The technical and economic advantages of lightweight aluminium alloy wheels

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Abstract
Lightweight aluminium alloy rolled wheels are compared with aluminium alloy cast wheels. Rolled wheels offer advantages of technical and economic nature that make them worthy of consideration with a view to their use also for mass production cars.

Riassunto
È proposto un confronto fra ruote leggere in lega leggera rullate e ruote in lega leggera fuse. Le ruote rullate presentano rispetto a queste ultime vantaggi di natura tecnica ed economica: è quindi prevedibile che anche per le autovetture di grande produzione, le ruote rullate in lega leggera potranno trovare ampio campo di impiego.

Introduction

Over the last twenty years, development of the automobile has been marked by one particular aim — energy saving — that at one stage was accorded top priority, and still ranks high on the list of objectives (1, 2, 3).
The need to cut back fuel consumption has spurred a weight-shedding process that is still in full swing. When the economic wind is blowing in this direction, steps are taken to replace steel by lighter materials or employ high-strength steels, which can therefore be thinner (4).

Plastic, composite materials and aluminium alloys have been to the fore in this weight reduction policy.

Each replacement of a material by another involves the adoption of new design criteria and new manufacturing methods. Since its underlying motive is a need to save, it offers the designer a chance to undertake a critical review of the components that make up a vehicle. It may even spur him to rethink the layout of the vehicle system as a whole.

It will often be found, however, that replacements which appear to be advantageous at first sight turn out to be inapplicable under current manufacturing conditions. By the same token, closer examination may show that changes that appear to be disadvatageous when first considered are in fact beneficial. An example of this second category will be described in this note. Owing to the high energy expenditure needed for the production of aluminium, indeed, the use of aluminium alloys in the place of steel would seem devoid of appeal, at all events as an economic proposition. An analysis of what has been produced so far, in fact, could well lead one to the conclusion that, assuming the same reliability is obtained, wheels cast in aluminium alloy offer no more than a very slight saving in weight when compared with conventional wheels made of steel. Often, indeed, cast aluminium wheels designed more with an eye to satisfying the whims of taste than in keeping with at least a general understanding of the actual stresses involved may even be heavier than steel wheels, and sometimes of doubtful reliability as well. On an average therefore, it can be stated that little more than a bare 5-10% weight saving can be expected (8).

New manufacturing procedures, however, are now opening up the prospect of achieving appreciable economic and technical advantages with regard to both sheet steel wheels and cast light-alloy wheels.

Processes for the production of aluminium alloy wheels

Nearly all alluminium alloy wheels are currently made in a single piece by gravity permanent-mould casting, low-pressure casting and pressure die casting. These processes result in wheels with plenty of aesthetic appeal, since the production methods involved place few constraints on the designer, but by no means excellent in terms of function. The particular drawbacks include: considerable thickness, high weight (generally not much less than that of steel wheels, and sometimes even more (5,8)), many rejects, relatively poor toughness and production rhythms that are usually on the low side.
Better mechanical characteristics can be obtained by

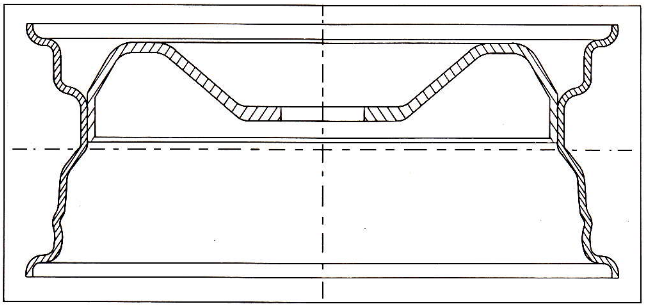


Fig. 1 - Wheel produced by an extruded rim welded to a pressed disc.

plastic deforming: monobloc wheels can be made by pressing and hot forming, or by rolling with fissuring of the cylindrical surface of a disc.
The process used for manufacturing light-alloy wheels in the United States is directly derived from that employed for steel wheels: the rim and the disc are both produced from aluminium alloy sheets at least double the thickness of the corresponding steel sheet.

Processes more advantageous than those referred to above are available for making non-monobloc aluminium alloy wheels. A method recently perfected in the Federal Republic of Germany (Fig. 1) uses extruded profiles to create the rim: these are curved and welded at their ends. They are also welded to the disc, which is formed by pressing or in some other way.

A process devised in Italy allows a uniform rim with no join welds to be made, by roll-shaping an extruded tube. This rim is then welded to a disc made by pressure die casting, or in some other way. The origin of this process lies in the results obtained in preliminary research conducted as part of the Italian National Research Council's purpose-oriented "Transport" project (7).

The advantages are considerable. The rim is in one piece, since it does not have a join likely to be responsible for mechanical discontinuity and small surface defects affecting the airtightness of tubeless tyres.
The new Italian process comprises two stages: preshaping and sizing. During the shaping stage, a deforming roll idling around an axis parallel to that of the tube presses it against the spindle and draws it along its axis, so as to make it take the shape of the spindle.

Sizing is done by pressing the tube against the spindle simultaneously across the full width of the channel by means of a suitable profiled tool. NC machines now in the course of completion will permit an output of over 100 wheels per hour.

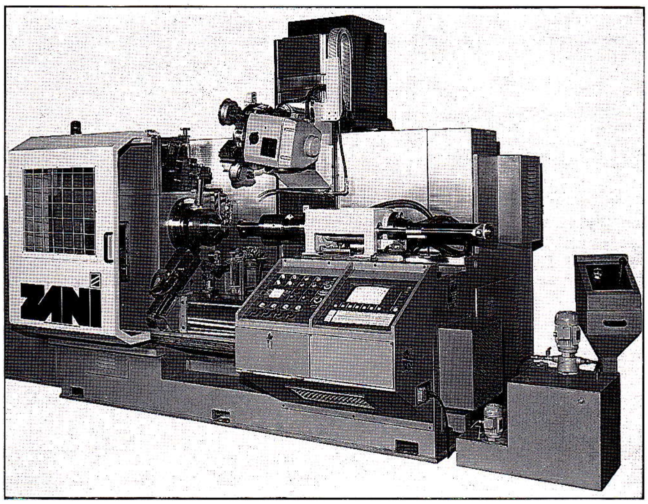


Fig. 2 - Equipement for production of rolled aluminium wheels.

Light aluminium wheels and energy saving

As we have seen, fuel saving has provided an incentive for the continuing efforts to reduce the weight of road vehicles. It has been calculated that a weight reduction of 1 kg will yield an average saving in petrol of 5 to 8 litres during an automobile life of about 100,000 kilometres (1,4).

In addition, mathematical models designed to reflect average running conditions (a mix of motorway, country and urban cycle driving) and current propulsion technologies (engines and transmissions) indicate that a 2% reduction in vehicle mass is equivalent to a 1% reduction in fuel consumption.
A greater saving is obviously possible the further one moves away from a state of uniform motion. Every braking action, in fact, results in the irreversible conversion of kinetic energy into degraded thermal energy.

Weight reductions are often impeded by their imposition of higher costs. On the other hand, new design solutions can bring these costs down to acceptable levels. At the same, a reduction in weight can itself be accompanied by lower overall costs, as when several functions are combined in a single component or assembly costs are lowered.

A vehicle's weight is primarily reduced by the employment of plastics and, to a lesser extent, aluminium. Over the last ten years, there has been a more marked increase in the use of aluminium alloys in the United States than in Europe, particularly through

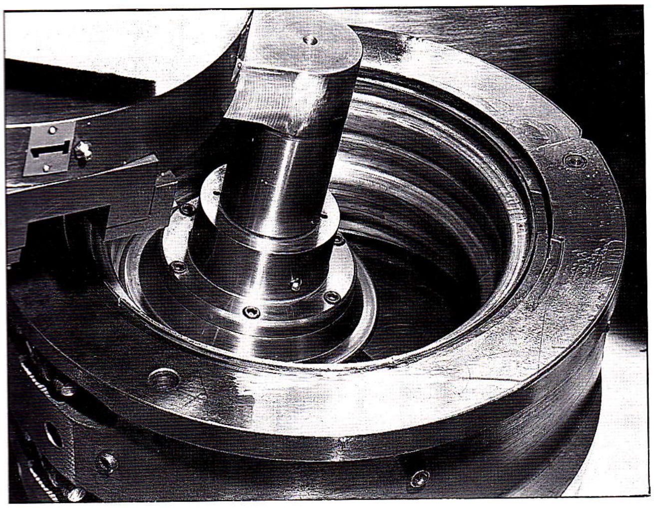


Fig. 3 - Detail of an equipment for production of rolled aluminium wheels.

their adoption for cylinder heads and gearboxes, i.e. parts that have been almost always made of aluminium in Europe for many years.

In the case of wheels, however, some 90% are still made of steel and somewhat over 10% in light alloys (5), nearly all of which are single-piece castings. Innovative deformation processes are likely to replace casting and secure alloy wheels a higher percentage of the market.
Let us now take a look at the balance between the energy expended to make a light-alloy wheel and that saved through weight reductions when light aluminium wheels are used instead of single-piece cast wheels.

It needs 18 kWh of electricity to produce 1 kg of primary aluminium, taking a figure of 0.4 as the efficiency of the process of converting thermal energy into electricity.
In the case of petrol, these 18 kWh correspond to 4.8 litres. In addition, since 50% of the initial raw material can be a primary alloy, and since account can be taken of the recycling of the wheel as scrap at the end of its working life, it can be assumed that the energy used to produce 1 kg of the alloy used in the wheel will correspond to not more than 2.5 l petrol equivalent.

The saving of material obtainable when a rim is made by plastic deformation and the disc is inserted is of the order of 50% (8).

It should be noted that the energy saving derived from driving with a lighter rim is greater than that estimated (and subsequently proved by experience) for reduction of the translating masses alone. A wheel is a feature of the vehicle's energy balance both as a translating member and as a revolving member on account of its moment of inertia.
A conservative estimate that the reduction in mass from 7.2 to 3.6 kg) is equally shared by the rim and the disc, and that the kinetic energy of revolution is about 60% of that of translation, allows the total petrol equivalent saving to be worked out as:
$5 \text{ to } 8 \times (3.6 + 1.8 \times 0.6) = 23.4 \text{ to } 37.4$ litres.
The difference between the casting energy and the mechanical energy needed for plastic deformation is insignificant.

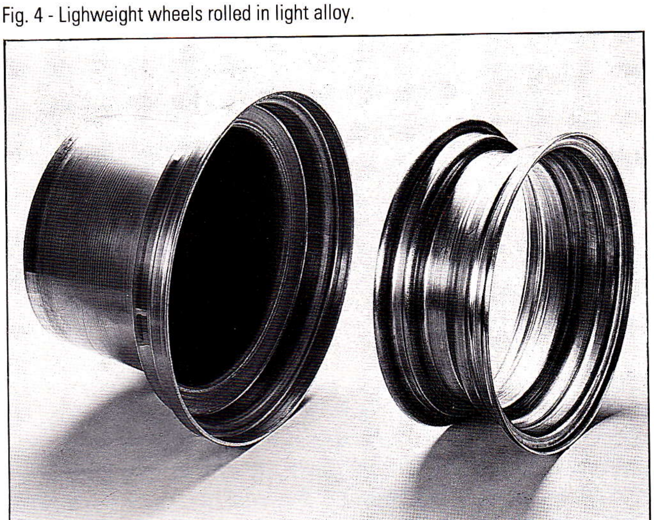
Summing up, therefore, the changeover from a single-piece cast wheel (mass 7.2 kg) to one made by plastic deformation of the channel leads to a saving of 3.6 kg of alloy, corresponding to $3.6 \times 2.5 = 9$ litres of petrol equivalent. To this must be added the 23.4 to 37.4 litres saved during operation.

Leaving aside the contribution of the central wheel disc, which is also endowed with rotational energy, it can be asserted that the energy saving ranges from 32 to about 45 litres of petrol per wheel.
The energy saving stemming from the replacement of five single-piece cast wheels with wheels manufactured by innovative processes in thus of the order of 150 litres.

The economic advantages offered by rolled wheels

There are several reasons why fabrication a single-piece cast wheel can be more expensive than that of a

Fig. 4 - Lighweight wheels rolled in light alloy.



turned tube wheel or one rolled from an extruded section:

1. The mass of a single-piece is about twice that of wheel made by rolling the channel on the lathe. The difference in cost of the raw material alone is of the order of L. 4200 per kg × 3.6 = Lire 15,000 per wheel.
2. Manufacturing rejects are greater in number in the case of single-piece cast wheels, since the casting process is more difficult to control than plastic deformation.
3. The machining offcuts and finishing costs associated with rolled wheels are virtually negligible.
4. Rolling can be used to create a variety of shapes. It also permits modularity of the production and pairing of the central disc and the channel. These two factors result in a wider range of better designed wheels.

The advantages of light wheels with regard to vehicle vibrational behaviour

The advantages conferred by light wheels are not limited to the substantial energy saving achieved in the course of their production and employment.

Equally and perhaps even more important, as well as being immediately noticeable when the vehicle is on the road, is the improvement in its dynamic (vibratory) behaviour.

In the case of a car, the ratio between the suspended mass resting on each wheel and the non-suspended mass (i.e. the wheels themselves, the suspensions, brakes, etc.) is between 15 and 4. This ratio has a substantial influence on the vibration pattern (9), since unevennesses in the shape of the road cause vibrations that influence a vehicle's roadholding and comfort.

Roadholding can be assessed by considering the value of the standard deviation of the dynamic load exchanged between the wheels and the road. If this is more than a third of the static load, there may be a loss of contact between the wheel and the road, assuming a Gaussian distribution of the statistical process used to define the irregularity of the road.

Roadholding, as defined in this preliminary fashion, obviously has a decisive influence on the transmissibility of the tangential forces (longitudinal traction and braking forces, and lateral forces) of the tyre, this being influenced by the vertical forces present from one instant to the next.

A 20% reduction in the non-suspended mass of an average sized vehicle on a mediocre road with average-sized irregularities during a journey at an average speed will result in an approximately 5% improvement in roadholding (i.e. in the standard deviation of the dynamic load). It should be noted that this improvement is by no means negligible, since application of the same parameter shows that the roadholding of a vehicle with optimised active suspension is in any event no more than 15% compared with that of the same vehicle with optimised passive suspension (10).

The vibrational comfort of a vehicle driven over poor roads is influenced by the magnitude of its non-suspended mass. For example, a 20% reduction of this mass leads to a 10% improvement in the level of comfort (evaluated as the acceleration of the suspended mass, weighed in accordance with ISO standard 2631). In practical terms, an average-sized car travelling at 20 m/s on a road surface with average unevenness will be able to cover another 100 km (470 km instead of 370 km) with the same level of passenger fatigue when its non-suspended mass is reduced by 20%.

Opinions differ, on the other hand, with regard to excellent roads. Indeed, there are some who consider that in this case the suspended: non-suspended mass ratio has very little influence on roadholding and/or comfort (10).

Other technological aspects of lightweight aluminium alloy wheels

Reduction of the weight of steel sheet wheels runs up against objective barriers posed by instability of the elastic equilibrium, a problem that becomes virtually unsurmontable below certain thickness values. Little benefit can be gained, therefore, from the use of high-strength steels in the manufacture of car wheels.

An interesting feature of aluminium alloys is their high thermal conductivity. Some recent wheels have been made with larger interiors so as to get the best advantage out of the characteristics of very low profile tyres (12) by greatly increasing the heat exchange surface with the surrounding environment as well.

The increased use of salts (especially chlorides) during the winter may be prejudicial to steel wheels, whereas those in aluminium alloys have a much higher resistance to corrosion.
The adoption of composite materials is not yet a current proposition. There are, indeed, several problems connected with their possible use in the future.

Alongside the advantages listed here offered by wheels made by rolling, mention must be made of a metallurgical and technological problem for which an answer is still awaited. Finished wheels may undergo a slight dimensional settlement when too much time elapses between extrusion of the tube and the rolling operation.

Conclusions

Processes whereby light wheels for cars are formed by rolling recently perfected both in Italy and abroad (7, 8) offer advantages of a technical, energy and economic nature that make them worthy of incentivation and consideration with a view to the construction of such wheels for mass-produced vehicles as well.

Cast light-alloy wheels made as a single piece at present hold about 10% of the market. This is indeed a high incidence, since their weight in the best of cases is only slightly less than that of steel wheels, while their cost is considerably higher.

Light-alloy wheels manufactured by plastic deformation (turning of an extruded tube or rolling of a channel section), on the other hand, weigh about half much as cast single-piece wheels and less than half of steel wheels. They permit energy savings at the manufacturing level as well as during use. Being lighter, they provide better roadholding, and make driving safer and more comfortable. They have a much better resistance to corrosion than steel wheels and can be created in a wider variety of shapes.

In view of these considerations, it may reasonably be predicted that automakers will tend to replace single-piece cast wheels by rolled wheels, not only on up-market vehicles, but also those that are mass-produced. Promising developments can also be envisaged for motor-cycles and commercial and industrial vehicles.

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