Materials for the fusible-core technique and half-shell technique

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HISTORICAL BACKGROUND
The first intake manifolds made of plastic were then called infeed manifolds, installed in a 6-cylinder horizontally opposed engine at the Porsche company (see Fig. 1). They must be characterised as a shining example of integrated design. This module unites air filter housing base, K-Jetronic housing and the top of the air plenum in a single component. It is interesting to see how the air plenum was completed: the base of the housing, with the six sockets for the individual cylinders, formed an airtight join using a groove-spring connection wetted with a solvent adhesive (phenol/water). Eight thread-forming screws ensured even contact pressure while the solvent was volatilised in the heat tunnel, thus ensuring additional strength at the join to supplement the adhesive effect.

After such a wealth of encouraging experience with glass-fibre-reinforced PA 66 in this sector, one would have assumed that subsequent development work would be progressed in the same material. However, in the early eighties Ford developed a BMC intake manifold for a 4-cylinder diesel engine based on polyester resin, which went into series production using the fusible-core technique (Fig. 3).

**Figure 1:** Intake manifold system from the Porsche company for a 6-cylinder horizontally opposed engine - series production started in 1972.

**Figure 2:** Air intake module from the Porsche company made of PA 66 with air filter housing base, K-Jetronic housing, and the top of the air plenum.

This engine featured another part made of glass-fibre-reinforced polyamide 66 - an intake air module (Fig. 2), which

**Figure 3:** Ford intake system made of BMC, manufactured using the fusible-core technique.

**Figure 4:** Welded intake manifold from PSA (1988). As a parallel development, PSA started series production of the first welded intake manifolds (Fig. 4) made of reinforced
Figure 5: First plastic intake system in thermoplastic with plenum, from BMW. PA 66 in 1988; when in 1990 the first intake manifold made of glass-fibre-reinforced PA 66 (Fig. 5) using the fusible-core technique went into mass production at BMW, other European car manufacturers like Porsche, PSA and Ford followed suit, until in early 1992 BMW again broke new ground with

Figure 6: Porsche intake system for a horizontally opposed engine.

Figure 7: Plastic intake system from PSA with plenum.

Figure 9: BMW plastic intake system for an 8-cylinder engine with built-on parts - currently the most complex known intake system, manufactured using the fusible-core technique.

Figure 8: Plastic intake system from the Ford company. fusible-core production of an injection-moulded intake system (Figs. 6 - 8) representing the largest and most complex design thus far implemented: it is installed in the new 3and 4-litre V8 engines (Fig. 9). The fusible core is made of a tin/bismuth alloy, consists of 10 individual cores, weighs over 90 kg when, mounted, and is injection-coated with 3.5 kg of polyamide. The eight intake pipes wind in a snail-like configuration around the central plenum, and flow into two flanges moulded one onto each side.

In the case of the polyamide intake manifolds for the new 6-cylinder Mercedes-Benz engines, in series production since 1992 (Fig. 10), development work encountered quite different difficulties: with an intake manifold length of 400 mm, the longest flow path (500 mm) thus far implemented in any intake system had to be mastered here, too, together with the concomitant manufacturing problems like core shifting, mould filling, etc. Another special feature of these intake manifolds is that a flap fitted in the centre of the plenum enables the plenum volume to be halved or doubled to suit the current speed range.

ADVANTAGES OF PLASTIC INTAKE MANIFOLDS

So what were the advantages of plastic intake manifolds compared to light-metal constructions? What were the underlying reasons for this development trend?

Firstly, thanks to their low density, and the low wall thicknesses which can be attained in an injection moulding process, plastics permit a significant weight reduction, of 50 to 60 percent compared with aluminium. An advantage which
pays off most especially in the engine area, because the engine constitutes a substantial accumulation of mass in the vehicle as a whole. If this mass can be significantly reduced, this has advantages not only for fuel consumption, but also for the overall dimensioning of the front of the car, the front axle, and of course the vehicle’s safety-relevant sections in the event of a crash.

Fuel can also be saved or performance enhanced by the fact that plastic intake systems exhibit a considerably smoother inner surface and thus lower flow resistances than light-metal components produced by sand casting. Engine manufacturers provide no data on how great these advantages are, but they cannot be insignificant, since racing engine manufacturers and engine tuners will go to great trouble to polish the interior of light-metal intake manifolds or to smooth the inner surfaces with plastic coatings.

Another advantage of plastic intake manifolds lies in the thermal insulation properties of these polymer materials: the air in the intake systems is not warmed up by the ambient air (up to 100°C) in the engine compartment to the same extent as with metal intake systems. This increases the cylinder fill, and optimises the combustion process.

The most important advantage of plastic intake manifolds, however, is the cost saving as compared to metal constructions. The sophisticated injection-moulding process renders reworking largely superfluous (at least with thermoplastics), and permits short cycle times. According to car manufacturers, the cost reduction achieved by using plastic parts made with the fusible-core process is between 10 and 30 % as compared with aluminium sand-cast parts, depending on the complexity of the intake system involved. With welded parts, this saving is as much as 50 percent.

Nor should the advantages of the injection moulding process be forgotten, since it enables ultra-complex components to be produced in one piece. This opens up opportunities for further cost reductions in the future, by integrating other elements into the intake system. Candidates for integration include fuel rail, throttle body, cooling water passages, etc., and in fact some of these options have already been implemented.

MATERIALS
In the recent past, a variety of materials have been proposed, tested, and actually used in series production of plastic intake manifolds. The thermosets used here are injection moulding compounds (BMC) based on unsaturated polyester resins (UP) and phenolic resins (PF). Although the first mass-produced intake manifolds made with the fusiblecore technique were in BMC-UP, and development work has been completed on intake manifolds made of phenolic resin injection-moulding compounds, thermosets could not compete with thermoplastics in terms of cost. Although these thermosets can be processed with significantly lower clamp forces, the production costs for thermoset parts are considerably higher than for thermoplastics, due to the longer processing cycles, the elaborate finishing required, and (in the melt-out process) the higher outlay involved in core casting and melting out. This drawback is exacerbated by the fact that openings essential for manufacture (like core mountings) cannot be inexpensively closed up with friction-welded plugs as is the case with thermoplastics. In addition since the density ratio between thermoplastics and thermosets is 1.4/1.9, the weight advantage over aluminium is no longer so significant.

Polyphenyl sulphide (PPS) and polyacrylamide have better mechanical strength and rigidity than polyamides, with significantly lower impact strength, and possess higher reserves in thermal and dimensional stability, but the disadvantages in processing and finishing, plus the significantly higher price of the material, outweigh the advantages by far. No ongoing intake manifold development work is currently known with these two materials.

Glass-fibre-reinforced polyamide 66 is thus virtually unchallenged at present as the material for series manufacture of intake manifolds in Europe, and for development work in Europe, the United States and Asia. However, intensive modifications of the standard material were needed in order to render it suitable for the stringent requirements posed by engine applications. In order to provide the performance expected from the material during a lifetime of up to 15 years, the products have to be specially optimised in terms of thermal stability, flowability and surface quality (Fig. 11); and in addition, after recycling this product has to function properly for many more years as a new component (Fig. 12).

<table>
<thead>
<tr>
<th>Location of sample removal</th>
<th>Impact resistance</th>
<th>Modulus of elasticity in extension</th>
<th>Tensile strength</th>
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| 15 a/b/c/d                | 35.3             | 66.9                             | -               |
| 16 a/b/c/d                | 55.5             | 58.9                             | -               |
| 17 a/b/c/d                | 37.0             | 46.9                             | -               |
| 18 a/b/c/d                | 37.6             | 48.6                             | -               |
| 19 a/b/c/d                | 60.9             | 55.5                             | -               |
| 20 a/b/c/d                | 47.2             | 63.5                             | -               |
| 21 a/b/c                  | 54.4             | 50.8                             | -               |
| 22 a/b/c                  | 44.2             | 41.5                             | -               |
| 23 a/b/c                  | 47.2             | 45.1                             | -               |
| 24 a/b/c                  | 51.9             | 50.7                             | -               |

Figure 11

This material may acquire a competitor in the form of polyamide 6, a slightly less expensive material from the polyamide family. The reason is its better weldability, and the higher weld line strength resulting, rendering this material a particularly attractive option for welded designs.
ULTRAMID Recycling
Intake system: BMW Ultramid A3H47 (kilometres travelled: 125,000)

Modulus of elasticity in extension

Tensile strength

Impact resistance

Elongation at tear

Figure 12:

In all other mechanical properties, and in long-term thermal stability, PA 6 is not significantly inferior to PA 66, and in processing PA 6 even offers advantages, thanks to the wider scope it gives for processing options. Slight disadvantages which have to be taken into account, however, are the somewhat higher moisture absorption and the concomitant alterations in properties and dimensions.

When chemical recycling is considered above and beyond material recycling, then PA 6 has advantages here as well, since it consists of only one monomer (caprolactam), whereas PA 66 is obtained by polyaddition of hexamethylene diamine and adipic acid. Chemical recycling of a single monomer is surely a more cost-efficient alternative!

PRODUCTION PROCESS
Currently the most important production process for intake systems is the fusible-core technique. This process has been described in detail in various publications, so that after a brief sketch of the basic process it would appear more profitable to deal with its more recent variations.

First of all, a core representing the internal contour of the subsequent intake manifold is made from a tin/bismuth alloy (melting point 138°C) in a low-pressure process using a rising casting technique. In the injection moulding die, this core is injection-coated with molten thermoplastic at 290°C, without the core itself being melted at all, since thanks to the metal alloy’s good thermal conductivity, the heat from the thermoplastic is passed very rapidly into the core’s interior. In the third stage of the process, the core is melted out inductively using electricity in a liquid heat transfer medium (see Fig. 13).

![Figure 14: Round-table intake system manufacturing unit from KFD](image)

While the core production process is a fully mature one, the subsequent steps and their interlinkage have been progressed during the course of recent years. The injection moulding operation has been shifted away from the traditional injection moulding machine with a horizontal clamping unit to machines with a vertical clamping unit and an automatic round-table design. The advantage of this kind of machine is that the heavy cores can be inserted and the injection-coated cores removed outside the actual injection moulding cycle. This means a significant reduction in production process cycle time, constituting an important argument when capital investments running into several million deutschmarks are concerned (Fig. 14).

The casting process and the injection moulding process had been optimised before introduction of the fusible-core technique for making intake manifolds. The third step in the process, however, is a new one: the melt-out. Large pump casings and water meter housings had been manufactured using the fusible-core technique for more than 15 years. They were melted out either in hot air inside a drying oven, or in hot oil, the former process being very time-consuming, and the latter environmentally counter-indicated and requiring intensive cleaning.

In the early days of intake manifold development work, one aim was accordingly to come up with a clean, fast melt-out process. The idea of using electrical induction, whose energetic field lines are capable of warming and melting only the metal and not the plastic, appeared to be a solution of striking simplicity. And in fact, large core weights of up to 40 kg could be melted out in 2 minutes with induction coils matched to the shape of the intake manifold concerned. However, thin films of metal and small metal particles adhering to the intake manifolds’ inside walls could not be
reached by the inductive field lines, and remained inside the component. BASF accordingly developed the combined process of inductive melt-out in the liquid heat transfer medium. The transfer medium used for this purpose was not steam, stinking oils, but Lutron brands developed specifically for this application, heated up to 165°C, and which melt out even the last remaining residues of metal.

This process is meanwhile used at all European intake manifold manufacturers, and there are melt-out baths where the liquid has not had to be changed for three years, which demonstrates the thermal stability of this substance.

There have been recent efforts to discontinue inductive melt-out and go back to a melt bath pure and simple. This is of course an alluring vision - you save the cost for the medium-frequency generator! But the price to pay is enormous bath volumes, because given a cycle time of 1 minute and a melt-out time of 1 hour, the melt-out bath must have room to suspend at least 60 intake manifolds! Baths of this kind measure 9 x 6 x 0.6 m, meaning that 32 t of Lutron have to be maintained at a temperature of up to 185°C. And if a production error leads to defective parts, the error concerned will not be noticed until 1 hour later, when the components re-emerge from the bath!

And what is to be done with the gigantic amounts of Lutron, if the liquid becomes unusable due to high thermal stresses, and has to be disposed of? There is at present only one legal option for disposing of heating bath liquid contaminated with heavy metal ions: incineration as special refuse.

And another question relating to the melt-out bath has not yet been adequately clarified: in the case of glass-fibre-reinforced PA components loaded with internal stresses at dwell times of 1 h at temperatures of up to 185°C, there is a risk of component distortion, since internal stresses will at these temperatures lead to relaxation phenomena in the material.

This kind of changeover from tried and tested processes to as yet untried procedures should not be made without prior cost-efficiency analyses and adequate preliminary technical studies.

One variation on the fusible-core technique is the solution-core technique, where the cores are injection-moulded from soluble polymers. Due to technical and environmental problems, however, this process did not get as far as the series production stage.

A process of increasing importance for intake manifold production is the half-shell technique, where two half-shells are injection-moulded either together in one injection moulding die, or in two separate dies, after which they are appropriately joined to form a single hollow body. The joining procedure used can be either gluing (as mentioned at the beginning of this paper), injection coating, or welding. Gluing the two half-shells cannot be regarded as a suitable process for mass production. Injection coating of the two half-shells along a circumferential flange is no longer often raised as a serious option, because as with gluing the manufacturing outlay is simply too high. The predominantly accepted method is now to weld the two half-shells using a vibration welding technique. In modern-day welding machines, the two half-shells with appropriate moulded weld flanges are rubbed against each other at a frequency of 240 Hz and an amplitude of ~0.5 mm, at the points of contact, the thermoplastic starts to melt, and when the vibration process is concluded and the material cools down, the parts will have been welded together (Fig. 15).

Figure 15: Example of a welded intake system
The advantages of this process compared to the fusible-core technique are obvious: lower capital investment and reduced manufacturing outlay mean that production costs are cut by 50%.

What are the limitations of this process compared to the fusible-core technique?

- Only relatively simple geometries can be welded.
- The circumferential flange is stylistically "unlovely".
- Passages separated from each other by only one wall cannot be welded without what is called weld spew.
- The weld line is a weak point, which reduces the bursting pressure of an intake manifold to as little as ~0.5% of the bursting pressure of a fusible-core intake manifold. (But design measures to increase the mechanical strength can bring about improvements here!)
- The weld line can lead to flow resistances at the inside walls of the intake manifolds, particularly when the seam runs at right angles to the air flow.
- Welding angle between 180° and 60°.

The first welded intake manifolds were used in diesel engines, since here no flashback can occur into the intake system (intake manifold backfire), and the lower bursting pressure is accordingly irrelevant. Under current pressures to cut costs, however, more and more car manufacturers are also developing welded intake manifolds for petrol engines: the argument previously put forward that the bursting pressure of plastic intake manifolds was too low is invalidated by pointing out that intake manifold backfiring does not occur in electronically controlled engines.

So it is generally expected that given success with this development work the quantity of welded intake manifolds will soon equal or even exceed the number of fusible-core versions.
One final process for intake manifold production should also be mentioned: extrusion blow-moulding, although it is still in the development stage for intake manifolds, it is already being used for series manufacture of air ducts, charging air pipes or intake air pipes. The first components made of unreinforced polyamide 6 at Volkswagen or of glass-fibre-reinforced polyamide 6 at Mercedes-Benz are already in series production using the classical extrusion blow-moulding process; for lower thermal stresses, however, there are also manifolds made of glass-fibre-reinforced polypropylene using the more recently developed three-dimensional blow-moulding processes (Fig. 16).

The design rules applying to intake manifolds are the same as for other thermoplastic parts: even wall thicknesses, no mass accumulations leading to distortion and longer cycle times! The customary wall thicknesses are around 3 mm, for reasons connected with the manufacturing process (ratio between flow path and wall thickness), and considerations of mechanical strength (vibration/noise). If higher component strength/robidity is required at certain points, ribs can be provided into the appropriate configuration. Special attention must be paid to the flange for securing the intake manifold to the cylinder head: high static continuous stress (screw connection) and high contact pressures are encountered here simultaneously. Depending on the screw distance involved, the flange should be 20 to 30 mm thick, so that the gasket still obtains sufficient contact pressure between two attachment points. Metal inserts or (for cost reasons) metal spacer bushes are absolutely essential here. If at all possible, the intake manifold should be gated to the flange, since this is the only way to ensure optimised flange planicity and thus a reliable sealing effect. Attachment points at the intake manifold can be executed both with appropriate inserts (installed by hot-pressing or ultrasonic processes) or also,

Figure 17: Example of gasket type and configuration.

Figure 18: Diagramatic representation of weld line design depending on the loading involved and the frequency of installation, as thread-forming screws. Moulded gaskets made of elastomers with a thermal stability above 150°C (Fig. 17) located in the bypass and mounted in a groove have proved a dependable choice for sealing purposes.

One special design feature is the welded flange: as a rim running around the plenum and the individual passages, it has to be designed and dimensioned so as to assure sufficient weld line strength both along and at right angles to the direction of vibration, but at the same time prevent weld spew occurring either inside or outside the intake manifold by providing
the air inlet of the throttle body.
The hydraulic pins do not leave behind an opening; surface markings at the worst.

CALCULATIONS
In order to ensure that a design's defects and weak points are detected and eliminated before the expensive injection moulding dies have been manufactured, various calculations for component and material behaviour are frequently made today after a preliminary design specification has been arrived at. Static or quasi-static calculations under internal-pressure loading using finite element analysis (FEA) provide data on the intake manifold's deformation behaviour (Fig. 21) up to bursting pressure. This calculation is particularly important for welded intake manifolds.

Figure 20: Illustration of the core support position.
In the first case, the openings for the core supports must later be sealed off by welded in plugs, if at the point concerned the design does not anyway entail an opening (e.g.
In addition, dynamic calculations of this kind can be used to predict accelerations, particularly of the throttle body whose function is such a sensitive issue. If these values should turn out to be unacceptably high, then measures can be taken at an early stage, like increasing the component rigidity, or providing appropriate supports.

An FEM analysis of the mould filling operation in the injection moulding process also provides important indications of how a component of such complex configuration as an intake manifold must be injected in an expedient and balanced fashion without the quality of the finished parts being significantly impaired by core shifts, air inclusions, joint lines or distortion.

Figure 24: Laser holographic picture of an intake system; mounted.

With the fusible-core technique, in particular, knowledge of the flow operations during injection are essential today in order to achieve maximised equilibrium in the stresses exerted by the injection pressures on the relatively soft core. But filling two differently sized mould cavities in a double mould also demands that a properly balanced casting system be calculated.

By extending this calculation procedure, it will in future also be possible to determine the core shifts of the fusible cores during injection moulding in advance. The calculation procedure needed is already available, but the computed results still have to be definitively compared with empirical data.

EXPERIMENTAL COMPONENT OPTIMISATION

In spite of all the accurate calculation procedures used, component behaviour still has to be tested under realistic conditions, and resultant optimisation of part design is in most cases essential. Static, dynamic and thermal component studies are the main focus here.

In this context, the static experiments involved are mainly flange studies concerning compression distribution and the sealing function. But optical procedures, too, like laser holography, provide important data on component behaviour, particularly on weak points in the design (see Fig. 24).

In the case of intake manifolds, knowledge of the bursting pressure behaviour is extremely important; bursting pressures can be determined both statically and dynamically, with the dynamic method, using a pressure build-up within a few milliseconds, being particularly good for simulating an actual backfire phenomenon.

Vibration studies using modal analysis provide important data on component behaviour in various frequency ranges, and thus indications for component optimisation.

Sound intensity measurements at the component enable the areas and surfaces from which the greatest sound radiation emanates to be localised and subsequently optimised.

This experimental method is particularly important, since it provides valuable data for improving the engine's noise characteristics, data which cannot be predicted by calculatory means.

This assortment of intake manifold investigation methods is rounded off by trials on thermal test stands. Besides general studies of the component at raised temperatures, the exhaust gas return system into the plastic intake manifold must be tested and optimised here. Using different exhaust gas temperatures, mixing ratios between exhaust gas and intake air, and by varying the entry points, the local thermal stresses on the plastic can thus be determined, and where necessary reduced by appropriate measures.

CONCLUSION

Plastic intake manifolds offer automobile manufacturers technical advantages and significant cost savings, which in the current situation of the automotive industry is of particular importance. These new developments in plastic parts open up new markets for component manufacturers, the machinery industry, and plastic producers. In the final analysis, the companies who profit will be those who make optimum use of experience gained in all the above-mentioned areas.