LATICONTHER: INNOVATION IN LIGHT AND DESIGN

Innovation in lighting industry will necessarily pass through energy saving and implementation of more flexible and user-friendly solutions. During the last years a great effort has been made to reduce energy consumption in home appliances of any kind and now the time for a major revolution in the technology of light sources for domestic and public appliance has come.

It is well known that power absorption of traditional filament lamps can be largely reduced by introducing LED based technology into dedicated projects.

IDEALED, a newborn company based in Northern Italy and dedicated to LED based solutions, has been developing new lighting devices dedicated to home and office applications whose accurate engineering includes polymer compound based heat sinks and overmolded transparent rubber sealing.
This new product range is thus completely polymer based and can be manufactured by advanced molding techniques allowing:

- cheap and fast production,
- environmental friendly transformation,
- easy raw materials handling,
- flexible industrial scaling.

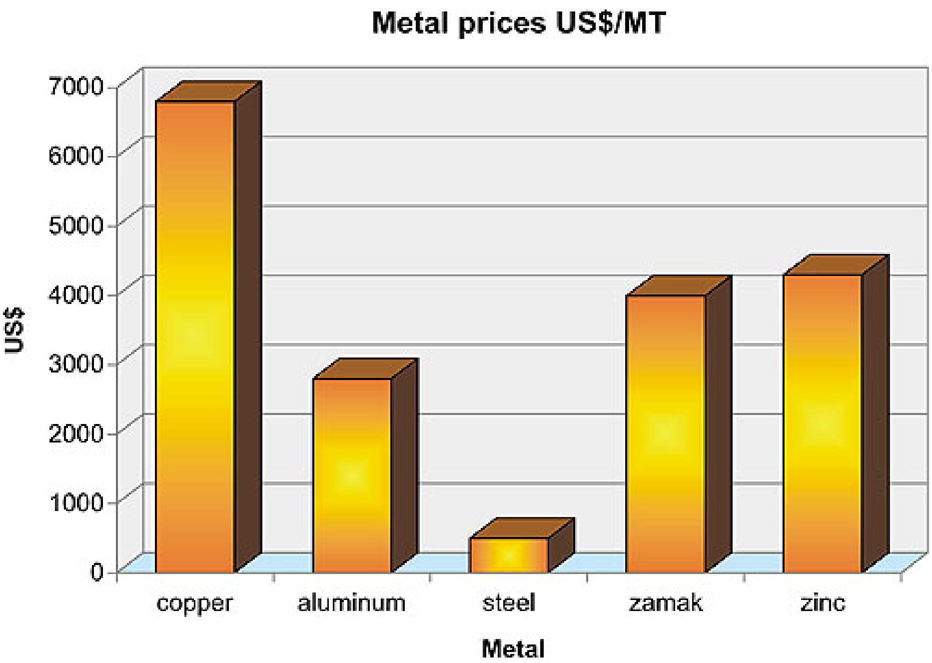

Fig. 1 – metal prices, end 2006

By injecting both heat sink and transparent sealing it is also possible to save assembly cost and time. Evident savings are also related to metal replacement leading to aluminum substitution by custom-made thermally conductive polymer compounds.

The development of this kind of innovative product required extensive engineering and collaboration in order to tailor-make special thermoplastic compounds, verify thermal and mechanical performance, test overall part performance in time and, more than anything, feasibility of injection molding.

For many of these aspects IDEALED worked in close contact with LATI, a major European compounder leader in high performance and special thermoplastic compounds. LATI took care of material tuning, co-design activity by finite element analysis as well as molding machine setup.

Implementation of thermally conductive thermoplastic in LED featuring devices started with the here described product and is now being extended to a whole range of IDEALED manufactured products.

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Fig. 2 – the brand new modular LED lamp featuring thermoplastic heat sink

New products

LEDs are electronic devices based on diodes transforming electric power directly into a beam of bright monochromatic light. This phenomenon does not require either high current or tension and for this reason power dissipation due to Joule effect is extremely low. Low working tension (12V) and very low amperage guarantee safe operation and handling. Rapidly improving quality of LEDS allows an electric efficiency higher than 30%, a performance up to 10 times better than conventional filament lamps. Nowadays evolution of LED technology is extremely fast due to a renovated interest in low-consumption environmental friendly light sources and thanks to its outstanding flexibility and overall performance.

Besides obvious low consumption, allowing LED lamps to deliver more than 60 lm/W (up to 80 lm/W, sept. 2006), LEDs also feature extra long working life with an estimated continuous operation time close to 100000 hours - on the contrary of ordinary filament lamps, lasting for no more than 4000 hours.

Long life ensures very low maintenance costs requiring no spare parts nor forced stops, a very important advantage for those applications where lamp failure can require an expensive substitution process such as public and road lighting, pavement spot lights and similar products.

In *figure 3*, the manufactured product here described is composed of a main circuit board carrying three to five new generation power LEDS, 3 watts nominal input each, mounted on a heat sink built to keep LED temperature below 70°C.

The heat sink was previously made out of machined aluminum. Metal can be a very cheap and interesting solution for mass production but typical transformation techniques, that is profile extrusion or die casting, do not offer any cost effective chances to innovative or custom made design.

Urgent need for tailor made heat sinks directed to the OEM at

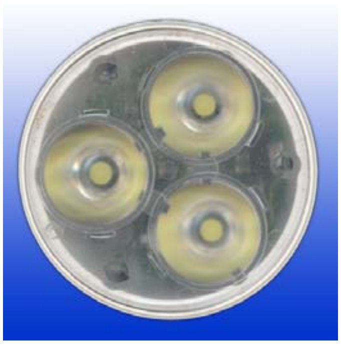

Fig. 3 – LED lamps on plastic radiator

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FIG.4 – original heat sink obtained by machined aluminium

switching to thermally conductive polymer compounds.

Injection molding offers many interesting industrial opportunities to integrate different production steps into a single operation. In this case it was possible to overmold the radiator directly onto the circuit board and complete the part by injecting a transparent elastomer too, sealing the electric components into the hollow cavity of the cooler. Thanks to these features the part can be quickly ready for further assembling, saving time and costly related operations. It must also be considered how the use of polymers instead of metals allows the OEM to get rid of the annoying disposal of non environmental friendly waste.

The so produced 9 to 15 watts lamp is hence completely water proof and can be used for submarine applications, for outdoor solutions and for all those environmental conditions where the presence of explosive or dangerous atmosphere makes this cold and safe light highly suitable.

Being completely modular and adjustable, this type of unit can be arranged into arrays creating any kind of lighting solution.

Once the all-plastic solution has been thoroughly tested, a similar approach has been extended to other manufactured products as single spot lights, beamers as well as battery torches and public signals.

Thermally conductive compounds

Considering the overall view of this project, it is easy to figure that the main quest is to create a thermally conductive compound from intrinsically insulating polymeric base resin. Project requirements to guarantee a successful application of this product are mandatory:

1 – thermal conductivity must be considerably higher than average values for plastics;
2 – the compound has to be easily transformed with injection molding technique by means of ordinary machinery and equipment;
3 – mechanical performance and impact resistance good enough to guarantee failure free operation also in case of accidental drop or shocks;
4 – good dimensional stability to ensure waterproof applications and no issues in assembling;
5 – satisfactory thermal behavior up to 100°C
6 – excellent chemical and moisture resistance, no stress cracking phenomena admissible;
7 – electrically isolative to safely house electronic devices and avoid sparks and discharge due to static buildup;
8 – linear thermal expansion comparable to metals.

Generally speaking, thermal conductivity for polymers is as low as 0.1-0.3 W/m°K. Comparing this value to typical metal ones, much higher than 100 W/m°K, it is evident how hard it can be to even think about an efficient cooling system based on polymer parts.

To develop a thermally conductive compound, PA12 has been chosen among many base resins thanks to its excellent capability to be filled with large amounts of additives without incurring separation between matrix and fillers, a phenomenon generating dust, particles and non processable pellets.

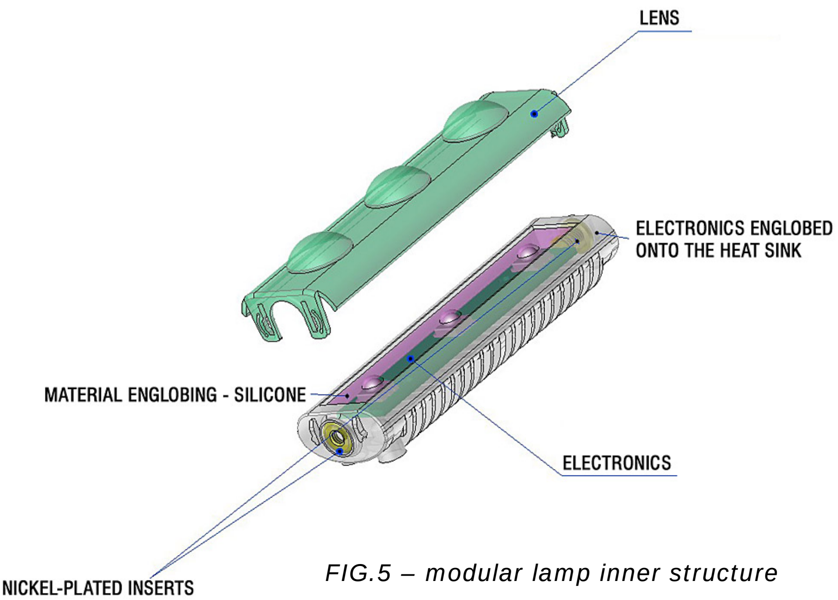

FIG.5 – modular lamp inner structure

MATERIAL	THERMAL CONDUCTIVITY (W/m^0K)
PE, high density	0.35
PP	0.12
PA66	0.80
PA66 40% CARBON FIBRE	1.70
ALUMINUM	237
COPPER	401

Many fillers may be suitable to formulate a good thermally conductive compound but the resulting material has to deal with high dimensional stability requirements, a primary factor leading to an immediate discard of fibers and whiskers of any kind. Anisotropy of such fillers would lead to local anisotropy of mechanical properties, specially elastic modulus, promoting differential shrinkage during cooling of molded compound and resulting in warped and tensioned manufactured products.

MATERIAL	LINEAR EXPANSION (10^{-6})
PE, high density	130
PP	110
PA66	90
PA66 40% CARBON FIBRE	15
ALUMINUM	18
COPPER	24

Also linear thermal expansion must meet isotropy requirements to avoid not uniformly dimensional variations during heating. Expansion coefficient must be as close to metals as possible otherwise internal breakage of printed circuit boards, solderings and connections may occur invalidating any benefit coming from plastic parts.

Electrical insulation can be achieved by excluding any carbon fiber or graphite based thermal conductive fillers, a problematic choice considering how efficient this kind of additive can be.

The best solution is thus obtainable by compounding PA12 with a mixture of conductive ceramics, mostly being different metal oxides, whose thermal conductivity is as high as 20-25 W/m°K.

Generally speaking, polymer compounds offer a very poor path to heat flow, specially when compared to ceramics.

The goal of compounding is to finely disperse conductive particles into the polymer matrix inhibiting efficient heat transmission. It is evident that the lower the filler content the worse the thermal performance.

Recalling theory of heat transfer, it can be easily found that the global heat exchange coefficient is strongly dependent on the amount of the less conductive contributor, as happens for series sum of electrical resistors

As the number of contacts among conductive particles increases a

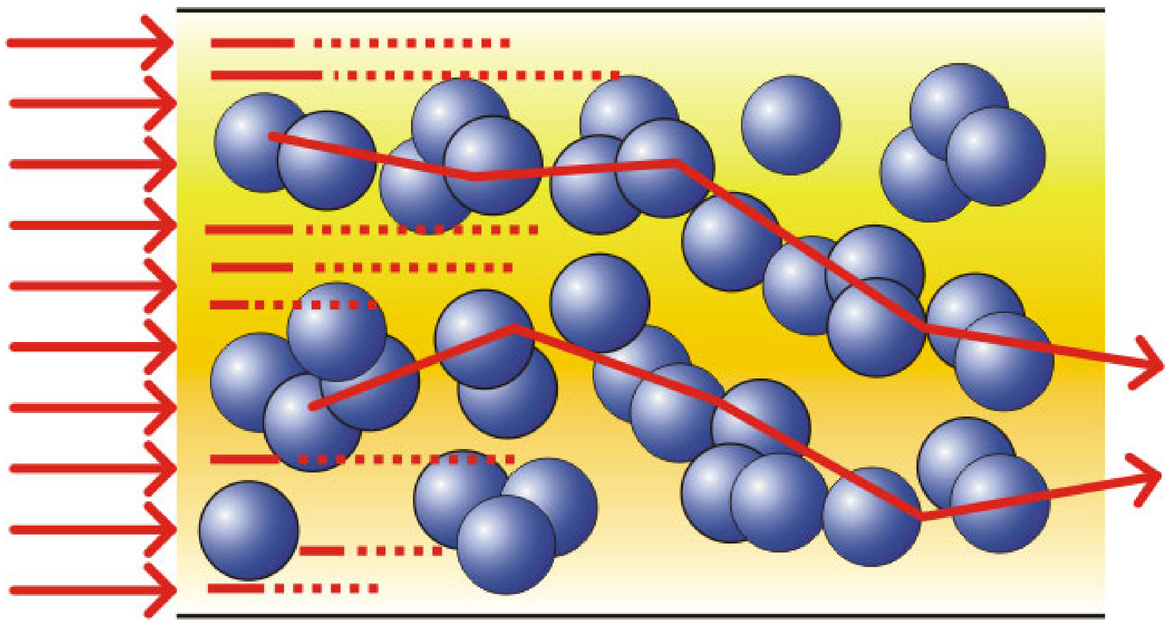

Fig. 6 – Incoming heat is partially dispersed into the polymer matrix, partially trasmissed through ceramics

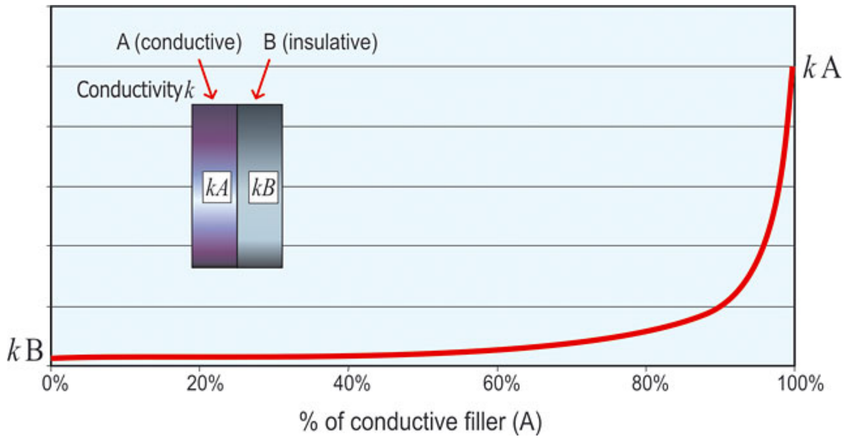

FIG. 07 – Thermal conductivity of coumpound vs. filler content

steep growth in thermal conductivity can be measured due to the enhanced capability of heat transport for the compound:

For this reason PA12 is filled up to 85% with ceramics by means of special extrusion techniques and equipment. Resulting compound features a considerably high count of contacts among ceramic particles offering a path to heat flowing through the material.

Thermal conductivity of the material is higher than 2 W/m°K, a value 10 to 20 times better than natural and reinforced polymers.

Many fillers were tested in order to find the best ratio between heat transfer efficiency and cost because a large number of ceramic products intended for heat transmission can be found on the market but their price is too high to release interesting alternatives to metals. The choice fell on a few metal oxides, no salt nor carbide nor nitride. Latter ceramics were also discarded for their extreme hardness resulting in severe wear of molding machines, nozzles and mold cavities.

Once thermal conductivity is obtained other properties have to be provided, mainly mechanical performance. First attempts led to extremely brittle materials, easily breakable even during production. An extra content of a specific elastomer can be added: for this goal many different additives had to be tested to find chemically affine modifiers showing adequate thermal behavior.

Even if the modified material features a lower amount of PA12, the presence of elastomers does not affect thermal performance of the heat sink.
Thanks to intrinsic white color of the filler, this thermally conductive grade met with the taste of designers being colorable and shades of grey and black have been chosen to provide extra aesthetic features to the product on the market.

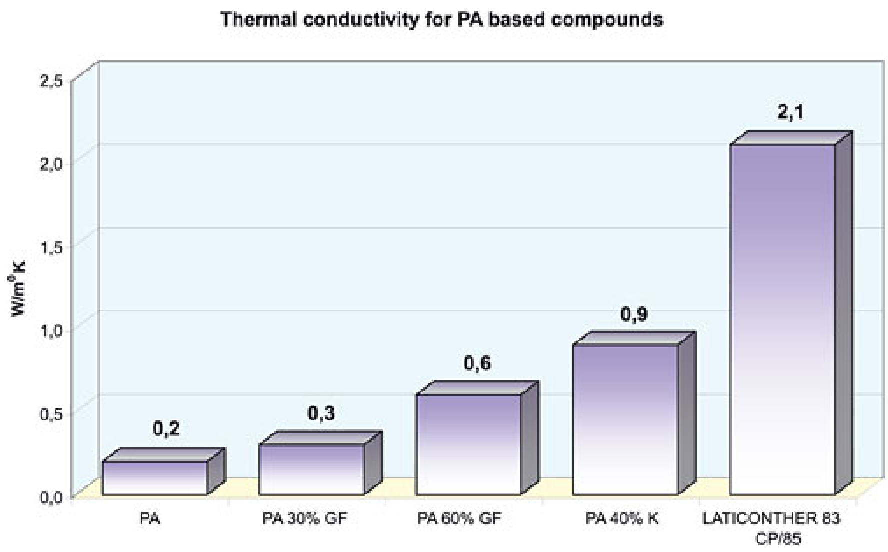

Fig. 8. thermal conductivity for PA based compounds featuring different fillers

Project development – thermal analysis

PROPERTY	LATICONTHER 83 CP/85	LATICONTHER 82 CP/80
DENSITY (g/cm^3)	3.09	2.88
LOAD AT BREAK (MPa) – ASTM D638	16	30
ELONGATION AT BREAK (%) - ASTM D638	5	0.8
ELASTIC MODULUS (MPa) – ASTM D638	900	7500
IZOD IMPACT (J/m)	90	60
DIELECTRIC STRENGTH (kV/mm)	25	25
THERMAL CONDUCTIVITY (W/m^{0}K)	2.1	2.0

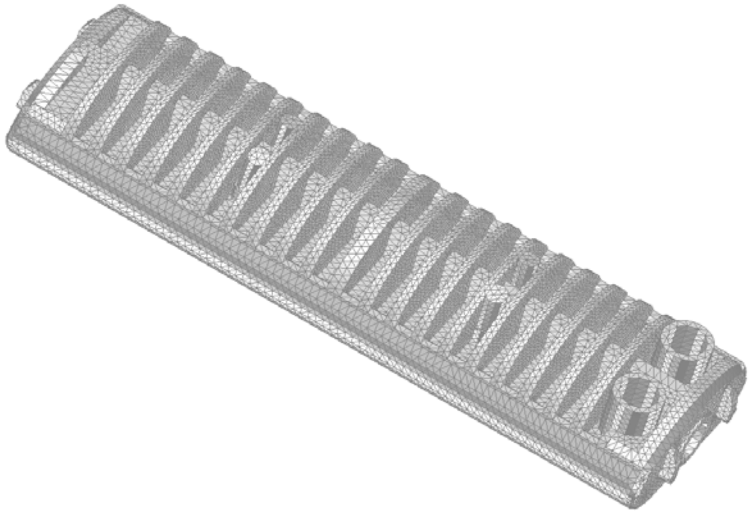

Fig. 09 – radiator finite element structure ready for computer simulation

Innovative products must undergo a deep and accurate project development process to achieve the best time to market and cost effective engineering.
Idealed and LATI worked in close contact to check out part feasibility, heat exchange efficiency, geometry design, mold layout and to tune in the molding process.
The very first step was to verify how thermally conductive compounds may replace aluminum heat sinks. Accurate finite element analysis has been performed in order to find out the most adequate cooler layout and fins design allowing the part to be cooled by natural convective air flow without any help coming from fans or external cooling devices. A model of the radiator based on tetrahedic and hexahedric elements has been generated and LEDs have been simulated as ideal heat sources.

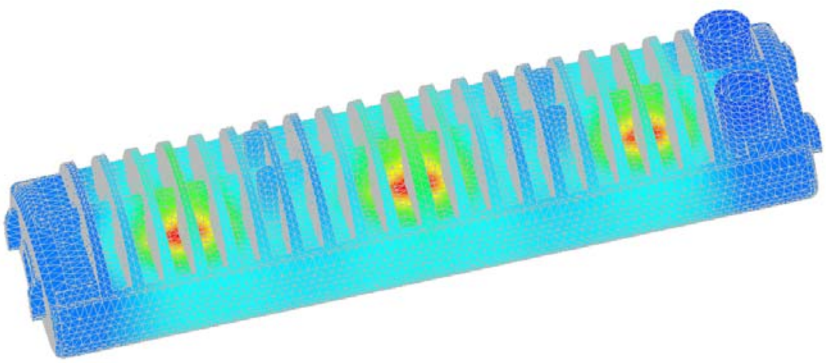

FIG.10 – Thermal finite element analysis, temperature output

The following boundary conditions have been applied during the calculation, introducing also several pessimistic hypothesis to carefully evaluate any possible hazard:

- steady state, no diffusive phenomena considered;
- natural air convection, ambient temperature = 25°C;
- nominal power input, per LED = 3W;
- LED conversion efficiency (also known as wall plug efficiency) = 30%;
- LED junction temperature = 80°C;
- full isotropy of material properties.

Hypothesis on wall plug efficiency are particularly strict for currently available LED sources, whose conversion can be higher than 40% and nears best fluorescent solutions.
As well known, junction temperature must be considered as the maximum temperature allowing the LED to work properly so 80°C was taken into consideration as upper limit, looking for lower values in order not to shorten the diode life.
A test material was used during the FE simulations to find out the most efficient fins layout whose structure had to be not just effective toward heat exchange but had also to be feasible by injection molding. For this reason no walls thinner than 1-1.5 mm were admissible and spacing among the fins had to be reasonably wide in order to guarantee proper filling, packing and extraction from the cavity. Pins were tested instead of fins but the feasibility of this solution, albeit very efficient, can not be considered because of the hazard of multiple breakages in the mold.
Once the heat sink gross layout has been checked and fixed via FEA, several different materials have been introduced in the discrete element property definition to understand how far it is possible to risk using conductive compounds. Results are show in the table below.

As evidenced by these data, polymeric heat sink is not conceivable unless specific thermal

HEAT SINK MATERIAL	LED TEMPERATURE
ALUMINUM	37^0 C
PA66 G/30	150^0 C
LATICONTHER 83 CP/85	65^0 C

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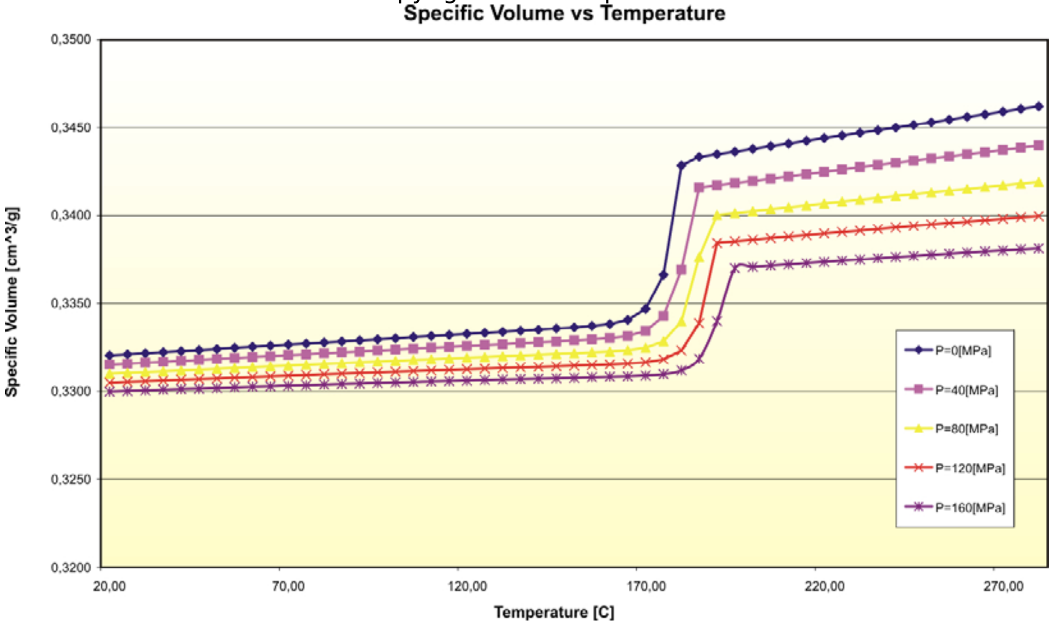

Fig.11 – PVT curves of 85% ceramic filled compound

properties are featured by the product. Ordinary PA66 30% glass fiber would not be suitable because of the excessive temperature reached next to the LED heat source. Although aluminum might guarantee 37°C, thermally conductive compounds allow the generated heat to be removed in a rather satisfactory way, scaling temperature down to 60°C close to the LED and to 45°C all over the fins surface.

Project development – fluid dynamical analysis

Because of particular thermal properties and extremely high filler content, molding of such a kind of compound must be intended as a new frontier of transformation process also for experienced molders and tool designers.

The following problems can be easily foreseen and have to be duly verified before proceeding:

- quick material cooling
- high melt viscosity
- uneven shrinkage behavior
- unpredictable deformation
- abrasion on screws, nozzles and equipment

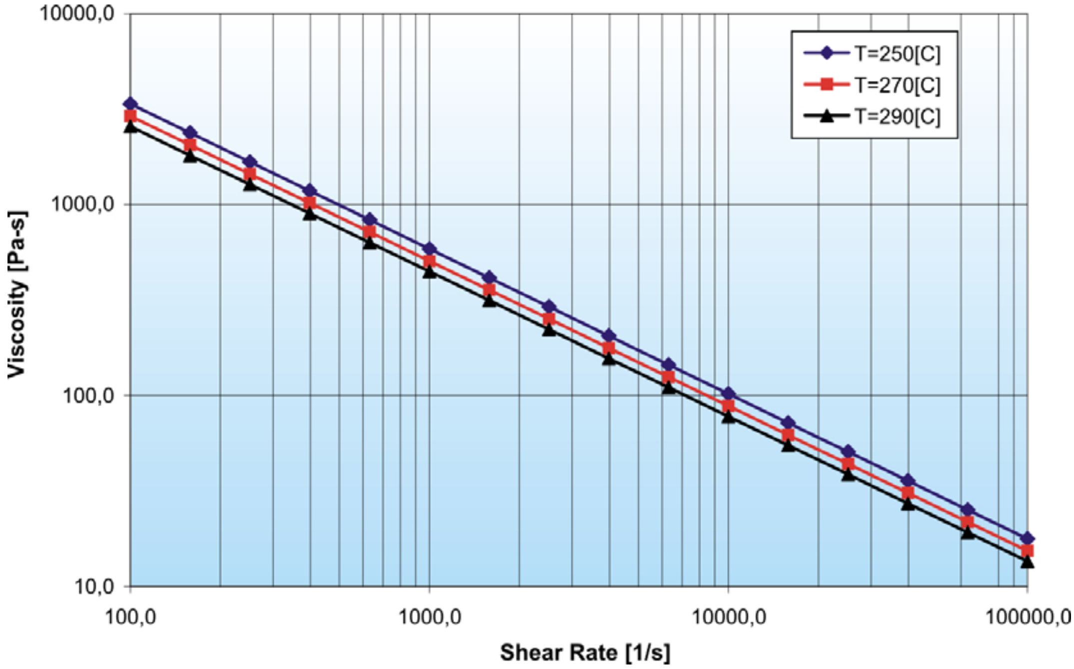

Fig.12 – viscosity vs. shear of 85% ceramic filled compound

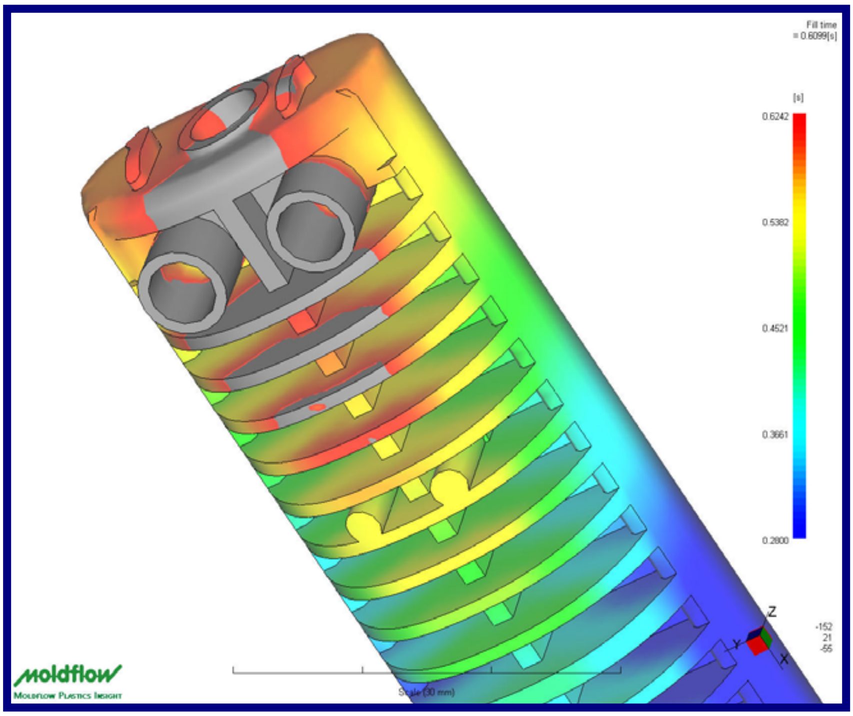

Fig.13 – short shot issues as detected by fluid-dynamical computation simulating mould filling

- extraction issues

A complete fluid dynamical simulation has been carried out including shrinkage, deformation and cooling process. The material has been thoroughly investigated and characterized to have a detailed description of rheological, PVT and mechanical properties.

By means of this numeric simulation many of the previously highlighted problems have been confirmed.

a – quick cooling. The melt compound freezes within an unusual short time, leading to short shots all over thinner walls as fins and seats. In addition to this severe issue, cooling reduces by far the packing pressure transmission generating warpage and deformation in the part because of not compensated local contraction of the polymer. Rapid freezing of gates and sprue forces the discarding of cheaper feeding solutions such as submarine gates, long runners on multi-cavity systems etc. To solve feeding issues the cavity has to be filled through a relatively wide double gate, section 4x3 mm, fed by a single short trapezoidal runner.

b – high melt viscosity. Because of the huge amount of filler – up to 85% - ceramic powders used for this conductive compound have been chosen also checking different melt viscosities. Molding conditions have been finely tuned to improve melt flow into the cavity:

- melt temperature = 255°C
- mold temperature = 70°C

Injection location has been carefully evaluated via simulation and testing in order to promote quick filling of the base of the radiator, leaving empty fins cavities until the end of the filling process. Fins are completed during the last phase when, thanks to a rapid melt flow front acceleration, shear rates generate friction peaks leading to local overheating and increased fluidity

c - uneven shrinkage behavior.
The heat sink geometry features large thickness differences between the walls of the electronic board enclosure and the fins.
Shrinkage is normally evaluated on a 3.5 mm thick specimen and for Laticonther 83 the following linear values apply:

- longitudinal 0.9-1.1%
- transversal 0.9-1.1%

With respect to nominal shrinkage data, it can be easily figured out how local linear shrinkage values can vary from a minimum of 0.2%, e.g. on the fins, up to 1.6-1.8% and even higher, e.g. along the frame of the circuit board enclosure. Fluid Dynamical simulation show consistent differences between peaks in volumetric shrinkages, the highest value being 10% along the massive board frame.

d - deformation. Although physical properties of this Laticonther grade can be considered as completely isotropic, large shrinkage differences due to wall thicknesses lead to local frozen tensions. Warpage occurred bending the manufactured product as shown. This kind of deformation was found on the first molded parts and was completely unacceptable because of its consequences on the electronic circuit board and on the sealing.
Besides obvious deformation issues, frozen tensions due to shrinkage promote cracks across the part that can be easily released because of the material intrinsic brittleness. Despite elastomer modification, it was necessary to introduce thermal annealing to guarantee a completely safe operation.

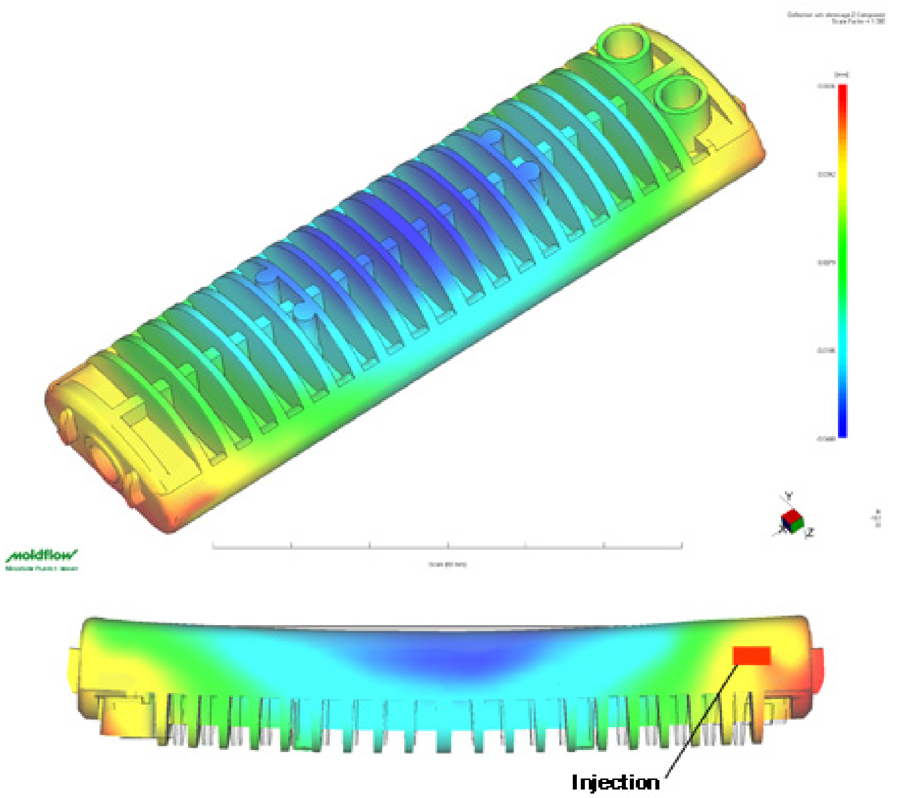

Fig.14 – deformation of the radiator as estimated via FEA

No further improvement could be made by increasing packing pressure as the electronic LED board might have been damaged.

e - wear on equipment. High shear stresses are typical of injection molding process, specially on gates, runners and along thinner walls. To avoid severe damage to extrusors, molding machines and mold only fillers with low abrasivity have been compounded into the material. Special steel has been applied to those mold regions where high friction was predicted.

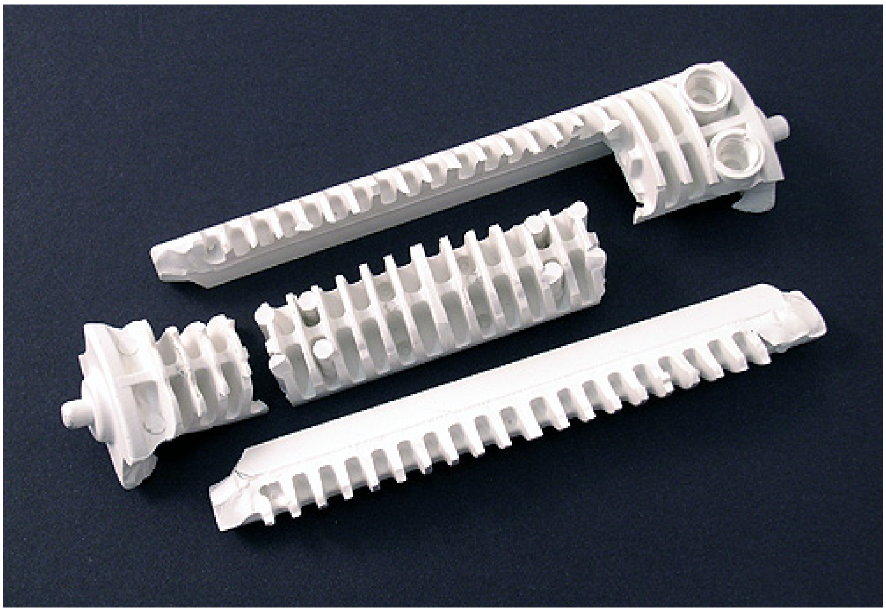

Fig. 15 – radiators broken during extraction

f - extraction issues. Resulting deformations and very quick cooling caused the part not to be released properly from the mold. Very low shrinkage of immediately freezing thinner walls was a severe consequence of high thermal conductivity of the compound leading to excessive breakage ratio of fins. Intrinsic brittleness of the material and extractors thrust were concause of sudden breakages during extraction. Those issues were solved by shortening cooling time, by polishing the mold below 0.40 Ra, by revising draft angle up to 3-5°.

It was not immediate to evaluate the right number of fins guaranteeing an efficient cooling and allowing the part to be filled on a feasible and well engineered mold. After some simulations and test trials it was decided to implement 1.5 mm thick fins spaced by 3 mm in order to promote convective heat extraction from the radiator.

6 - Conclusions

LED technology and thermally conductive thermoplastic compounds, various experiences and ideas coming from engineers belonging to different sectors, here working together to give birth to a new innovative product. For both technical solutions a bright future has to be foreseen. Many opportunities for LED based lighting devices and good metal replacement possibilities for conductive compounds can become a reality by means of engineering and codesign.

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