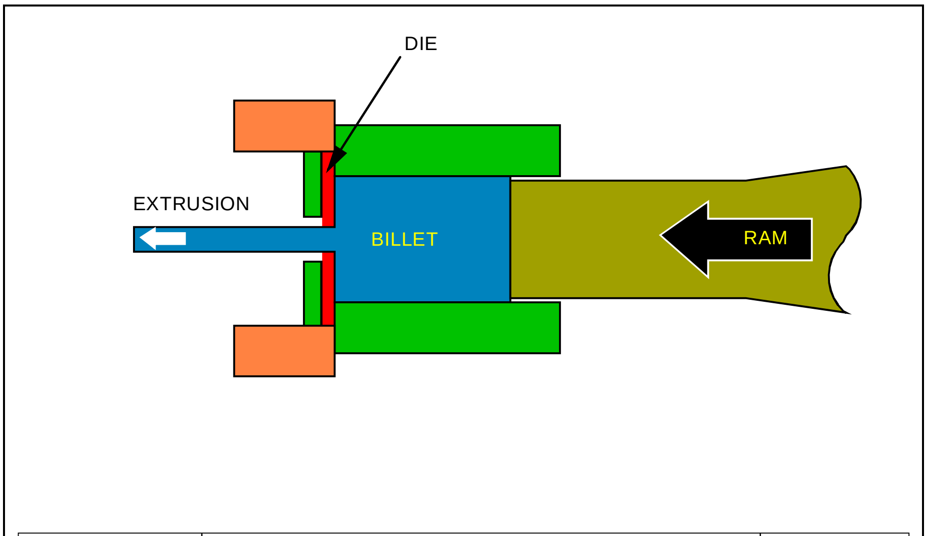
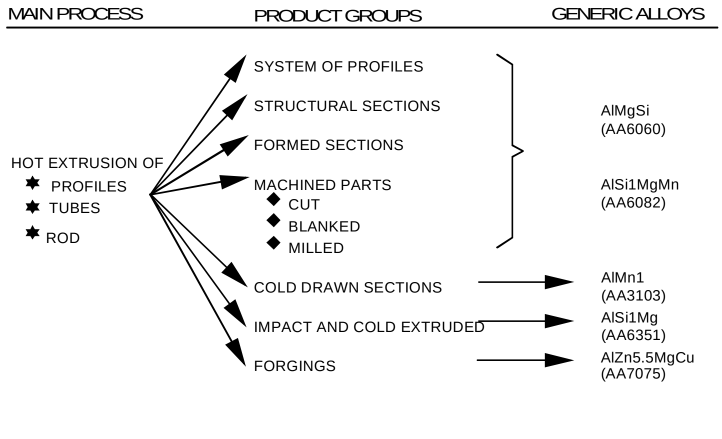
1302.00 Introduction

The term extrusion is usually applied to both the process, and the product obtained, when a hot cylindrical billet of aluminium is pushed through a shaped die (forward or direct extrusion, see **Figure 1302.00.01**). The resulting section can be used in long lengths or cut into short parts for use in structures, vehicles or components. Also, extrusions are used for the starting stock for drawn rod, cold extruded and forged products (**Figure 1302.00.02**). While the majority of the many hundreds of extrusion presses used throughout the world are covered by the simple description given above it should be noted that some presses accommodate rectangular shaped billets for the purpose of producing extrusions with wide section sizes (**Figure 1302.00.03**). Other presses are designed to push the die into the billet. This latter modification is usually termed "indirect" extrusion (**Figure 1302.00.04**).

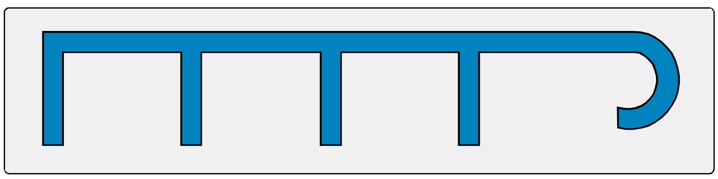


Forward or Direct Extrusion 1302.00.01

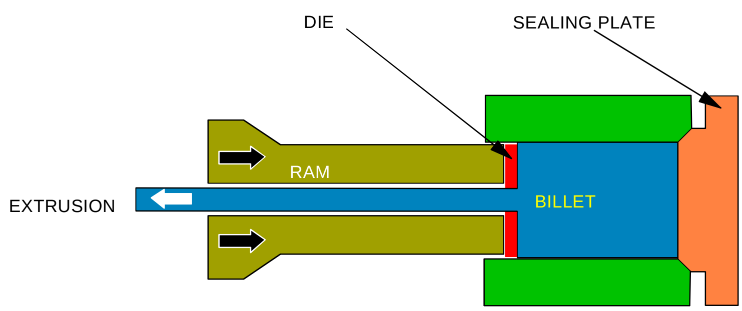
The versatility of the process in terms of both alloys available and shapes possible makes it one of the most valued assets in helping the aluminium producer supply users with solutions to their design requirements.



Extrusions 1302.00.02



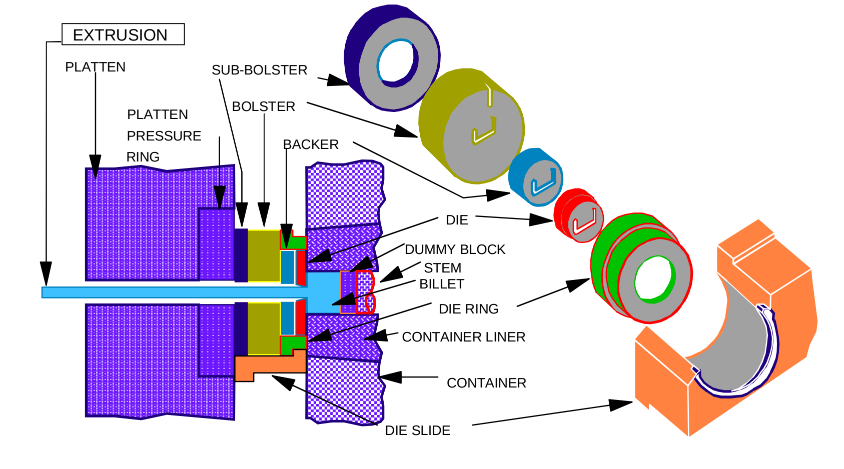
Rectangular Billet 1302.00.03



Indirect Extrusion 1302.00.04

1302.01 The Extrusion Process

The fundamental features of the process are as follows: A heated billet cut from DC cast log (or for small diameters from larger extruded bar) is located in a heated container, the actual temperatures of both varying according to alloy and other operation conditions discussed later, but usually around 450 °C - 500 °C. At these temperatures the flow stress of the aluminium alloys is very low and by applying pressure by means of a ram to one end of the billet the metal flows through the steel die, located at the other end of the container to produce a section, the cross sectional shape of which is defined by the shape of the die (**Figure 1302.01.01**). The maximum length of the section depends on the volume of the billet (cross-section x length) and on the extrusion ratio, i.e. the ratio of cross-section of the billet to the cross-section of the extrusion. When it is necessary to obtain very long length of section, as for instance in electrical conductors, it is possible to introduce successive billets into the container and produce a continuous product. The interaction between alloy composition, conditions of billet and container, extrusion ratio and extrusion speed affects metal flow and the resulting properties and structure of the section and its surface finish, while the actual die configuration and the condition and shape of the bearing surfaces over which the hot aluminium flows and the die temperature also contribute. When we add the way in which the section is cooled and handled after leaving the die it can be seen that a process described as being like "squeezing tooth paste from a tube" does have a quite complex set of parameters to control but at the same time a wide variety of means to produce the characteristics required from the product. The importance of the process to the aluminium industry and its customers is well illustrated by the fact that over the past 20 years, at four year intervals, five international conferences have been held in USA at which some 600 technical papers on the extrusion of aluminium and its alloys have been presented. A sixth such conference will be held in 1996. Few, if any aspects of the process, the products, their uses**,** their recycling and predictions for their future have failed to receive attention.



TALAT	Typical Die Tooling Assembly For Forward Extrusion	1302.01.01

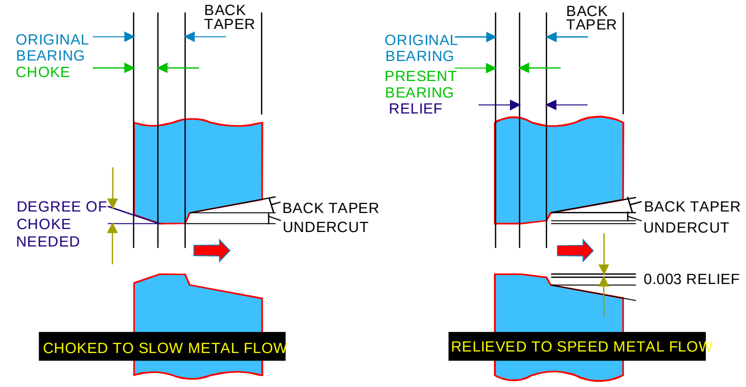
The temperature at which the section leaves the die must not be so high as to cause cracking of the product surface or cause it to develop "pick-up" which could make its appearance unacceptable. The emerging temperature is affected by many of the factors mentioned above and its control is, therefore, possible in a number of ways. Since for economic reasons it is desirable to extrude as fast as possible, thus obtaining maximum output from the press, much attention has been paid to the design of the bearings and to various die cooling techniques so that the temperature build up in the extruding metal caused by metal deformation and friction is kept to a minimum and/or reduced by cooling the die itself or the emerging product.

All aluminium alloys can be extruded but some are less suitable than others, requiring higher pressures, allowing only low extrusion speeds and/or having less than acceptable surface finish and section complexity. The term "extrudability" is used to embrace all of these issues with pure aluminium at one end of the scale and the strong aluminium/zinc/magnesium/copper alloys or other (see **Figure 1302.01.02**). Because of the mentioned complex interaction of process factors this rating can be seen to be arbitary!

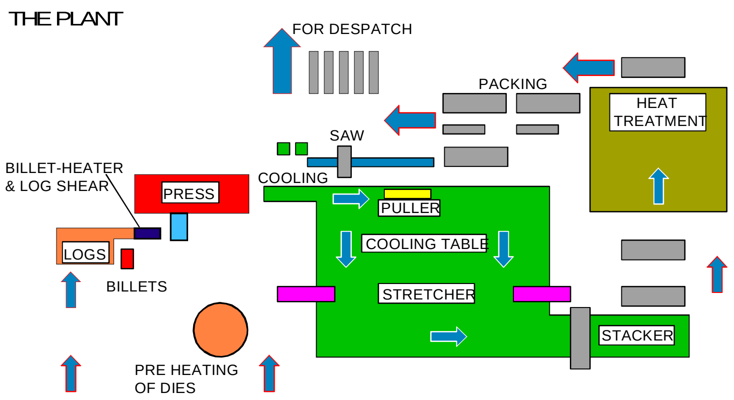
ALLOY	RATING	ALLOY	RATING
EC	150	6063	100
1060	150	6066	40
1100	150	6101	100
1150	150	6151	70
2011	15	6253	80
2014	20	6351	60
2024	15	6463	100
3003	100	6663	100
5052	80	7001	7
5083	20	7075	10
5086	25	7079	10
5154	50	7178	7
5254	50		
5454	50		
5456	20		
6061	60		

TALAT Training in Aluminium Application Technologies | Relative Extrudability of Aluminium Alloys | 1302.01.02

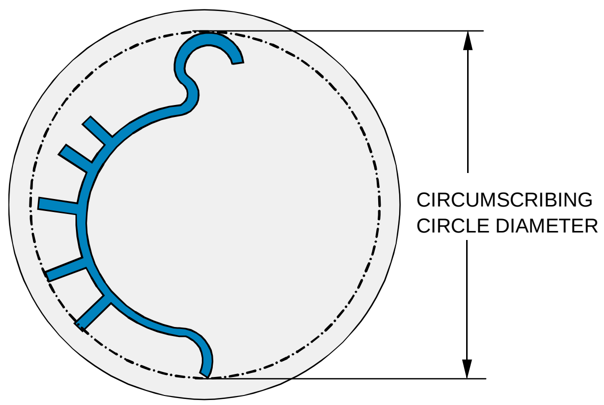
Depending on the size of the section and the size of the billet it is possible to extrude more than one section per die, up to say eight, thus greatly increasing the press output. The exact location of the section shapes around the axis is important to ensure that the sections all emerge at the same speed in order to facilitate handling. Also, even for single hole dies the metal flow through the die must be controlled by die bearing design and section orientation with respect to the die axis so that uniform speed by all parts of the section is achieved (**Figure 1302.01.03**); otherwise the section will deflect on emerging and suffer shape distortion. When the sections of heat treated alloys leave the die they can, depending on the alloy and section thickness, be quenched either in water or by air cooling, thus rendering a "solution heat treatment", or be taken from the press for formal solution heat treatment in a furnace. After either of these operations the sections receive a stretch of between 1 and 2% to remove residual stress followed by artificial ageing to stabilize their properties. The temper designations for extrusion products are numerous and a number of typical ones are shown; the most common are T4, T5 and T6.



Methods for Slowing or Speeding Metal Flow Through an Extrusion Die | 1302.01.03

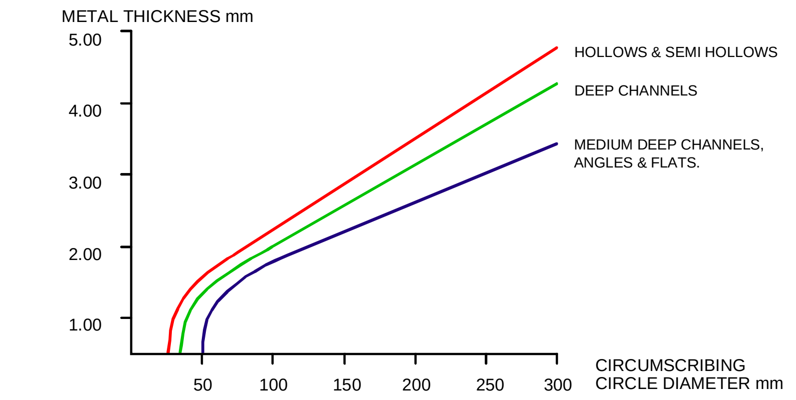


The Process - An Overview | 1302.01.04

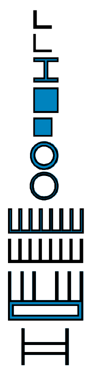


Cylindrical Billet | 1302.01.05

A typical extrusion plant layout is shown in **Figure 1302.01.04**. Press load capacities range from a few hundred tonnes to as high as 20.000 tonnes although the majority range between 1.000 and 3.000 tonnes. Billet sizes cover the range from 50 mm diameter to 500 mm with length usually about 2-4 times the diameter and while most presses have cylindrical containers a few have rectangular ones for the production of wide shallow sections. Obviously the overall dimensions of a section are related to the billet diameter (**Figure 1302.01.05**), and the minimum section thickness relates to the location of the section within this "circumscribing circle", the complexity of the section and the alloy see **Figure 1302.01.06, Figure 1302.01.07,** and **Figure 1302.01.08**). The minimum thickness possibly is about 0.5 mm. With these limitations taken into account it is no exaggeration to say that a designer can have any shape he requires, a claim supported by the fact that some extruders have over 100,000 dies at their disposal. In designing a section to meet his requirements a user is well advised to consult at an earlier stage with the suppliers. Both solid and hollow sections can be supplied by any extrusion plant, but there are differences in the philosophy of design and manufacture of the dies for the latter which affect both cost and quality of the product; also some structural features of the product may require modification for better extrudability.

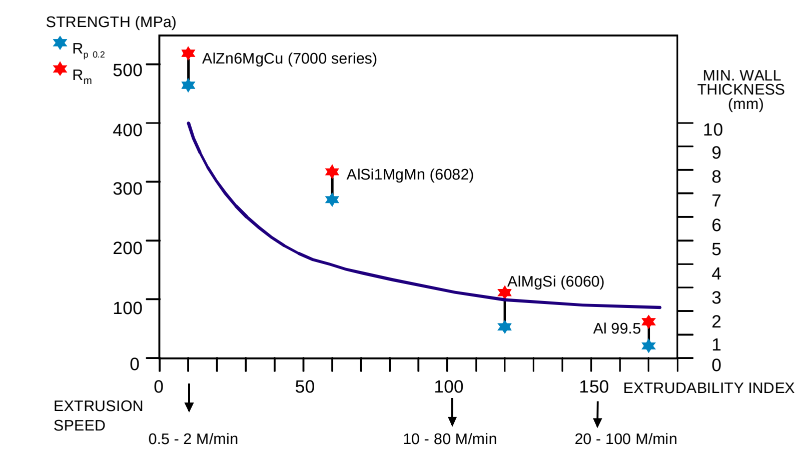


TALAT | A Guide to Minimum Section Thickness for 6063 Extrusions | 1302.01.06



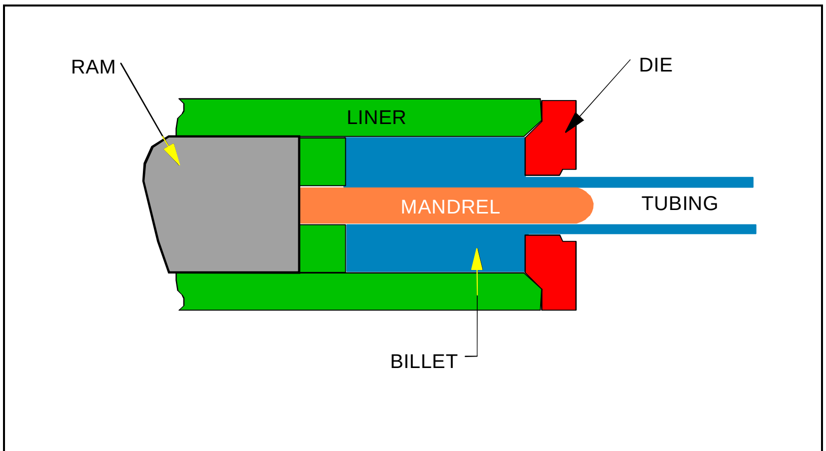
SECTION TYPE	CCD mm	THICKNESS mm	SHAPE FACTOR
	142	2.5	300
	70	1.5	500
	112	5.0	152
	142	SOLID	15
	70	SOLID	30
	50	3.0	247
	50	1.5	494
	210	3.0	190
	210	2.0	285
	140	2.0/6.0	183
	40	2.0/1.5	430

TALAT | Shape Factor Values $\text{SHAPE FACTOR} = \frac{\text{PERIPHERY}}{\text{CROSS SECTION AREA}}$ | 1302.01.07

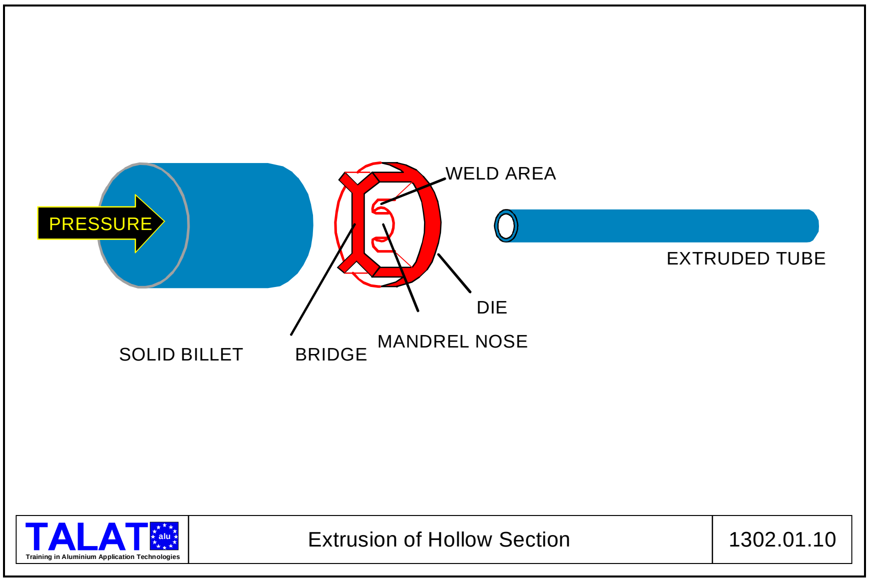


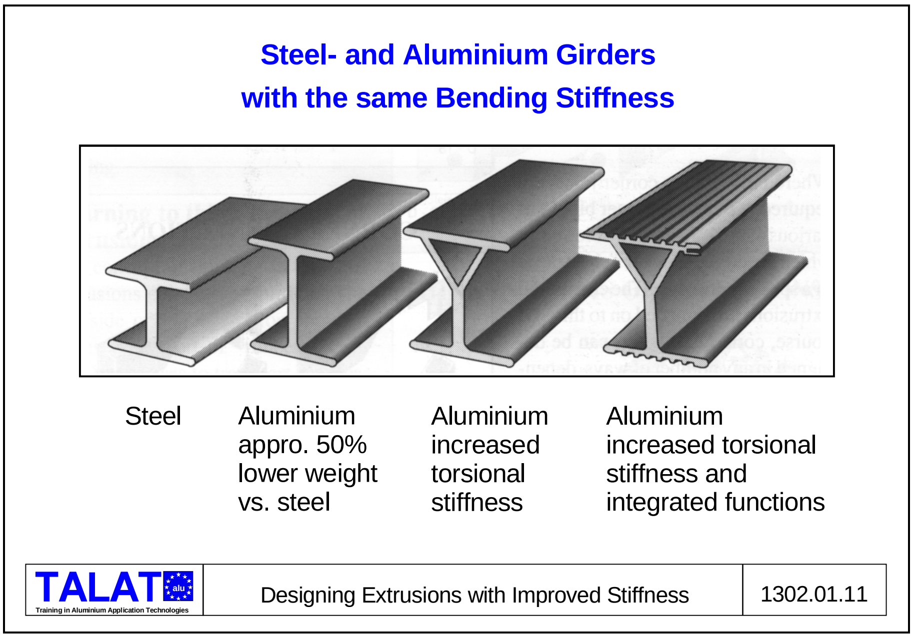
TALAT | Extrudability of Various Alloys | 1302.01.08

Simple hollow sections such as rounds, squares and ovals can be produced from a hollow billet using a mandrel (**Figure 1302.01.09**). Here the product has a uniform structure across the section. More complex sections are made using bridge or port hole dies in which the metal flows around a shaped bridge and joins again by hot pressure welding in a mixing chamber (**Figure 1302.01.10**). The design of such dies requires a great deal of experience although the use of C.A.D. and the understanding of metal flow is helping to add "science" to what is in effect an "art". Because the deformation experienced by the "welds" is different from that received by other parts of the cross section a metallurgical examination of the cross section reveals differences in grain structure at the welds and if the mixing chamber design and extrusion conditions are less than optimum the weld lines can be obvious on the section surface. When properly made, however, the difference in structure causes no significant reduction in section performance, although mechanical tests across the weld do show how some reduction in both strength and elongation do occur. Hollow sections made from bridge dies are used in critically stressed applications, the accumulated experience of both producers and users guaranteeing their integrity when produced under the controlled conditions obtaining in reliable producers plants.



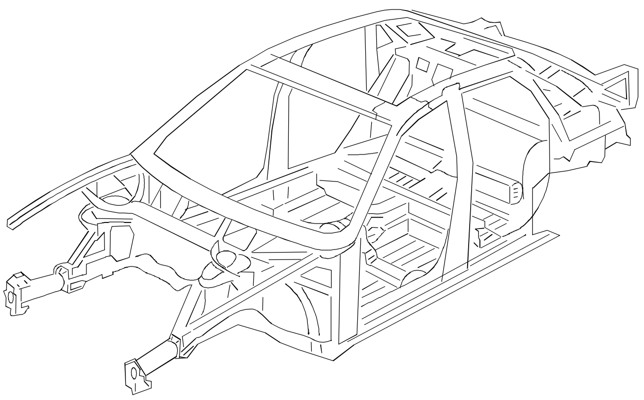
TALAT | Extruding Tubing with Die and Mandrel | 1302.01.09





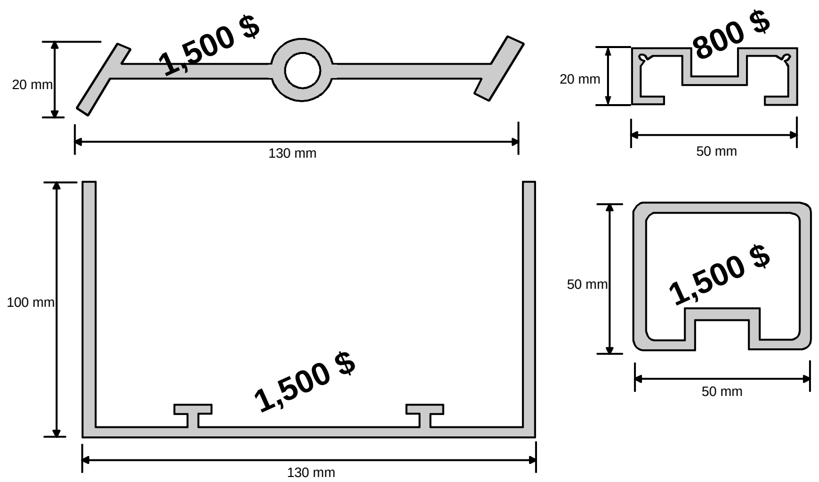
The ease with which aluminium alloys can be extruded to complex shapes makes valid the claim that it allows the designer to "put metal exactly where it is needed", a requirement of particular importance with a relatively expensive material. Furthermore, this flexibility in design makes it easy, in most cases, to overcome the fact that aluminium and its alloys have only 1/3 the modulus of elasticity of steel (**Figure 1302.01.11**). Since stiffness is dependent not only on modulus but also on section geometry it is possible, by deepening an aluminium beam by around 1,5 times the steel component it is intended to replace, to match the stiffness of the steel at half the weight. Also, at little added die cost, features can be introduced into the section shape which increase torsional stiffness and provide grooves for say fluid removal, service cables, anti-slip ridges etc. Such features in a steel beam would require joining and machining, thus adding to the cost and narrowing the gap between initial steel and aluminium costs. Good examples of this use of the flexibility of extrusions in design are found in the use by AUDI of over a hundred different extruded shapes in space frame construction (**Figure 1302.01.12**). The cost of extrusion dies obviously has to be taken into account in costing the use of extrusions but because the operating temperatures for aluminium are low compared with the temperatures at which steels can be used, viz around 500 °C, no special steels are required for dies thus keeping material costs low (**Figure 1302.01.13**). Obviously, very complex wide hollow dies are much more expensive than those for small solid sections but the latter cost as little as a few hundred ECU, and while the former might cost several thousand ECU the advantages to be gained by their use, particularly when large quantities of section from any one die are required, can readily counter that cost, as is well demonstrated by the extensive use of large, very complex sections in rail and road transport (**Figure 1302.01.14**).

Audi A8 Aluminium Spaceframe

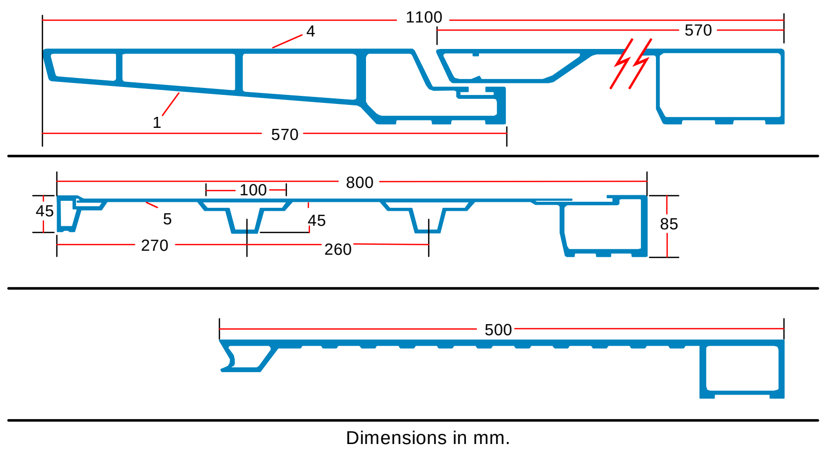


TALAT Training in Aluminium Application Technologies | Audi A8 Aluminium Spaceframe | 1302.01.12

Tool Cost (US $)



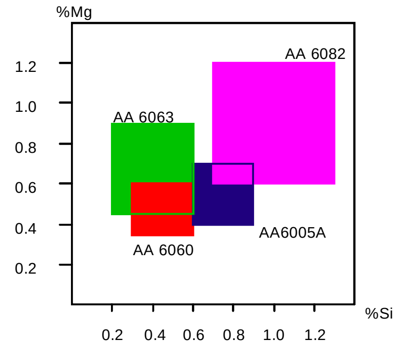
TALAT Training in Aluminium Application Technologies | Example of Tool Costs for Extrusions | 1302.01.13



TALAT Training in Aluminium Application Technologies | Hollow Sections Produced Using Rectangular Container | 1302.01.14

1302.02 The 6000 Series Alloys

As indicated in earlier sections all aluminium alloys can be extruded. However, while large quantities of pure aluminium are extruded for production of electrical conductors, strong alloys in the 2000, 7000 and 8000 series used for spars and stringers in airframe construction and large sections in the 5000 series employed in marine structures, the biggest share of the extrusion market is taken by the 6000, AlMgSi series (see **Figure 1302.02.01, Figure 1302.02.02** and **Figure 1302.02.03**). This group of alloys have an attractive combination of properties, relevant to both use and production and they have been subject to a great deal of R & D in many countries, mainly UK, USA, Germany, France, Switzerland and Japan. The result is a set of materials ranging in strength from 150 Mpa to 350 Mpa, all with good toughness and formability. They can be extruded with ease and their overall "extrudability" is good but those containing the lower limits of magnesium and silicon e.g. 6060 and 6063 extrude at very high speeds - up to 100 m/min with good surface finish, anodising capability and maximum complexity of section shape combined with minimum section thickness. Their strengths are at the bottom end of the range, and they find wide use in architectural applications where shape and finish are more important than strength. Also, the elastic modulus of all the 6000 series is the same, as is their fatigue strength when welded and these two facts coupled with the other attractive features of the 6063/6005A type make them of increasing value in transport applications. Here stiffness and fatigue often override strength as a requirement, and the complexity of thin sections possible with the lower strength versions means that maximum advantage can be taken of the reduction in welding costs made possible by their use. Rail coach construction reflects this situation and it is in this application that full advantage has been taken of the aforementioned use of rectangular containers to allow production of wide sections. The stronger 6082 type alloys are used for members where tensile strength and impact resistance as well as stiffness and fatigue are important. All of the 6000 series alloys suffer a reduction of strength at the fusion welds used in construction and this has to be taken into account in design. There is ample data to show how this is done.



TALAT | Composition of some AlMgSi Alloys | 1302.02.01

ALLOY BS 1474 (1987)	Si	Fe	Cu	Mn	Mg	Cr	Ni	Zn	Ti	OTHERS EACH	OTHERS TOTAL
6063	0.20-0.60	0.35	0.10	0.10	0.45-0.90	0.10	-	0.10	0.10	0.05	0.15
6063A	0.30-0.60	0.15-0.35	0.10	0.15	0.60-0.90	0.05	-	0.15	0.10	0.05	0.15
6082	0.70-1.30	0.50	0.10	0.40-1.00	0.60-1.20	0.25	-	0.20	0.10	0.05	0.15
6101A	0.30-0.70	0.40	0.05	-	0.40-0.90	-	-	-	-	0.03	0.15
6463	0.20-0.60	0.15	0.20	0.05	0.45-0.90	-	-	0.05	-	0.05	0.15
2014A	0.50-0.90	0.50	3.90-5.00	0.40-1.20	0.20-0.80	0.10	0.40	0.25	0.15-0.20 ◆	0.05	0.15

◆ Ti + Zr

TALAT | Chemical Composition of Some Aluminium Alloys Produced as Extrusions | 1302.02.02

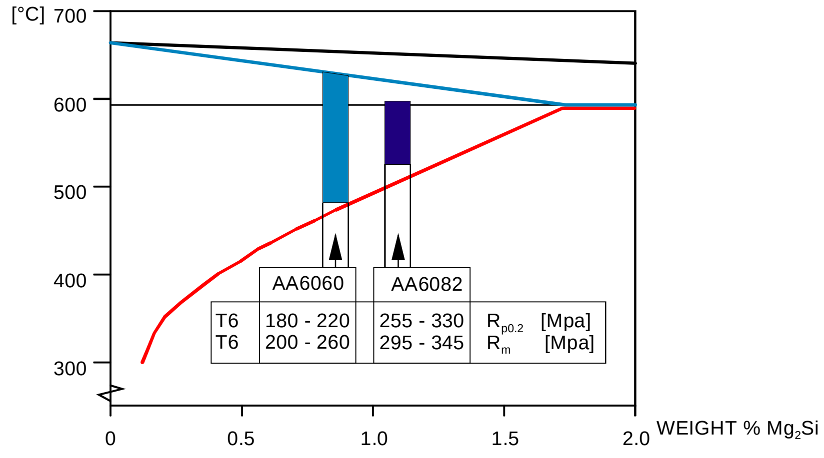
ALLOY	TEMPER	MAX. THICKNESS mm	0.2% PS N/mm^2	ULTIMATE STRENGTH N/mm^2	% ELONGATION $5.65\sqrt{So}$	% ELONGATION 50 mm
6063	F	200	-	100	13	12
	T4	150	70	130	16	14
	T5	25	110	150	8	7
	T6	150	160	195	8	7
6063A	T4	25	90	150	14	12
	T5	25	160	200	8	7
	T6	25	190	230	8	7
6082	F	200	-	110	13	12
	T4	150	120	190	16	14
	T5	6	230	270	-	8
	T6	20	255	295	8	7
6101A	T6	-	170	200	10	8
6463	T4	50	75	125	16	-
	T6	50	160	185	10	-
2014A	T4	20	230	370	11	10
	T6	20	370	435	7	6

So = cross-sectional area

Source: Aluminium Extrusions - a technical design guide, The Shapemakers, UK, 1991

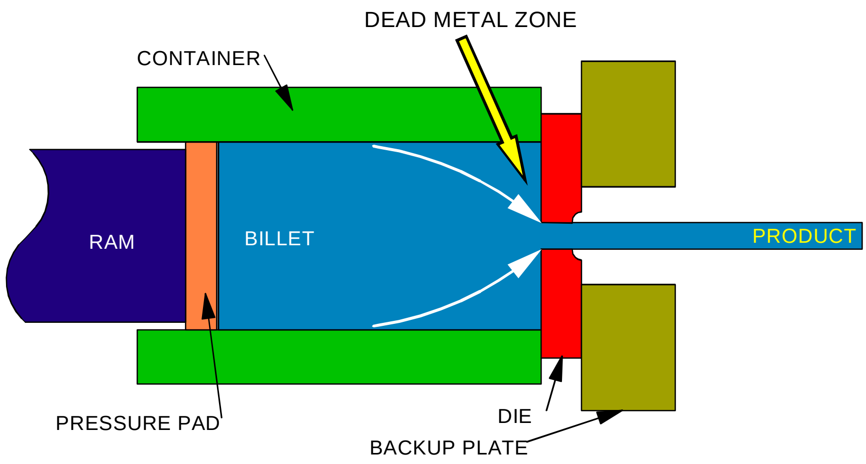
TALAT | Properties of Some Aluminium Alloys Produced as Extrusions | 1302.02.03

A further advantage of the use of 6063/6005A type alloys lies in their attractive response to the thermal treatments required to provide their properties. All of the 6000 series alloys have to be quenched from the "solution heat treatment" temperature in order to achieve their optimum mechanical properties, the critical temperature range depending on the actual composition. Also the cooling rate from the S.H.T. temperature is important. For the 6063 types the range of temperature from which quenching takes place is wide and for most sections cooling in air provides an adequate rate, particularly if forced air cooling is employed. While the stronger, 6082 types can be quenched at the press, i.e. the heat generated in the extrusion process is sufficient to provide S.H.T. the alloys are quench-sensitive and require water cooling for other than thin sections. The gentle rates occurring with air cooling have the added advantage of reducing or avoiding any distortion of the sections (see **Figure 1302.02.04**).



TALAT Training in Aluminium Application Technologies | Phase Diagram for AlMgSi Alloys | 1302.02.04

Metal flow during the extrusion (in forward extrusion) is such that the surface of the extruded product does not derive from the billet surface but is created as a result of shear across a "dead metal zone" (**1302.02.05**). It is, therefore, not necessary to remove the billet cast surface prior to extrusion (in the indirect process there is no dead metal zone and the product surface is created from the billet surface thus requiring that the billet be scalped). At the beginning of the forward process little work has gone into the product and, depending on section size, alloy thickness of section, etc. a portion of the extrusion is cut off as a discard to avoid supplying material with reduced properties. Also care is taken to avoid any back-end defects at the end of the cycle. These effects are well understood and the precautions needed to avoid them affecting material supplied to the user are established.



TALAT | Flow Metal in Direct Extrusion | 1302.02.05

In forward or direct extrusion the ram pressure not only has to deform the metal but also overcome the friction between the billet and the container. With the indirect process the billet and container do not move relative to each other and so all of the available press load is used for deformation. In consequence of these differences indirect extrusion has the following advantages:

Longer billets can be extruded, i.e. for a given extrusion ratio longer sections can be produced.

Higher extrusion ratio can be used.

Extrusion temperatures are lower.

Extrusion speeds are higher.
Uniform metallurgical structure is achieved.

However, since the extruded product has to pass through the hollow stem of the ram the size of the section is restricted. In fact, surprisingly, little use has been made of the indirect process.

1302.03 Literature

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1302.04 List of Figures