5 – Design Examples

Redesigning the Wheel

Rotating parts of plastics – gears, pulleys, rollers, cams, dials, etc. – have long been a mainstay of industry. It is only recently that the design potential of plastics has been considered for larger rotating parts such as bicycle, motorcycle and even automobile wheels. Since the type of loading may be substantially different, it seems appropriate to review some of the considerations which must be taken into account when designing a wheel in plastic – particularly in the rim and web or spoke area.

Web and Spoke Design

From a moulder's viewpoint, the ideal wheel would have a constant wall thickness throughout to facilitate filling and to provide uniform cooling in the mould. In place of spokes, the area between the hub and the rim would be a solid web to provide symmetrical resin flow to the rim and to perclude weld lines at the rim. Actually, wheels of this sort have found commercial application, though with slight modifications for structural improvement.

The wheel and the pulley shown in Fig. 5.01 typify this type of design. The 114 mm diameter pulley of DELRIN® acetal resin replaces a die cast part at a lower cost and weight.

While the web is solid, axial stability is provided by the corrugated surface. This web form was chosen over radial ribbing because it does not produce the heavy wall developed by ribbing (Fig. 5.02) and the resultant differential in radial shrinkage, nor is there as great a possibility of air entrapment during moulding.

When spokes are necessary – where side wind loading is critical or minimum surface area is desired – care should be taken in specifying the number of spokes and the wall thickness and in designing the juncture of the spokes with rim and hub. The greater the number of spokes the better. For example, if five spokes with a wall thickness twice that of the hub and rim were used, differential shrinkage could lead to out-of-roundness at the rim. On the other hand, ten spokes of the same wall thickness would provide the structure required as well as uniform shrinkage.

Also, the smaller the distance between spokes at the rim, the less the variation in rim rigidity as it rotates. Since the deflection of the rim will vary as the cube of the distance between the spoke support points, doubling the number of spokes will reduce the deflection by a factor of eight for a given rim cross section. The wall thickness of the spoke should be constant between the hub and rim to provide balanced cooling. Ribbing for axial reinforcements should be added to the edges of the spokes for minimum change in wall section (Fig. 5.03).

Spokes should be contoured into the hub and rim to improve flow in moulding and reduce stress concentration at the juncture. This is particularly important at the rim as such contouring will reinforce the rim, thus reducing deflection under load.
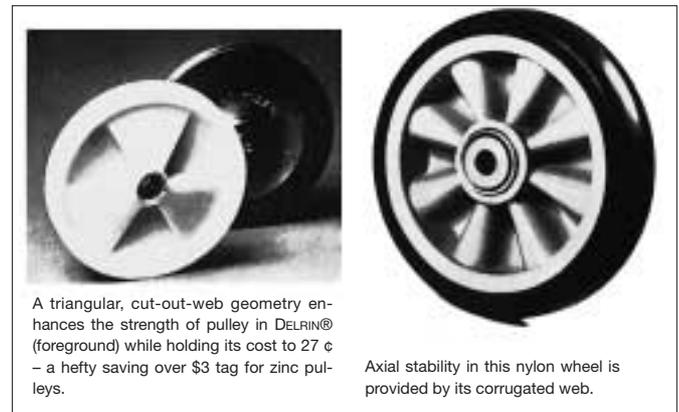

A triangular, cut-out-web geometry enhances the strength of pulley in DELRIN® (foreground) while holding its cost to 27 ¢ – a hefty saving over $3 tag for zinc pulleys.

Axial stability in this nylon wheel is provided by its corrugated web.

Fig. 5.01   **Typical web design for plastic wheels**

Usual rib design with large increase in wall thickness at intersection.

Staggered rib design with small increase in wall thickness at intersection.

Corrugated rib design with minimum increase in wall thickness.
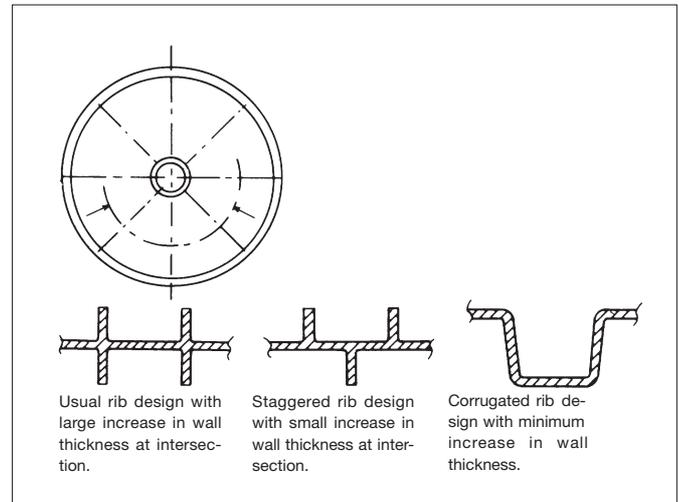
Fig. 5.02   **Wheel design with ribs versus web**
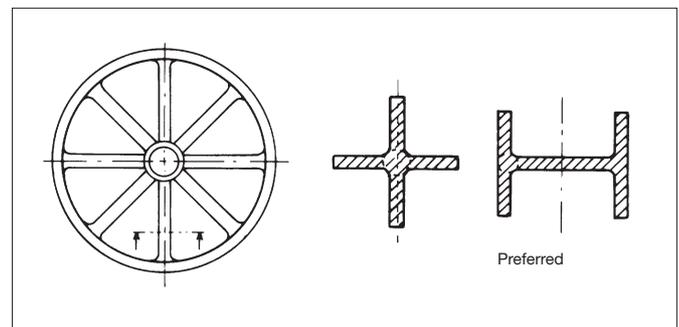

Preferred

Fig. 5.03   **Design of wheel spokes**

Rim Design

Rim design requirements will vary depending upon whether or not a tire is used and whether the tire is solid or pneumatic.

Tireless wheels are frequently used on material handling equipment where vibration and noise are not critical.

Impact resistance is of prime importance in this type of service, and rims are frequently moulded with wall thickness up to 9,5 mm. The lengthened moulding cycle can increase processing costs to a point where it can be more economical to mould a wheel in a thinner wall and – using the wheels as an insert – mould an elastomeric tire around it.

If a pneumatic tire is used, the rim will be under constant pressure and the effect of creep on rim geometry must be taken into account. It can be shown that the outward force exerted on the rim is a product of the pressure in the tire and the radius of the tire cross section, plus the direct pressure force on the rim itself. Referring to Fig. 5.04 A the stresses in the critical cross section are:
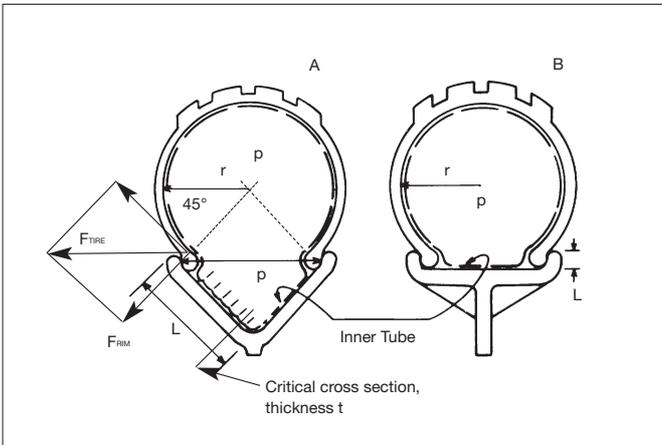

Fig. 5.04 **Wheel rim designs**

$$F_{TIRE} = pr \, sin \, (45)$$
$$F_{RIM} = F_{TIRE} \, sin \, (45)$$

bending stress:

$$\sigma_B = 6 \, (F_{RIM} \, L + \tfrac{1}{2} \, pL^2) \, / \, t^2$$

membrane stress:

$$\sigma_M = F_{RIM} \, / \, t$$

For r = 16 mm, L = 18 mm, t = 8 mm and p = 0,5 MPa

this gives:

$$F_{RIM} = 4 \, N$$
$$\sigma_B = 14,5 \, MPa$$
$$\sigma_M = 0,5 \, MPa$$

It depends on the design temperature, if the total stress of 15 MPa is low enough to keep the creep strain limited. Lower stress levels can be obtained by keeping the rim height (subject to internal pressure) low, see Fig. 5.04 B. Radial ribbing can be added as shown to further stiffen the rim for radial loads.

Pressure Vessel Seals

Seals in end closures of cylindrical pressure vessels should be placed carefully to minimize creep. Fig. 5.05 A shows examples of wrong application (creep decreases pressure on seal so that it becomes untight); a proper solution is given in Fig. 5.05 B.

In cases of an end cap with a snap-fit joint, the cover should be designed such, that the pressure acts on the inner cylinder only, see Fig. 5.06.
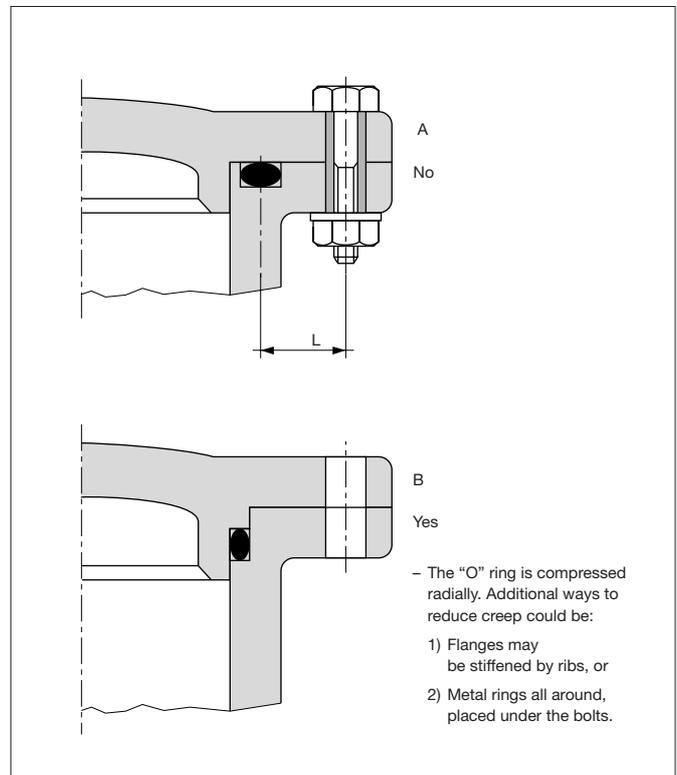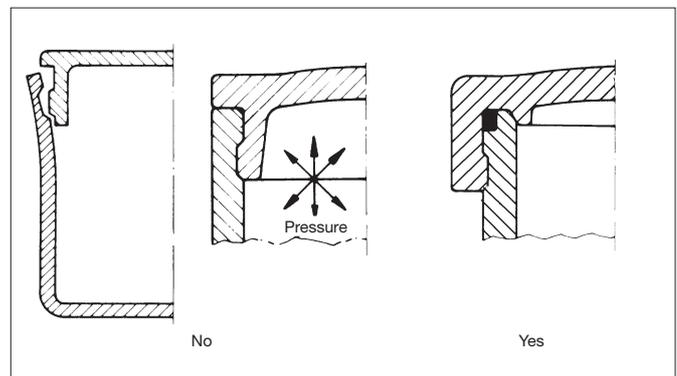

Fig. 5.05 **Sealing of bolted end-closure**

Fig. 5.06 **Sealing of snap-fit cover**

Cost Effective Design vs Raw Material Cost

While one of the primary jobs of the product designer is to develop the most cost effective design, he often is misled by specifying the material with the lowest price tag. The fact that this is not the route to cost effectiveness is demonstrated by the following examples:

Bicycle Wheel Design

In the specification of a material for a bicycle wheel, the prime consideration is usually finding the proper combination of toughness with stiffness. Among materials that could be considered as a substitute for glass-reinforced ZYTEL® ST which has been used for years in this application, one that comes close to meeting the physical requirements (allowing for a proper margin of safety) while offering a sizeable reduction in resin price is a reinforced (20 per cent glass fibres) grade of polypropylene (see Fig. 5.07).
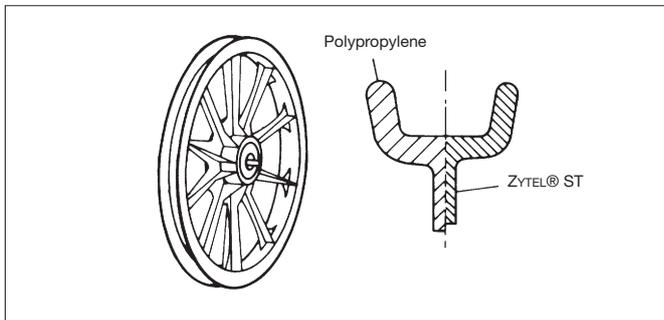

Fig. 5.07 **Wheel rim in ZYTEL® versus polypropylene**

While the wheel designed for polypropylene would require an additional 145 grams of material to meet the stiffness requirements, a dramatic savings would be realized if only resin price were considered.

	ZYTEL® ST	Polypropylene
Wheel Weight	0,91 kg	1,05 kg
Resin Price (per kg)	$ 4.12	$ 1.76
Resin Cost per Wheel	$ 3.73	$ 1.86

NB: given prices are subject to changes!

But other factors affect cost. Employing a single cavity mould, a 4,9 meganewton press can turn out 250000 nylon wheels a year of ZYTEL® ST on a two-shift basis. Because of polypropylene's longer processing time – a 130 second cycle vs 60 seconds for the nylon wheel – two single cavity moulds would be required to match production.

Similarly, since material volume is greater, two 5,8 meganewton presses would be needed.

The direct investment would more then double, and, when amortized interest charges and increased machine time and labour costs are calculated, the picture changes. (No attempt was made to factor in the added cost of quality control problems that might be expected because of thicker walls). Add in normal selling expenses and return on investment and the comparison looks more like this:

	ZYTEL® ST	Polypropylene
End-User Price per Wheel	$ 6.01	$ 5.77

Though that's still a four percent advantage in the selling price of the polypropylene wheel, it does little to offset the vast superiority of the nylon wheel in terms of something as meaningful as impact strength. The Izod impact strength of ZYTEL® ST 801 nylon resin (1000 J/m at ambient temperature and 50% RH) is 20 times greater than that of polypropylene.

While the "cheaper" wheel would provide the same stiffness and safety factors at room temperature, these properties would not keep pace with those of the nylon wheel. At 65°C a not uncommon wheel temperature in the Southern countries, the strength and stiffness of the wheel in polypropylene would be only about 80 per cent of the wheel in ZYTEL® ST. The same would hold true for creep resistance, which is critical for pneumatic tire retention during operation.

Such other marketing and manufacturing disadvantages of the polypropylene wheel as 16 per cent greater weight and its bulky appearance reveal that ZYTEL® ST is indeed the wiser choice.

Chair Seats Reevaluated

The same kind of study was conducted on a product that is already being mass produced in a "cheaper" plastic, the typical lightweight chair found in waiting rooms and institutions. An impact-modified, glass-reinforced nylon at $ 3.95 per kg was substituted for unreinforced polypropylene selling at $ 1.08 per kg. A chair seat was designed in each material, using a rib reinforcement pattern that provided equal factors of safety and stiffness with a minimum volume of material (see Fig. 5.08). Again, using the same typical cost factors for annual production of 250000 units, the results were not surprising.
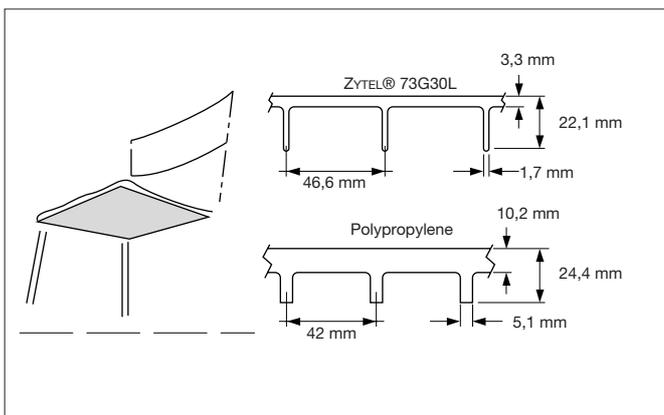

Fig. 5.08   **Chair seat in glass fibre reinforced ZYTEL® versus polypropylene**

	ZYTEL® 73G30L	Polypropylene
Seat Weight	1,27 kg	2,29 kg
Resin Cost	$ 5.01	$ 2.47
End-User Price per Seat	$ 7.21	$ 6.72

NB: given prices are subject to changes!

The end user price includes an additional $ 0.36 cost per part occasioned by the longer cycle time (100 seconds vs 35 seconds for the glass reinforced ZYTEL® seat) required for polypropylene – reducing what, at first, seemed like a 19 per cent price advantage to a 13 per cent advantage. That advantage can be more than offset, however, by the elimination of moulded-in metal inserts for leg and arm attachment and shipping cost benefits of a seat that weighs 44 per cent less.

Even more significant, the glass reinforced ZYTEL® seat would exhibit much higher creep resistance, particularly where chairs are stacked in high temperatures storage areas. It also offers much better impact resistance, a critical consideration in institutional usage.

Wheelbarrow Frame – a Potential Design

While some barrow makers already produce a product that takes advantage of the light weight and rust and corrosion resistance of high density polyethylene or polypropylene in the box, none – to the best of our knowledge – have built a frame in plastic. This analysis supplies a possible reason why: In a lower cost plastic, it would be both too heavy and too expensive!

Based on equivalent stiffness and safety factors, appropriate cross sections were determined in frames (see Fig. 5.09) of RYNITE® 530 engineering thermoplastic polyester, a PET (polyethylene terephthalate) resin reinforced with 30 per cent glass fibres, and of polypropylene resin, also reinforced with 30 per cent glass fibres.
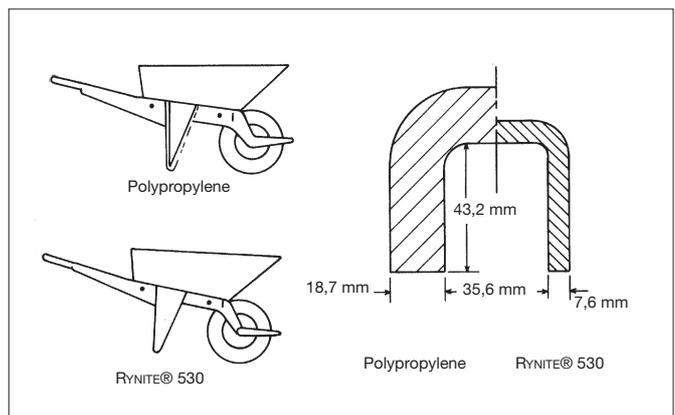

Fig. 5.09   **Wheelbarrow frame in RYNITE® versus polypropylene**

Here are the results:

	RYNITE® 530	Polypropylene
Frame Weight	8,16 kg	16,78 kg
Resin Price (per kg)	$ 3.24	$ 1.83
Resin Cost	$ 26.46	$ 30.71
End-User Price (per Frame)	$ 36.86	$ 43.61

NB: given prices are subject to changes!

Again, volume and cycle time (65 seconds for RYNITE® thermoplastic polyester vs. 120 seconds for polypropylene) necessitates use of two moulds and two larger machines for processing 250000 polypropylene frames a year. And as before, the product in the cheaper material suffers in a comparison of such properties as strength, stiffness and impact resistance at temperature extremes. The expensive materials is the most cost effective.

The bicycle wheel, seat and wheelbarrow frame examples clearly show that a truly cost effective design analysis must include performance, manufacturing and marketing considerations and that the more expensive material is often the most cost effective, particularly where the end item is under stress.