Trends in the improving economic use of aluminium

R. T. PARKER

INDUSTRIAL usage of aluminium is increasing at a rate of about 10% every year. Whereas in 1958 the total world production of primary metal was rather less than 4 m short tons, in 1968 it is expected to be over 9 m tons. The principal uses of this metal in selected countries are shown in Table I.

TABLE I Consumption of aluminium by different industries

	(% of total usage) U.S.A.	U.K.	India
Building ...	16	10	3
Electrical ...	13	14	50
Transport ...	25	34	11
Packaging ...	9	9	7
Engineering ...	8	10	2
Domestic and consumer products ...	11	12	18
Miscellaneous ...	8	11	9

The reasons leading to the initial usage of aluminium for any given application are usually either technical or strategic. Considerations of weight, durability, appearance or conductivity may lead to the adoption of aluminium in preference to other materials or, alternatively, shortages of domestic supplies of other materials and of foreign exchange, may dictate the employment of locally produced aluminium.

Nevertheless, once an application is established for technical reasons and is seen to be commercially rewarding, it will inevitably attract competition from other materials. Uses for strategic reasons are also under

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SYNOPSIS

Although aluminium and its alloys are used largely because of their intrinsically attractive mechanical or chemical or physical properties, there is often a need to better the cost factor, particularly when aluminium is in competition with some cheaper materials. The cost of aluminium components can be reduced in a number of ways, for example, by changes in dimensions and weight while still satisfying the same performance requirements, by more efficient use of the mechanical properties of existing alloys through refinements of design procedures, by improved processes of protection and sometimes by radical changes in the design of a component. Examples in these different areas are :

1. *The thickness of roofing sheet has decreased substantially over the years as a result of increased knowledge of the rate of corrosion and of the design of profiled sheet.*
2. *Canning applications provide a striking example of downward trends in dimensions. Twelve years ago beverage cans were being made with weights of 32 gm. Now, similar cans are available at half the weight.*
3. *Al-Mg-Si structural alloys have been standardised and codes of design practices established that enable more efficient and cheaper structures to be designed.*
4. *In electrical power cables, aluminium is already an attractive alternative to copper. However, by departing from the designs established for copper and utilising the properties of aluminium, a cheaper and more efficient cable can be produced.*
5. *Development of welding techniques and weldable alloys has contributed to the more efficient design of road transport vehicles, ships' superstructures and heavy engineering plant.*

Each of the above developments has resulted from a better knowledge of the fundamental properties and behaviour of aluminium gained by research.

pressure, this time from Government sources, to make the best use of indigenous resources. Some examples of aluminium uses which have attracted competition are listed in Table II.

TABLE II Competitors of aluminium

Use	Reason for use	Competition
Electric conductors	Good price/conductivity ratio	Sodium conductors
Windows and building components	Durability	Plastic and plastics-coated steel
Aircraft	High strength/weight ratio	Special steels
Foil packaging	Impermeability	Treated paper

This emphasises the need for efficient design to keep costs to a minimum, even when the application is based on sound technical reasons. The principal ways in which the costs of aluminium construction can be reduced are :

1. Reduction in dimensions and weight

Every design includes a factor of safety to allow for uncertainties of behaviour. The more that is known about the performance of aluminium in service the easier it is to design efficiently without waste of metal. Thus, the accumulation of laboratory data on corrosion, creep, fatigue and other factors will assist designers to economise the use of metal. Another way of decreasing metal weight is the development of stronger alloys with other properties equal to those of the alloys they replace, although the durability of alloys usually decreases as the strength increases.

2. More efficient use of metal

The safety factor used in designing aircraft structures is about 1·2, whereas in engineering structures it is usually 2 to 3. Yet aircraft are just as safe as highway bridges or dragline booms.

The difference lies in the greater testing and more accurate design methods adopted by the aircraft engineers. Similar techniques adopted by structural engineers would lead to more efficient structures and less wastage of metal.

3. Improvements in methods of protection

Designers dealing with problems of deterioration in service can either allow sufficient metal to take care of the deterioration or they can provide some means of protection to prevent it. Aluminium, fortunately, is amenable to a number of protective treatments, such as anodising, lacquering, painting and chemical conversion coating that will preserve both an attractive surface appearance and the underlying metal agaist attack.

4. New concepts in design

Engineers and designers faced with a new material often try to handle it by the same methods of those to which they are accustomed. Thus, early motor-cars strongly resembled horse-drawn carriages and the first cast iron structures were designed with joints of the type used in wooden structures. Similarly, aluminium has often been treated in the same way as the metal it replaces. However, by recognising that it has many special properties such as high formability, extrudability, etc., skilled designers can produce more efficient and therefore more economic structures.

Some examples of how the principles outlined above have been applied in practice are quoted in the following sections :

Corrosion studies applied to roofing sheet and water pipes

The two principal requirements of a roof are that it should provide an impervious covering for the building and that it should resist the natural forces (wind, snow, hail, etc.) to which it is subjected.

Aluminium corrugated sheet has been used for more than 50 years and has given excellent service. However, early experience showed that perforations could develop in certain types of atmosphere and for this reason heavy gauge sheet (0·03 in. to 0·06 in.) was commonly employed. The sheet was formed with semi-circular corrugation of the design previously employed for galvanised steel.

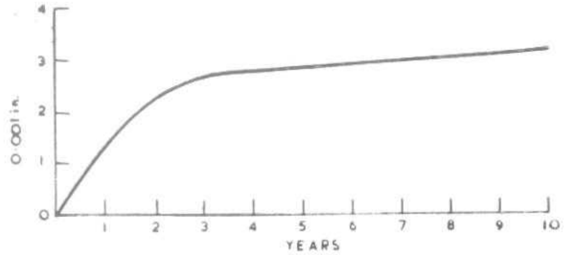
Since the critical factor in leakage through a roof is perforation of the sheet, the pitting behaviour of aluminium in air controls the effective life of roofing sheet, and this is an aspect of the behaviour of aluminium that has been extensively studied. Exposure tests for periods of up to 25 years coupled with laboratory investigation of the mechanism of pitting has shown a relationship between pit depth and time of the form :

$$d = kt^{\frac{1}{3}}$$

where d = pit depth in mils
t = time in years

k is a constant, depending on atmospheric conditions, varying from 1·0 for mild sites to 2·0 for aggressive sites. A typical pitting rate curve for roofing sheet is shown in Figure 1 which indicates that the pitting rate is rapid for the first two to three years and then decreases. After three years, no further significant pitting occurs. By using information of this type the actual thickness of sheet required for a particular environment can be calculated and the roof can be designed efficiently.

The semi-circular corrugated profile commonly employed can be shown by structural analysis to be inefficient, as too much material is located near the neutral axis and not enough at the extremities.



1 *Typical pitting rate curve for aluminium roofing sheet*

New profiles have therefore been developed in which better distribution of metal is obtained, giving greater strength with less weight. Some examples of these profiles are illustrated in Figure 2 and Table III.

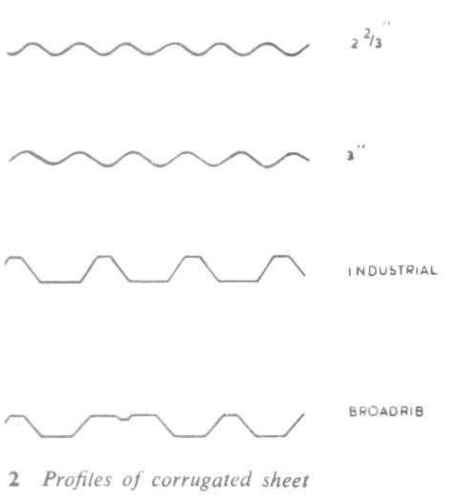
TABLE III Allowable loads for various profiles

Profile	Maximum allowable load lb/sq.ft (based on 22 s.w.g. (0·028 in) sheet with 6 ft purlin spacing, multi-span)
2⅔ in. circular	7
3 in. circular	12
Broadrib	39
Industrial	40

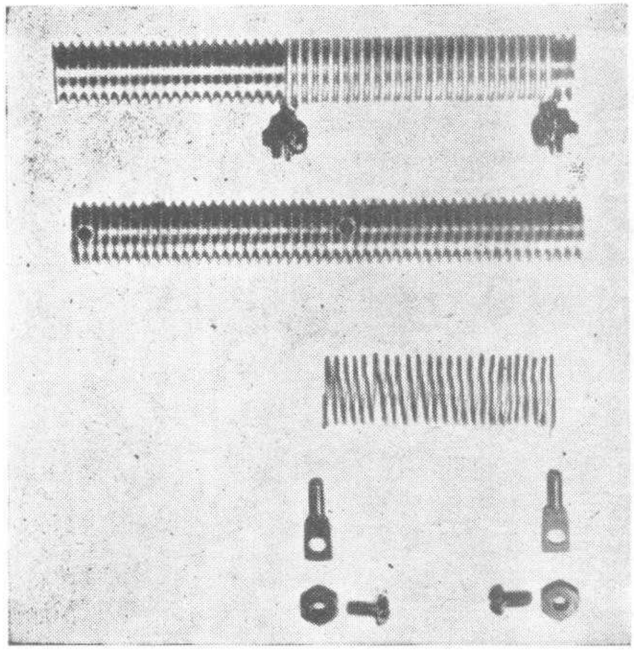
Aluminium pipes and tanks used for natural fresh water must be similarly resistant to pitting attack, but here the problem is more complicated because natural waters vary greatly and have widely varying concentration of impurities.

A laboratory test was carried out[1] in which aluminium was exposed to natural waters from all over the world, and the results analysed by computer. This gave a formula enabling the pitting rate to be calculated for any supply water whose chemical analysis is known. It enables the suitability of aluminium in any water to be investigated and the most economic system to be designed. It can be used to determine the minimum thickness of metal required, or to predict the useful life of a given size of pipe.

Often, a quick answer is required on the suitability of aluminium for service in a given environment and it is not possible to wait several years for the results of exposure tests. To provide usable information in a short space of time a test has been developed[2] by which information on the corrosivity of an atmosphere can be assessed in 90 days. A composite 'wire-on-bolt' specimen, Fig. 3, is weighed before and after the exposure and its loss of weight gives an indication of the type of environment (rural, industrial or marine, or a combination of these) at the site. The bolts are made of aluminium, steel, nylon, copper and zinc, and the wires are of aluminium or zinc.



2 *Profiles of corrugated sheet*



3 *Component parts of wire-on-bolt specimen*

Using structural aluminium efficiently

The efficient use of aluminium in structural applications, which may range from window frames to railway wagons, or from crane jibs to pressure vessels, depends on a proper understanding of all its properties. The mere substitution of aluminium for other materials is seldom satisfactory ; an aluminium structure should be designed as such from the outset.

The chief appeal of aluminium to the structural engineer lies in its high strength-to-weight ratio and in its excellent corrosion resistance. The former property is particularly valuable in transport applications where the metal's light weight minimises the running costs of vehicles and enables greater unit payloads to be carried, and the latter property permits a low general level of maintenance.

The high first cost of aluminium compared, for example, with steel, means that for economy, not only must the metal be used to its full potential, but also that the design must have a high degree of precision. This can be illustrated by experience in recent years in the UK where much attention has been paid to structural design methods. When aluminium began to be used for structures after the Second World War, little or no guidance was available for designers. The Institution of Structural Engineers, therefore, produced in 1950 a 'Report on the structural use of aluminium alloys'. This was followed in 1962 by a second edition of the Report, and now a Code of Practice on Structural Aluminium Design is about to be issued by the British Standards Institution.

In the period covered by these three documents, the knowledge of aluminium design has increased noticeably, as a result of practical experience and of laboratory research. Two good examples of this increase in knowledge are provided by the treatment given to welding and fatigue in the three publications and compared as follows :

	1950	1962	1969
Welding of aluminium structures	Not recommended	Permitted in certain cases	Comprehensive design instructions given
Design against fatigue	Attention drawn to dangers of fatigue	Further information given, but no design stress quoted	Recommended working stresses specified

Designers working to the new Code of Practice will be able to design much more economic structures with no sacrifice of safety. Indeed, because the conditions giving rise to failure are so much better understood, modern structures should be safer than those designed when information was not so precise.

The general aim should be to produce the cheapest structure which will just be adeqaute for its intended purpose. Marginal savings are important with an expensive material, but a too-precise design may defeat its own purpose by increasing the cost of fabrication. It is therefore necessary to balance these two factors carefully to determine whether or not a particular refinement is justified. The saving of a few pounds weight is economical in an aircraft, but may not be in a roof truss.

Choice of alloy is clearly important—roughly speaking, the stronger an alloy, the higher its price. A lower strength alloy which is more readily weldable or has exceptionally good corrosion resistance to a certain environment may be more economical in the long run. Likewise there may be no point in using a high-strength alloy for a fabricated structure which will fail by elastic instability because since the modulus of elasticity of all aluminium alloys is sensibly the same the design criteria are predominantly geometrical under those conditions. Also when fatigue is concerned the design of the component, rather than its strength, will be the controlling factor.

Aluminium electrical conductors

The high conductivity and low weight of aluminium have made it an attractive material for the electrical engineer ever since it became available in quantity at the end of the nineteenth century. Its successful application in the three main fields of use—overhead line conductors, underground insulated cable and transformer windings—depended however, on an appreciation of its limitations as well as its advantages and the adoption of design principles that compensated for these limitations.

In most conductor applications, the competing material is copper, which in many ways is almost the perfect material for the purpose. It has high strength, high conductivity and good ductility. Its main disadvantages are : fluctuating price structures and occurrence in only a few countries.

Aluminium has lower strength and lower conductivity than copper, but a more stable price structure and widespread availability, which, combined with its good strength/weight ratio, make it the logical choice for many electrical engineering applications.

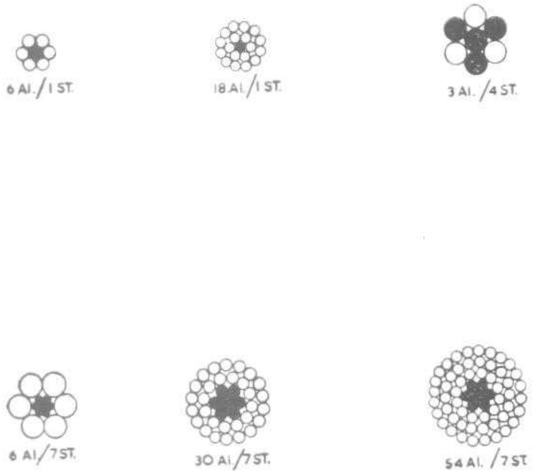
The principal properties of aluminium and copper are compared in Table IV together with those of a stronger aluminium alloy, also widely used in the electrical industry.

TABLE IV Properties of aluminium and copper

	Aluminium 99·5%	Aluminium alloy D50S Al-$\frac{5}{8}$% Mg, $\frac{1}{2}$% Si	Copper
Density g/cc	2·70	2·70	8·89
Tensile strength tons/sq. in.	4	13	16
Young's modulus(10^6 p.s.i.)	10·0	9·5	16
Resistivity (microhm-cm)	2·83	3·13	1·72
Melting point °C	659	659	1083
Specific heat	0·23	0·23	0·092

Overhead conductors

The cost of an overhead system lies as much in the towers, insulators and other supporting equipment as



4 *Typical strandings of bare A.C.S.R.*

in the conductors themselves. Thus the prime requirement of the conductor is high strength/weight ratio so that the towers can be spaced widely apart. The classical solution to this problem, which has been in use almost unchanged for about 60 years, is a composite conductor of high conductivity aluminium wires surrounding a core of high tensile steel wires. The combination gives the required strength and conductivity at a lower cost than can be achieved in any other way. Another benefit of this type of construction is that the aluminium/steel ratio can be varied within wide limits to change the mechanical properties of the conductor (Fig. 4).

Underground cable

The earliest insulated cables were rigid bars or tubes of copper supported in ducts, but installation difficulties and the need for a more flexible construction soon led to the adoption of stranded conductors built up from a number of wires. This enabled the cables to be bent round corners during installation. Early aluminium cables were copies of this copper construction and the conductor consisted of a number of aluminium wires stranded together into a sector-shaped conductor. Because the aluminium had a lower conductivity, the cable was larger than its copper equivalent by about 20% and this sometimes led to difficulties in installing the cable in the ducts used for the smaller copper cable.

Analysis of the problem led to the conclusion that stranding of the aluminium conductors was not always essential for reasons of flexibility, particularly in the smaller sizes of cable. Experiments with solid-sector cables, or "solidal" soon demonstrated that such cables had adequate flexibility and overall size almost the same as their copper equivalents. In addition, because no wire drawing and stranding were required and because the amount of insulation used was reduced, the cost of the cable could be less than that of the stranded type of cable. Solidal cables are now commonplace in distribution systems (Fig. 5), although

5 *Installing solidal cable at Parma, Italy*

much early opposition had to be overcome from engineers who found difficulty in accepting that a solid cable could be easily handled.

Transformer windings

The problem in introducing aluminium into transformer windings is probably the most difficult of all, because of space limitations imposed by the magnetic circuit. The coil of conductors has to fit into a hole or 'window' in the iron laminations originally designed for copper conductors. Any increase in the size of the window will lead to increased cost and decreased efficiency. The problem has been solved by replacing a multilayer coil of round wires with a winding of flat aluminium strip or foil interleaved with insulation (Fig. 6). Because there is no waste air space in the coil, as there is with round wires, the strip coil can occupy the same window space as the copper equivalent ; with round aluminium wires, this would not be possible.

An interesting feature of this type of construction is that transformers made with aluminium coils were subsequently found to have technical advantages arising from the use of flat strip. In particular, their behaviour under impulse conditions is superior. The implication here is that the proper approach to design is to establish the properties required from the finished component and then develop material to meet these requirements. This is in contrast to the conventional approach, which is to take existing material (in this case copper wire and steel laminations) and build the best possible component using them. Wide-strip coils for transformers are now common in North America and are becoming increasingly used in Europe and the U.K. Automatic winding machinery has been developed which enables coils of this type to be made at high speed.

Development of welding techniques and weldable alloys

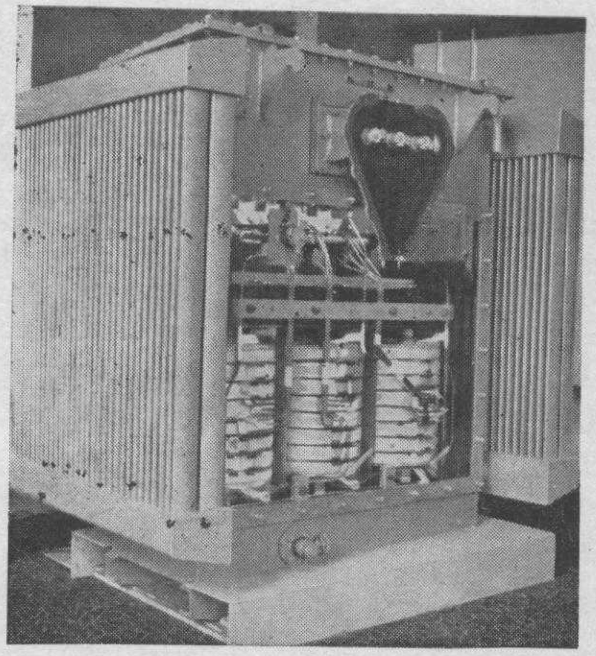
Thirty years ago aluminium was virtually unweldable. The only process used was the slow, expensive and often unreliable gas welding technique and this limited the expansion of aluminium into the structural and heavy engineering fields. The introduction of shrouded-arc welding and using argon or helium gas changed this situation radically and showed that welded aluminium structures were technically feasible.

However, two major difficulties became apparent as the uses of welding developed commercially. The first was that the hand-operated tungsten arc processes were slow, and therefore expensive, and they required a great deal of skill on the part of the operator. Secondly, metallurgical problems arose from the heating effect of the welding arc. This caused local annealing and loss of strength near the weld and also gave rise to corrosion hazards.

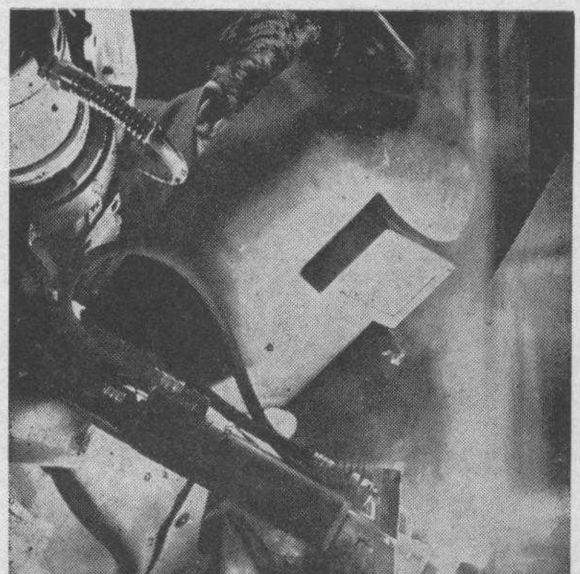
Laboratory research on the welding of aluminium was therefore directed towards the development of faster and more automatic welding techniques and to the evolution of alloys and filler materials that were less sensitive to the effect of weld heat.

Welding processes

The original tungsten arc (TIG) welding method applied an arc to the workpiece through a non-consumable tungsten electrode, with separate filler wire being fed in manually. The first development from this process was MIG welding in which the electrode and filler wire were combined in a single wire passing down the centre of the welding torch. This increased the rate of metal transfer and enabled welding in thicker grades of material to be carried out two or three times faster than with TIG welding. Nevertheless, the process was still a manual one and required a fair degree of skill from the operator. The need for mechanised welding became apparent when aluminium plate $\frac{1}{2}$ in. to 2 in. thick was being considered for ships, superstructures and this problem was solved by mounting MIG torches on travelling carriages and redesigning the equipment and techniques so that much heavier welding currents could be used. Such automatic processes only worked in the horizontal position and could not be used for site welding in the construction industry, for example, in atomic energy plant. Laboratory investigation of the problems in positional welding led to the development of mechanised vertical welding techniques in which the weld bead is contained by a graphite mould while it is still liquid (Fig. 7). Thus,



6 *500 kVA transformer with aluminium strip windings*



7 *Mechanised vertical MIG welding with graphite shoe to control weld bead*

8 *Aluminium beer can*

site welding can now be carried out with completely mechanised equipment giving more consistent and often cheaper welds. The same principles are also being applied to the development of mass-production welding techniques for thinner material.

Development of alloys

One of the early discoveries in welding aluminium was that the composition of the filler alloy played a critical part in obtaining sound welds and in ensuring satisfactory service behaviour. Much research has been devoted, therefore, to the design of filler materials that are compatible with the parent metal and which give the minimum loss of properties in the welded zone.

Loss of strength after welding is a major problem in designing efficient welded structures, because the metal adjacent to the weld bead is virtually in the annealed condition. Much effort has gone into the evolution of naturally age-hardening Al-Zn-Mg alloys of low quench-sensitivity which are solution heat treated by the welding heat. The welds then self-harden over a period of about four weeks to a strength almost that of the parent metal. Many incidental problems had to be overcome, principally one of susceptibility to stress corrosion, but satisfactory welded structures of high strength can now be produced. Alloys of this system are now being employed for welded military bridges, dump trucks, cranes, etc.

The development of the aluminium beer can

The first metal beer cans (Fig. 8) resembled bottles in shape and could be filled on bottle filling lines. The aluminium version consisted of an impact extruded body with a seamed-on base ; the neck of the body was machined to permit the use of standard bottle crowns for sealing. The body-plus-base weight for this type of can, for 12 imp. fluid oz. capacity, was 50–60 gm. The disadvantages of this form of can were primarily its cost, but also difficulty in stacking and the excessive amount of space required to stack a number of cans within a refrigerator.

As standard can-filling machines became available and were installed by the breweries, a 2-piece design of aluminium can was introduced. This consisted of a closed-end impact extruded container, with parallel side walls integral with the base. The lid was concave, and seamed onto the can body. The body was in 2S, weighing around 36 gm (a later version in 3S weighed 32 gm), and the concave lid in M57S, weighing approximately 9 gm.

The concave ends used on these cans often give rise to violent release of the contents, know as 'gushers' when opened by claw-type openers. This led to the development of flat ends in stronger materials. These were so successful that at least one U.S. brewery fitted one of them on each tinplate can for easier opening, and called them 'soft tops'.

Up to this time brewers had demanded that aluminium cans should be suitable for use in the same filling equipment as used for tinplate cans, or if modifications were necessary, these should be of a minor nature. Aluminium cans capable of being used on the tinplate filling lines were not competitive in price because of the higher cost of the basic material, and sales promotion had to be based on their better appearance and improved beer-keeping characteristics. However, a change of outlook began to take place in the U.S., chiefly as a result of one brewery becoming involved directly in the production of cans ; once the principle of special filling equipment for aluminium cans had been established there were increased efforts to make lighter cans that were mechanically adequate yet also competitive in price. Several cans appeared on the market as a result of these efforts, with body weights well below the 32 gm which were the lightest produced by the earlier method when using special alloys.

Impact extrusion followed by ironing (wall-thinning) was the technique responsible for some of the lighter cans ; using 3S alloy the can body weight was reduced from 32 to 21 gm. The simple impact extruded can had a wall thickness of approximately 0·012 in., while the impact extruded and ironed can had a wall thickness of 0·008 in. Although the wall-thinning accounted for the major part of the weight reduction, an improved base form made an important contribution.

Even lighter cans were produced by ironing cups drawn from stronger alloy sheet in intermediate tempers. These cans had a body weight of as little as 16 gm with a wall thickness of 0·006 in.

During the lightening of the can bodies a parallel development occurred with beer can ends. In 1962 an aluminium end was developed with a score line enclosing a keyhole-shape panel with a tab attached by a rivet formed in the material of the end itself. This type of aluminium end, after many minor modifications, is now being used in many countries both on tinplate and aluminium can bodies. The alloys used are of the Al-Mg-Mn type, i.e. 5082, 5086, E54S or 5182, and give an overall weight for the end and tab of 6–6½ gm.

Recent reports indicate that the limit in lightweight cans has not yet been reached, and body weights of 13·5 gm and 12·2 gm have been mentioned as possible, by using material with a higher starting temper, and or by using stronger alloys. Other recent developments have resulted in a can necked-in at the mouth so that the seam does not overhang the wall. This has been adopted to overcome a handling problem experienced during filling the cans, but it also marginally reduces the weight of the end.

Conclusion

These illustrations taken from a wide range of aluminium applications, all point to the same conclusion : that mere substitution of one material for another rarely gives continuing satisfactory results. The initial substitution must be accompanied by a study of the new material and its properties, so that efficiency of design can be obtained in the shortest space of time. Fortunately, aluminium has been the subject of continuous research in many countries for many years and a wealth of useful information is available to the designer wishing to use this metal.

References

1. Pathak, B. R. and Godard, H. P. : *Nature* **215**, 1 June 1968. pp. 893, 894.
2. Doyle, D. P. and Godard, H. P. : *Nature* **200**, 21 December 1963, pp. 1167, 1168.

Discussions

Mr **V. P. Agarwal** (Rourkela Steel Plant, Rourkela) : How does the aluminium can compare with the conventional "tin cans" from the economic point of view ?

Dr. **R. T. Parker** (Author) : In many countries aluminium cans will be more expensive than tinplate cans. The only exceptions are likely to occur in countries which have to import tinplate, but have domestic supplies of aluminium. In other countries the price difference will depend on the relative costs of aluminium and tinplate, the weight of each metal in the container and the rates of production.

In many western countries the packaging industry is willing to pay a slight premium for aluminium containers because of other advantages which accrue. Some of these advantages are : easier opening of the cans, increased shelf life and freedom from corrosion and the possibility of all-round decoration of the container.

Mr. **S. K. Sanyal** (Defence Research Laboratory, Kanpur) : What are the conditions of exposure for determining the IPI of Aluminium and were they bare panels or coated ?

Dr. **R. T. Parker** : Outside exposure test of aluminium in various atmospheres is carried out by exposing small panels about 8 in. × 8 in. mounted on racks at 45°C. If the object is to determine the exposure behaviour of bare aluminium then of course the panels are uncoated but similar tests are carried out on painted and anodised panels to determine the degree of protection afforded by such coatings.

Mr. **L. J. Balasundaram** (National Metallurgical Laboratory) : Dr. Parker mentioned that sodium is replacing aluminium. I would like to know in what applications sodium is replacing aluminium and in what form it is used.

Mr. **Devendra Sahai** (Bhilai Steel Plant, Bhilai) : Dr. Parker has mentioned in his paper that sodium may replace aluminium as electric conductor. Of course, aside from abundance and ease of production the outstanding economic characteristic of sodium is its low cost. Its conductivity of about a third that of copper is more than compensated by an 8 to 1 advantage in density. I would like to know from the author if sodium conductors have been used anywhere in England and how inherent weaknesses such as reactivity are overcome.

There is another modern use of sodium based on its good thermal conductivity. Since sodium neither captures nor slows down neutrons readily, it is the most heavily favoured coolent for the coming generation of fast breeder power reactor.

Dr. **R. T. Parker** : Sodium has been used commercially for feeder cables in the U. S. A. The metallic sodium is extruded into a plastic sheath to give a single core cable. Special connecting devices are of course required. The usage at the moment is quite small and sodium is not expected to capture a major share of the cable market in the U. S. A. In the U.K. there is no commercial use of sodium cable, but tests are being carried out in various laboratories. The distribution system in the U. K. is different to that in the U. S. A. and makes much greater use of multi-core cables ; it does not seem likely that sodium will be suitable for cables of this type.

Sodium, as Mr. Sahai points out, is a very reactive metal and must not be allowed to come into contact with the atmosphere. For this reason special manufacturing techniques for cables are necessary, by which the sodium is extruded into plastic tubes in the absence of air.