Breakthrough in Power Magnetics Materials
功率磁性材料的突破

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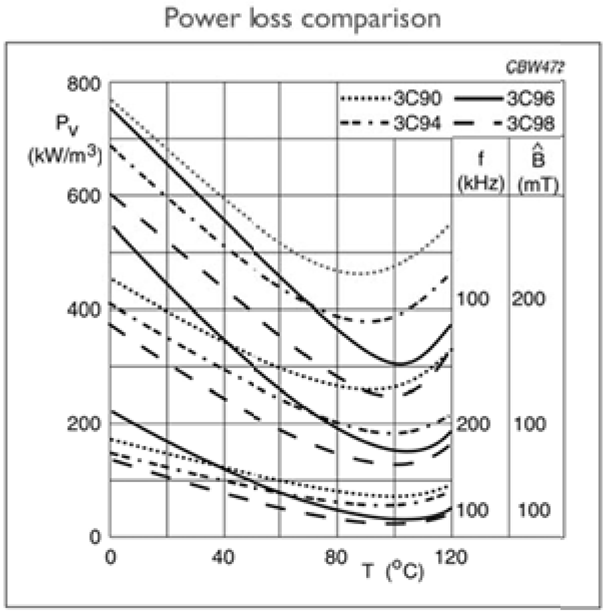
With the advancements in Gallium Nitride (GaN) and Silicon Carbide (SiC) materials in the last 5 ‑ 10 years there has been renewed interest in advancements in magnetic materials for power inductors and transformers. The last few years at the Applied Power Electronics Conference and Exposition (APEC) there have been more intense discussions regarding the future of power magnetics materials.

过去5 - 10年间，氮化镓（GaN）和碳化硅（SiC）材料取得长足发展，因此业界对功率电感和变压器的磁性材料的发展重新产生了兴趣。在最近几年的国际电力电子应用会议暨展览会（APEC）上，关于功率磁性材料未来发展方向的讨论越发激烈。

Incremental Improvements in Magnetics Core Materials
磁芯材料的渐进式改进

The ferrite and powdered core manufacturers have been making incremental improvements to their various materials in the last few decades. The saturation flux densities of ferrite materials have increased and core losses for both ferrite materials and powdered core materials have been reduced in general. Figure 1. compares the core losses for 3C90 ferrite (released in early 90’s) with various ferrite materials released up until 2014. The graph clearly shows the incremental reduction in core loss from 3C90 to 3C98. However, even with these improvements design engineers are always asking for further improvements in core materials.

在过去几十年中，铁氧体和粉芯制造商一直在对其各种材料进行渐进式改进。铁氧体材料的饱和磁通密度增加，铁氧体材料和粉芯材料的铁损大幅降低。图1比较了90年代初期推出的3C90铁氧体磁芯与截至2014年发布的各种铁氧体材料的磁芯损耗。该图清楚地显示了从3C90到3C98的磁芯损耗递减。然而，即使有了这些改进，设计工程师仍不断要求进一步改进磁芯材料。



功率损耗比较

Figure 1. Core losses from Ferroxcube 3C96－3C98 Brochure
图1. Ferroxcube 3C96 - 3C98手册给出的磁芯损耗

For some time now, design engineers desired the soft saturation characteristics of a powdered core, but with the core losses closer to those of a power ferrite material. Design engineers presently either have to use ferrite cores with a large gap, litz wire, and implement construction methods to deal with the fringing flux losses or use powdered cores and deal with the high core losses. Some have used hybrid solutions where they used one ferrite E core half and one powdered E core half, but those have been in the minority.

近些年来，设计工程师都很看重粉芯的软饱和特性，但是希望其磁芯损耗能够达到接近功率铁氧体材料的水平。目前设计工程师要么使用气隙较大的铁氧体磁芯，利兹线，并借助结构方法来解决边缘磁通损耗，要么使用粉芯并想办法解决高磁芯损耗。一些人使用了混合解决方案，让磁芯一半使用铁氧体E磁芯，另一半使用粉末E磁芯，但是这样的解决方案并不多见。

New MAGMENT Core Material
新MAGMENT磁芯材料

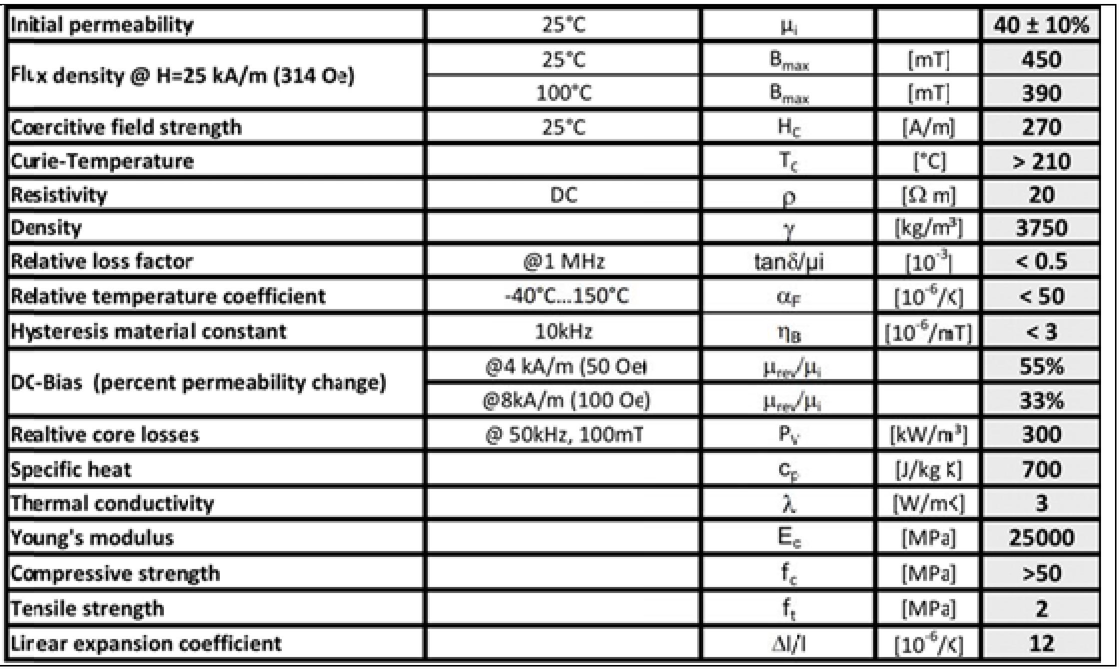
In 2016 MAGMENT (MAGnetic ceMENT) introduced a novel core material that has the highly desired combination of soft saturation characteristics of powdered core material and an almost 60% reduction in core losses when compared to SiFe powdered core materials. This material is a patented concrete with magnetizable particles embedded in a cement matrix manufactured in a pressureless process. Furthermore, the magnetizable particles are actually recycled ferrite with carefully selected characteristics. The features of this MAGMENT material are:

2016年，MAGMENT（MAGnetic ceMENT）推出了一种新型磁芯材料，是粉芯材料软饱和特性与磁芯损耗减少近60％（与铁硅粉芯材料相比）的高度理想组合。这种材料是一种专利混凝土，可磁化颗粒经由无压工艺嵌入水泥基体。此外，可磁化颗粒实际上是拥有精选特性的再利用铁氧体。这种MAGMENT材料的特点是：

- Permeability in the same range as powder core materials
  与磁粉芯材料拥有相同数量级的导磁性
- High DC-bias capability
  高直流偏置性能
- Saturation reached only at very high fields
  仅在极高磁场中达到饱和
- Very low core losses
  极低的磁芯损耗
- Very high thermal conductivity to efficiently dissipate heat
  极高的导热率，热量快速消散
- Concrete-like mechanical robustness in a very broad temperature range
  在极宽的温度范围内，保持与混凝土同样的机械强度

MAGMENT’s first released material has a permeability of 40 and is designated as MC40. The material details are shown in Figure 2. MAGMENT in 26 (MC26) and 60 (MC60) permeabilities are being developed now and will be released later in 2017.

MAGMENT的第一代材料磁导率为40，命名为MC40。材料详情如图2所示。目前正在开发磁导率为26（MC26）和60（MC60）的MAGMENT，并将于2017年晚些时候推出。



初始磁导率	Initial permeability	25°C	μ_i		40 ± 10%
磁通密度@H=25kA/m（314 Oe）	Flux density @ H=25 kA/m (314 Oe)	25°C	B_{max}	[mT]	450
		100°C	B_{max}	[mT]	390
矫顽磁场强度	Coercitive field strength	25°C	H_C	[A/m]	270
居里温度	Curie-Temperature		T_C	[°C]	> 210
阻抗	Resistivity	DC	ρ	[Ω m]	20
密度	Density		γ	[kg/m^3]	3750
相对损失系数	Relative loss factor	@1 MHz	$\tan\delta/\mu i$	[10^{-3}]	< 0.5
相对温度系数	Relative temperature coefficient	-40°C...150°C	α_F	[10^{-6}/K]	< 50
磁滞材料常数	Hysteresis material constant	10kHz	η_B	[10^{-6}/mT]	< 3
直流偏置（磁导率变化百分比）	DC-Bias (percent permeability change)	@4 kA/m (50 Oe)	μ_{rev}/μ_i		55%
		@8kA/m (100 Oe)	μ_{rev}/μ_i		33%
相对磁芯损耗	Realtive core losses	@ 50kHz, 100mT	P_V	[kW/m^3]	300
比热	Specific heat		c_p	[J/kg K]	700
导热率	Thermal conductivity		λ	[W/mK]	3
杨氏模量	Young's modulus		E_c	[MPa]	25000
抗压强度	Compressive strength		f_c	[MPa]	>50
抗张强度	Tensile strength		f_t	[MPa]	2
线性膨胀系统	Lirear expansion coefficient		$\Delta l/l$	[10^{-6}/K]	12

Figure 2. Technical Data for MAGMENT MC40 material grade
图2. MAGMENT MC40材料等级的技术数据

For further information on the MAGMENT MC40 material refer to the full datasheet.
有关MAGMENT MC40材料的更多信息，请参阅官方网站上完整的参数表。

MAGMENT not only created a material with soft saturation characteristics and lower core losses, but the MAGMENT material allows for the reduction of manufacturing costs and therefore, overall power inductor costs. Traditionally large power inductor designs are wound around a large powdered toroid or on a bobbin with E cores then inserted in to the wound bobbin. In other words, the winding follows the core geometry. For some larger power designs, the finished inductor is then placed in an aluminum case for optimal heat dissipation and encapsulated with an epoxy that has some thermally conductive capabilities. This is especially done with inductors that will be exposed to harsh environments.

MAGMENT材料不仅具有软饱和特性和较低磁芯损耗，而且其制造成本得到进一步降低，从而降低了功率电感的整体成本。传统上，大功率电感设计时，铜线缠绕在大型粉末环形线圈上，或缠绕在具有E磁芯的骨架上，然后再插入缠绕骨架中。换句话说，绕线要由磁芯的几何形状决定。对于一些更大功率设计，可将成品电感元件随后放置在一个铝制外壳中，以获得最佳的散热效果，并用具有一定导热能力的环氧树脂封装。该设计尤其适合于恶劣环境中工作的电感元件。

On the contrary, when using MAGMENT material the appropriate air coil is designed, along with the appropriate Aluminum box, and then the MAGMENT material is simply poured over the air coil that is centered in the Aluminum box. This ensures a complete magnetic filling of the available volume within the housing yielding maximum performance and cooling. With a MAGMENT design the core geometry follows the winding. As compared to the conventional manufacturing of winding around cores and sealing with a potting material, the flowability of MAGMENT materials allow for simple “wind and magnetic pour” process, which goes along with absolute shape and size flexibility. This allows to both tailor components to minimize material utilization and to any given space constraints by a special magnetic design algorithm yielding lowest cost as compared to any other inductive technology.

当使用MAGMENT材料设计电感元件时，只需采用相应的空心线圈与铝制外壳设计，并将MAGMENT材料简单浇筑在铝制外壳中央的空心线圈上即可。这确保了磁性材料在壳体内达到其最大填充容积，从而获得最佳的性能和冷却效果。采用MAGMENT设计时，磁芯的几何形状取决于绕线方式。与绕线的常规制造方法相比，即围绕磁芯绕制并用灌封材料封装，MAGMENT材料本身具有的流动性使得简单的“绕制和磁性浇注”工艺成为可能，同时带来绝对的形状和尺寸灵活性。由此我们可以通过定制组件来尽可能减少材料用量，以及通过专有的磁性设计算软件来打破设计空间限制，得到比任何其他电感技术都更低的成本。

See figure 3 for an example of a MAGMENT power inductor. The design algorithm can minimize either cost or total losses.
参见图3，MAGMENT功率电感元件示例。我们的设计计算软件可以尽可能降低成本或总损耗。

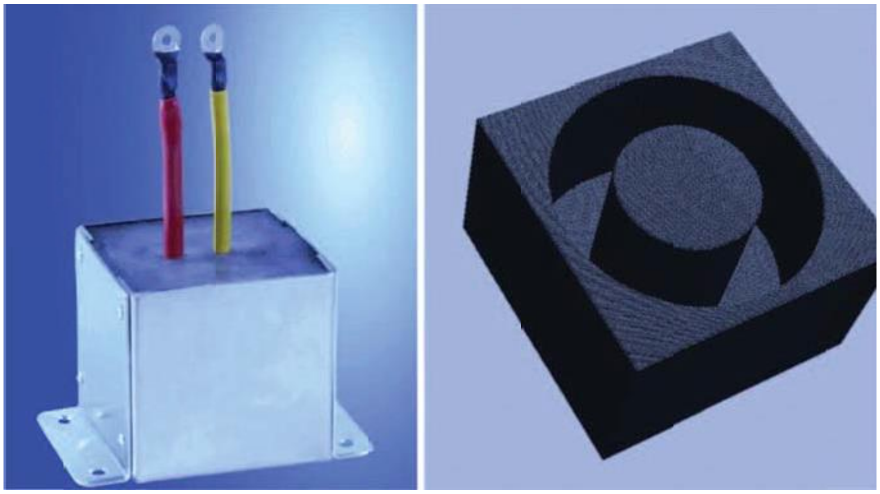
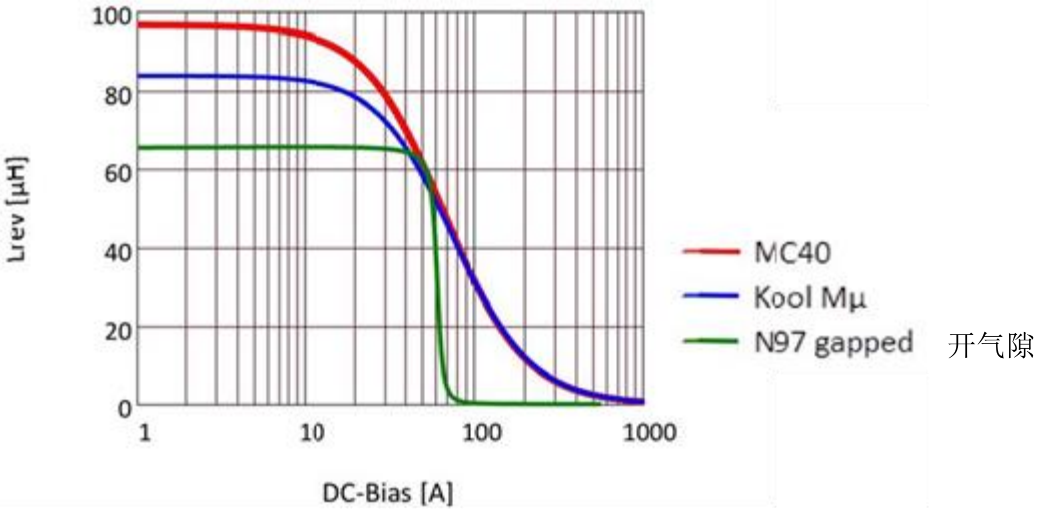


Figure 3. MAGMENT inductor (left) depicting its magnetic material shape (right)
图3. MAGMENT电感元件（左）与其内部磁性材料形状（右）

With this proprietary design algorithm MAGMENT optimizes the electrical design and core geometry which results in the typical inductance vs. current curve shown in figure 4.

采用这种专有的设计计算软件，MAGMENT可以优化电气设计和磁芯几何结构，从而得到如图4所示的典型电感与电流曲线。



直流偏置[A]

Figure 4. Inductance vs. Current of geometry optimized MAGMENT inductor
图4. 经MAGMENT电感元件几何优化后的电感与电流

Comparing a Traditional Power Inductor to a MAGMENT Power Inductor
传统功率电感元件与MAGMENT功率电感元件相比较

A customer approached MAGMENT with the traditional inductor shown in Figure 5. It used a SiFe 40µ toroid with an inductance of 34 µH @ 30A peak. This inductor had the following mechanical dimensions: 45 mm x 45 mm x 28 mm and the customer requested a MAGMENT inductor with the same mechanical dimensions, less overall losses, and a reduced cost.

图5显示了一个客户向MAGMENT提供的传统电感样式。它使用了一个SiFe 40μ环形线圈，30A峰值电流下的电感为34μH。该电感具有以下机械尺寸：45 mm x 45 mm x 28 mm，客户要求MAGMENT电感具有相同的机械尺寸，更少的整体损耗和更低的成本。

Figure 5. Traditional inductor using SiFe 40µ － 34µH @ 30Apeak
图5. 使用SiFe的传统电感元件在30A峰值电流时产生40μ- 34μH的电感

Additional data on the traditional inductor the customer provided is shown in Table 1.
客户提供的传统电感元件的附加数据如表1所示。

								损耗[W]				重量[g]	
								磁芯	DCR损耗	ACR损耗	总计	磁芯	铜
								LOSSES [W]				WEIGHT [g]	
	µ	N	le [mm]	Ae [mm²]	DCR [mOhm]	ACR [mOhm] @ 75 kHz	B [mT]	Core	DCR LOSSES	ACR LOSSES	Total	Core	Copper
Traditional Inductor	40	34	81.5	67.2	10	566	45	1.20	4.49	0.41	6.10	39	50
传统电感元件													

Table 1. Technical data for Traditional inductor using SiFe 40µ.
表1. 使用SiFe 40μ的传统电感元件的技术数据。

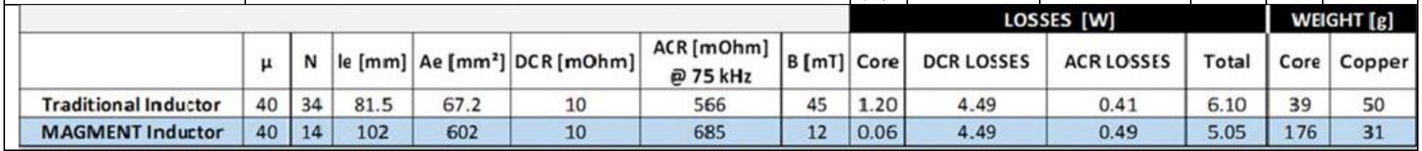
The MAGMENT design team used the proprietary design algorithm mentioned earlier and developed a MAGMENT inductor very similar to the one shown in Figure 6. The final MAGMENT inductor met the requested mechanical dimensions of 45 mm x 45 mm x 28 mm and had an almost 18% reduction in overall losses. Equally a important, the MAGMENT inductor is approximately 25% less in cost.

MAGMENT设计团队使用前面提到的专有设计计算软件，开发了一个与图6所示非常相似的MAGMENT电感元件。最终MAGMENT电感满足了45 mm x 45 mm x 28 mm的机械尺寸，同时整体损耗减少了近18％。同样重要的是，MAGMENT电感的成本降低了大约25％。

Figure 6. Typical MAGMENT inductor using MC40 40µ
图6. 用MC40 40µ材料制成的典型MAGMENT电感元件

Table 2 compares the MAGMENT inductor to the traditional inductor in detail. One of the first things to note is that the turns of the MAGMENT inductor are reduced by almost 60% and this is possible because of the large core area of the MAGMENT inductor. Consequently, the flux density of a MAGMENT inductor was reduced by 74%. This is possible because as mentioned earlier with a MAGMENT design the core geometry follows the winding. Finally, the core loss of the MAGMENT inductor is only 0.06 W while the traditional inductor had 1.20 W of core loss. This large reduction in core loss in the MAGMENT inductor results in the almost 18% reduction in overall losses.

表2详细将MAGMENT电感元件与传统的电感元件进行了比较。首先要注意的是，MAGMENT电感元件的圈数减少了近60％，因为MAGMENT电感元件的磁芯面积很大。因此，MAGMENT电感元件的磁通密度减少了74％。能实现这一点是因为之前提到的MAGMENT设计中磁芯的几何形状取决于绕线。最后，MAGMENT电感元件的磁芯损耗仅为0.06W，而传统电感元件的磁芯损耗为1.20W。MAGMENT电感元件的磁芯损耗大大降低，总体损耗降低了近18％。



								损耗[W]				重量[g]	
								磁芯损耗	DCR损耗	ACR损耗	总计	磁芯	铜
								LOSSES [W]				WEIGHT [g]	
	µ	N	le [mm]	Ae [mm²]	DCR [mOhm]	ACR [mOhm] @ 75 kHz	B [mT]	Core	DCR LOSSES	ACR LOSSES	Total	Core	Copper
Traditional Inductor	40	34	81.5	67.2	10	566	45	1.20	4.49	0.41	6.10	39	50
MAGMENT Inductor	40	14	102	602	10	685	12	0.06	4.49	0.49	5.05	176	31
传统电感元件													
MAGMENT电感元件													

Table 2. Traditional inductor and MAGMENT inductor comparison – 34uH @ 30Apeak
表2. 传统电感元件在30A峰值电流时产生的电感

The inductance vs. current graph in figure 7 clearly shows that the performance of the MAGMENT inductor at peak current is equivalent to the traditional inductor.

图7中的电感与电流的关系图清楚地表明，MAGMENT电感在峰值电流下的性能与传统电感相当。

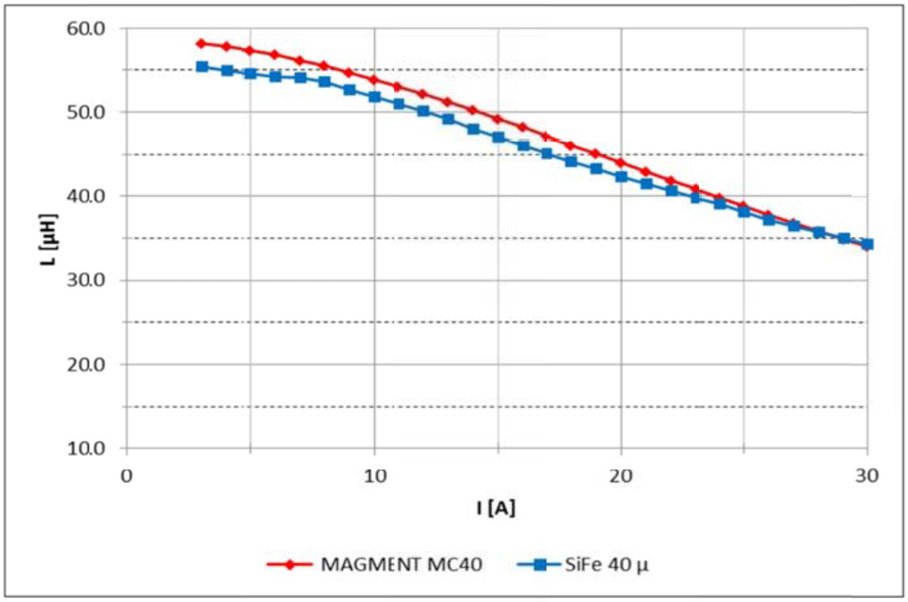


Figure 7. Inductance vs. Current comparison of MAGMENT and Traditional Inductor
图7. MAGMENT与传统电感的电感与电流比较

Further Analysis
深入分析

While reviewing table 2 it is evident that this particular MAGMENT inductor will weigh more as a result of the MC40 material which weighs more when compared to the SiFe material. In the above comparison, if the size of the inductor was not a constraint then the losses of the MAGMENT inductor could be further reduced. It is important to note that since a MAGMENT inductor generally will have more surface area than a traditional inductor the MAGMENT inductor can have higher DCR and yet have less measured temperature rise. In this comparison the traditional inductor has a calculated thermal resistance of 24.6℃/W which results in calculated temperature rise of 150℃. On the contrary, the MAGMENT inductor has a calculated thermal resistance of 7.3℃/W which results in a calculated temperature rise of 37 ℃. MAGMENT inductors tested by customers in their application circuit have shown the benefits of the larger surface area and resulting reduced temperature rise.

如表格2所示，与SiFe材料相比，由于MC40材料的重量更大，很明显这种特定的MAGMENT电感元件将更重。在上面的比较中，如果电感的尺寸不再成为一个约束条件，那么MAGMENT电感的损耗可以进一步降低。需要注意的是，由于MAGMENT电感元件的表面积通常比传统电感元件的更大，所以MAGMENT电感可以具有更高的DCR，但是测得的温升却更低。在这项比较中，传统电感的热阻计算值为24.6° C/W，计算出的温升为150° C。相比之下，MAGMENT电感的热阻计算值为7.3° C/W，计算出的温升为37° C。由客户在其应用电路中测试的MAGMENT电感已经表现出更大表面积带来的益处，以及由此带来的温升降低。

Conclusion
结论

The proprietary magnetic design algorithm is a powerful tool that the MAGMENT design team utilizes to completely optimize MAGMENT inductors for all types of applications. Future application notes will discuss total losses further and the magnetic design algorithm in more detail. The MAGMENT material is a magnetic material that is revolutionary and as mentioned in beginning of this application note has the following features:

我们专有的磁性设计计算软件是MAGMENT设计团队为各种应用领域的电感元件进行全面优化的强大工具。在未来更多的应用说明中，我们将进一步详细讨论总体损耗和磁性设计算法。MAGMENT材料是一种革命性的磁性材料，如本应用说明的开头所述，其具有以下特点：

- Permeability in the same range as powder core materials
  与磁粉芯材料拥有相同数量级的导磁性
- High DC-bias capability
  高直流偏置性能
- Saturation reached only at very high fields
  仅在极高磁场中达到饱和
- Very low core losses
  极低磁芯损耗
- Very high thermal conductivity to efficiently dissipate heat
  极高导热率，热量快速消散
- Concrete-like mechanical robustness in a very broad temperature range
  在极宽的温度范围内，保持与混凝土同样的机械强度
- In general, lower costs when compared to equivalent traditional inductors.
  一般来说，与等效传统电感元件相比，其成本更低。