BAOSTEEL

新能源汽车驱动电机用无取向电工钢

NON-ORIENTED ELECTRICAL STEELS
FOR TRACTION MOTOR
OF CLEAN-ENERGY VEHICLES

EVI

创享改变生活 Creation Beyond Vision

宝钢电工钢
Baosteel Electrical Steel

CERTIFIED
Intertek

1 宝钢EVI理念 | EVI Philosophy in Baosteel

成为用户真诚可靠的材料供应商及其解决方案的合作者，实现可持续、共赢发展。

To be a sincere and reliable partner for our customers in providing electrical steels and solutions to achieve win-win collaboration for sustainable development.

2 宝钢EVI文化 | EVI Culture in Baosteel

用户思维——源于用户、服务用户、成就用户

协同思维——同一目标、网式工作、众口同声

进取思维——精于专业、诚于奉献、超越期待

Customer Thinking——From customer, Serve customer, Achieve customer

Synergy Thinking——Same target, Net-working, One voice

Enterprising Thinking——Professional, Sincere dedication, Exceed expectation

3 宝钢新能源汽车驱动电机用无取向电工钢EVI | Non-oriented Electrical Steel's EVI in Baosteel for Traction Motors of Clean-energy Vehicles

宝钢为新能源汽车驱动电机提供从选材设计到产品制造的技术支持

- 电机设计选材支持，实现目标性能和控制成本；
- 铁芯用材和结构优化，实现性能提升或技术降本；
- 铁芯加工制造支持，实现材料与装备最佳匹配；
- 新产品、新技术的推荐应用，提升新能源汽车的竞争力。

Baosteel could offer a variety of specialized services and technical support from material selection in design to manufacturing of iron cores of traction motors for clean-energy vehicles, including:

- To support customers in electrical steel grade selection for motor design to achieve target performance and cost control.
- To support customers in optimization of material and structure of motor core to achieve performance improvement or cost reduction.
- To support customers in iron core manufacturing to achieve a good match between material and working facilities.
- To recommend customers with new products and new technology to improve the competency of their new products.

4 新能源汽车驱动电机用无取向电工钢产品体系 | Non-oriented Electrical Steel Product System for Traction Motor of Clean-energy Vehicles

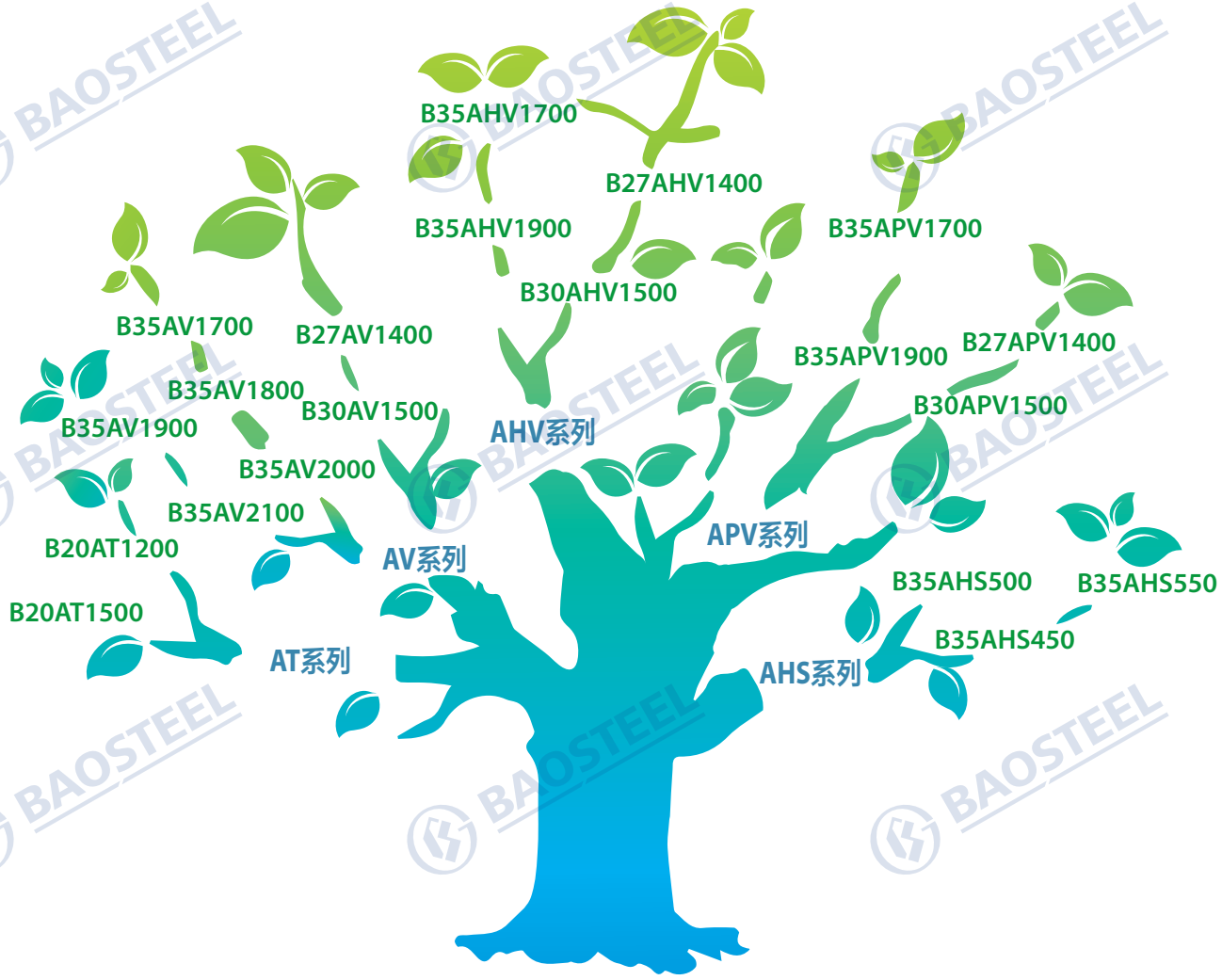
永磁同步电机是新能源汽车驱动电机的发展主流，要求具有高效率、高转矩、高安全性以及小体积等特性。

宝钢的系列无取向电工钢产品具有中高频低铁损、高磁感和高强度的特点，满足各类电机的设计和运用需要。

- 低损耗AV系列：具有低铁损、高强度系列化的特点；
- 高效AHV系列：磁感、铁损、强度三者综合性能优异；
- 高磁感APV系列：更高的磁感，满足高转矩、电机小型化的需求；
- 高强度AHS系列：高强度，应用于高转速或超高转速转子；
- 薄带AT系列：中高频下低铁损，应用于高转速或超高转速电机。

新能源汽车驱动电机用无取向电工钢产品树

Product Tree of Non-oriented Electrical Steels for Traction Motors of Clean-energy Vehicles



Permanent magnet synchronous machine (PMSM) is the mainstream of traction motor of clean-energy vehicles, requiring high efficiency, high torque, high reliability, compact volume, and etc. Non-oriented electrical steel series in Baosteel could meet the requirements from all kinds of high performance motors with features of low iron loss at mid and high frequency, high induction density and high strength.

- Low loss AV series: low iron loss, high strength;
- High efficiency AHV series: good overall performance in induction density, iron loss and strength;
- Super induction APV series: high induction density to satisfy the needs for high torque and compact design of motors;
- High strength AHS series: high strength for high speed rotor of high speed motors;
- Thin gauge AT series: low iron loss in mid and high frequency for high speed motors.

5 新能源驱动电机用无取向电工钢全面技术解决方案 | Total Solutions of Non-oriented Electrical Steel for Traction Motor of Clean-energy Vehicles

A

涵盖宝钢所有牌号产品的电磁、力学、涂层性能。

Covering all Baosteel grades , the database has the magnetic, mechanical and coating properties of the products.

B

利用电磁仿真软件有效分析各牌号应用的电机特性（效率、力矩）

Analysis of motor performance (i.e., efficiency, torque) with simulation software

D

总结整理冲片、叠片、焊接、装配等一般性规律，为快速处理类似问题提供指导。

Manufacturing problem solving solutions accumulated for reference guidance to quick trouble shooting in punching, laminating, welding, assembling process

C

铁芯片激光切割设备
铁芯片线切割设备
铁芯损耗测试仪
电机性能测试平台

Laser cutting machine, and wire-electrode cutting machine for prototype core making; Iron loss tester, motor testing platform

5.1 完善的材料数据库支持 Complete Material Database Support

电磁仿真设计

- 各种交直流磁化曲线数据
- 特殊波形下交流磁性
- 直流偏置磁性

Magnetic simulation for motor design

- DC &AC magnetization curves
- AC magnetization curves under special waveforms
- DC offset magnetization curves

安全性设计

- 高低温下力学性能变化
- 高低温下磁性变化

Safety design

- Changes in mechanical property with temperature
- Changes in magnetic performance with temperature

转子应力分析

屈服强度、抗拉强度
疲劳强度、弹性模量

Stress analysis in rotor

Yield strength, tensile strength,
fatigue strength, elastic modulus

冷却系统设计

导热系数、热膨胀系数

Cooling system design

Heat coefficient, expansion coefficient

持续更新和完善的新能源汽车驱动电机用无取向电工钢性能数据库，为用户提供从机械性能、基础电磁性能及特殊工况性能等一系列全套的数据支持。根据用户的多样化需求，可提供性能指标与原始曲线数据等各种形式数据。

An updating and complete database of non-oriented electrical steel for traction motor of clean-energy vehicles provides our customers a strong support with mechanical properties, magnetic properties under normal and special working conditions. Data could be in format of performance index or original test curves points according to customers' requirement.

新能源汽车驱动电机用无取向电工钢性能数据库
Non-oriented Electrical Steel Database for Clean-energy Vehicles

典型电磁性能 Typical magnetic properties	**高低温机械性能** (-40℃~250℃) Mechanical properties at various temperatures (-40℃~250℃)	**其他物理性能** Other physical properties
20Hz~10kHz交流磁化曲线 20Hz~10kHz AC Core loss Curves	**屈服强度** Yield strength(N/mm^2)	**导热系数** Heat coefficient
直流磁化曲线 D.C. Magnetization Curve	**抗拉强度** Tensile strength(N/mm^2)	**膨胀系数** Expansion coefficient
20Hz~10kHz高低温磁化曲线 (-40℃~150℃) 20~10kHz Magnetization Curves at various temperatures (-40℃~150℃)	**延伸率** Elongation(%)	**弹性模量** Modulus of elasticity
特殊波形磁化曲线 AC iron loss curves under special waveform	**疲劳强度(室温)** Fatigue strength(ambient temperature)	**弯曲次数** Number of bends

5.1.1 磁性测试平台 Magnetic Properties Test Platform

完备的材料性能测试平台，可为用户提供各种尺寸的材料在很宽频率范围（20Hz~10kHz）、较宽场强范围下（~100kA/m）的磁性数据，以及J-P、J-H、H-μ等各种电磁性能曲线的测量，最大程度地挖掘材料特性。

With complete material properties test platform, Baosteel could provide customers with magnetic properties data at any frequency between 20Hz and 10kHz and magnetic flux density up to 100kA/m, the measurement of B-P, B-H and B-μ and other forms of magnetic properties curves, to fully make use of the material properties at the greatest extent.

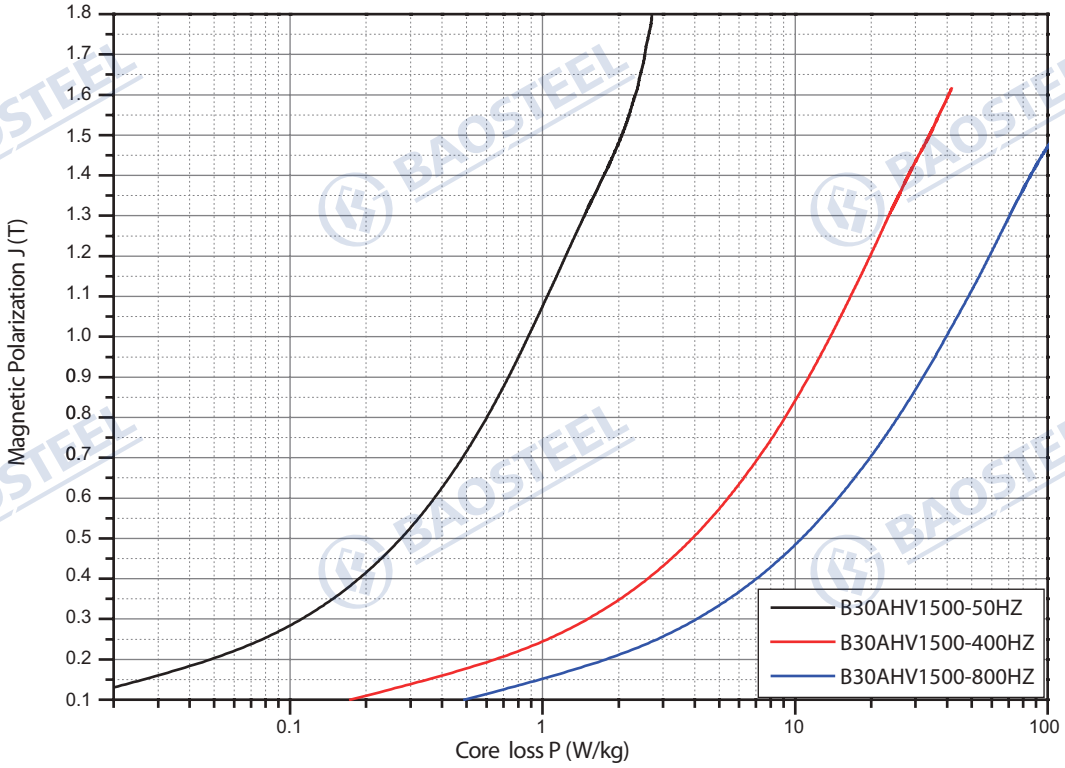
5.1.2 主要牌号典型性能数据 Main Grade Typical Properties

类型 Type	牌号 Grade	铁损 Core loss (W/kg)	磁极化强度 Magnetic polarization(T)		屈服强度 Yield strength (MPa)
		P10/400	J50	J100	
低损耗AV系列 Low loss AV series	B27AV1400	12.6	1.64	1.76	450
	B30AV1500	13.5	1.64	1.76	455
	B35AV1900	17.5	1.68	1.80	400
高效AHV系列 High efficiency AHV series	B27AHV1400	12.7	1.66	1.78	403
	B30AHV1500	14.0	1.67	1.79	405
	B35AHV1700	16.0	1.67	1.79	400
高磁感APV系列 Super induction APV series	B27APV1400	12.1	1.69	1.81	403
	B30APV1500	13.4	1.69	1.81	405
	B35APV1900	17.0	1.70	1.81	400
薄带AT系列 Thin gauge AT series	B20AT1200	10.6	1.65	1.77	403
	B20AT1500	12.2	1.65	1.77	410

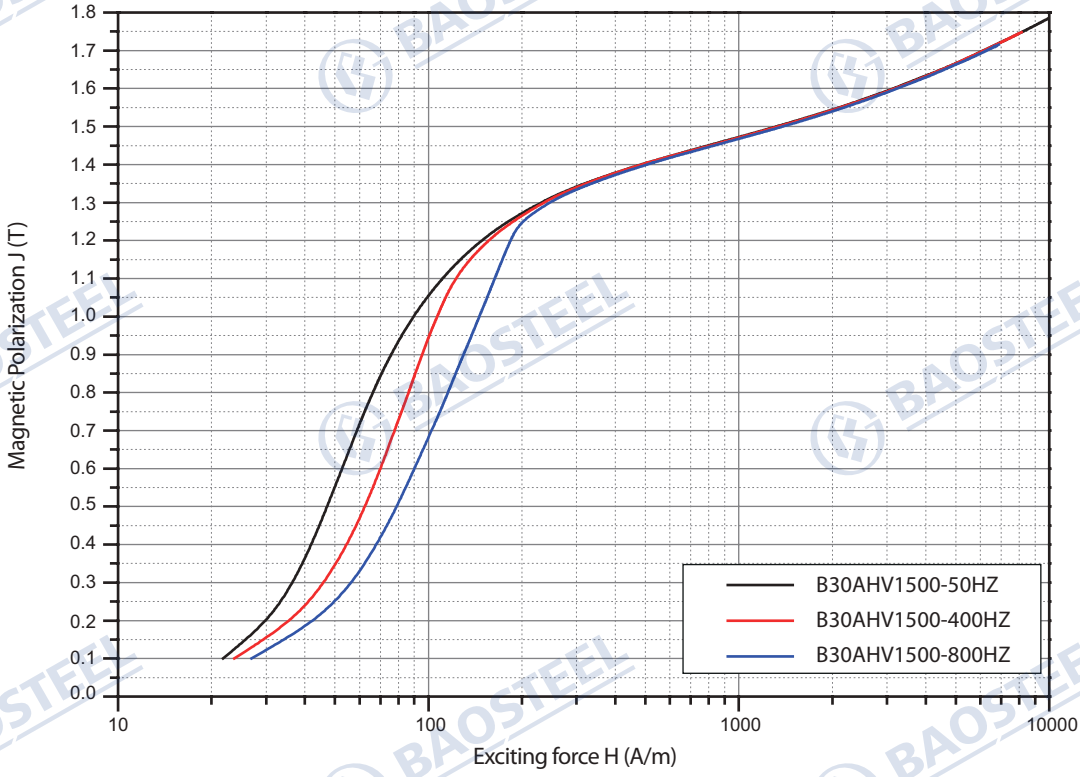
注：上述性能数据为典型值而非供货保证值。
Note: The typical values are not for guarantee.

5.1.3 典型产品电磁性能曲线 Magnetic Property Curves of Typical Product

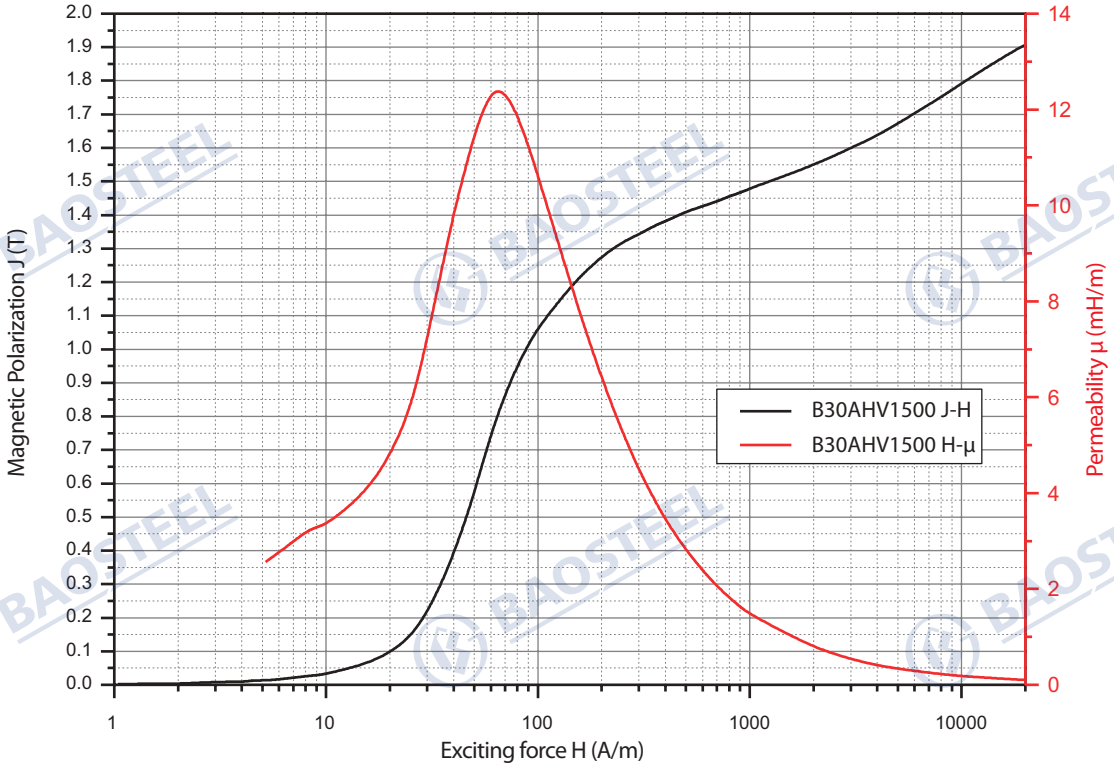
■ **铁损曲线** Iron loss curves



■ **交流磁化曲线** AC magnetization curves

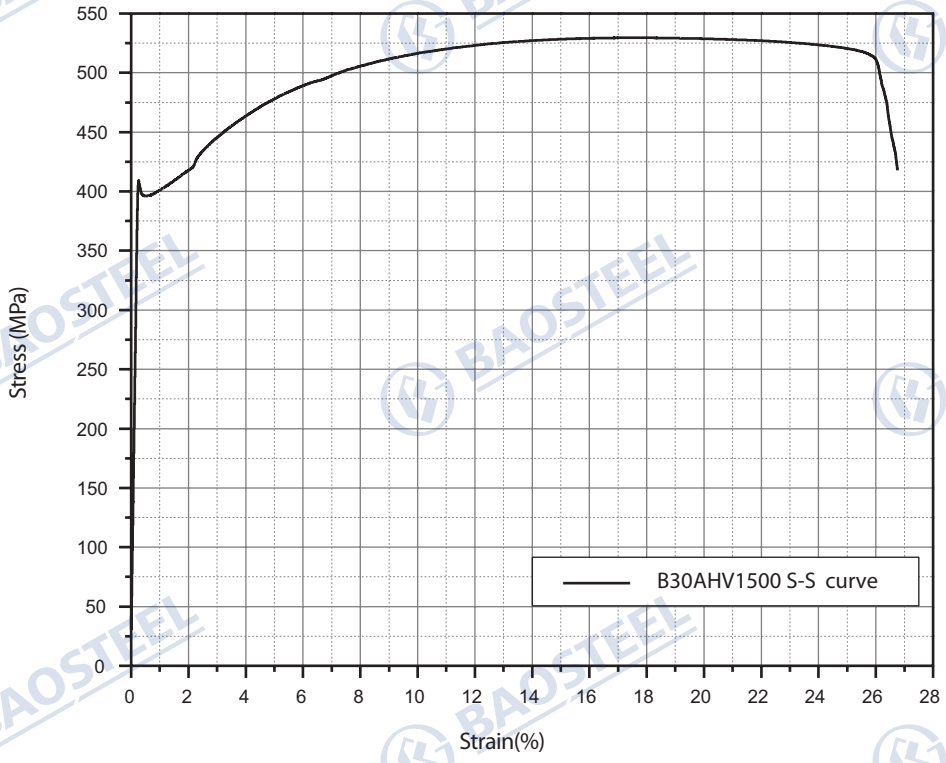


■ **直流磁化及磁导率曲线** DC magnetization curves

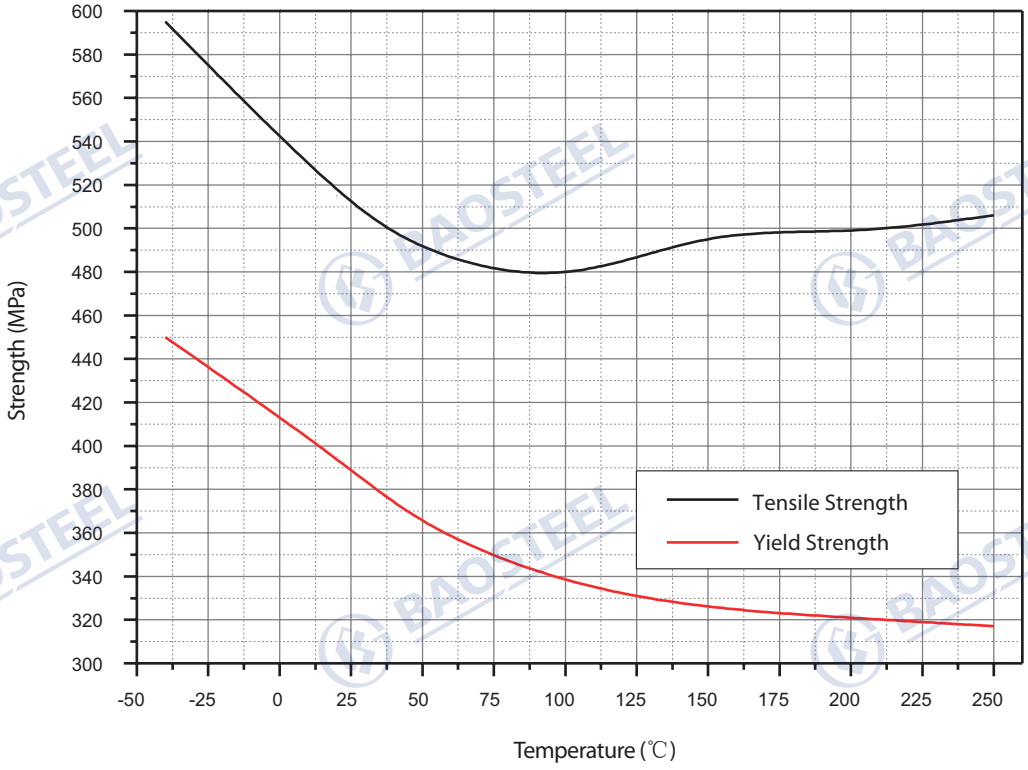


5.1.4 力学性能曲线 Mechanical Property Curves of Typical Product

■ **B30AHV1500常温应力应变曲线** B30AHV1500 strain-stress curve at ambient temperature

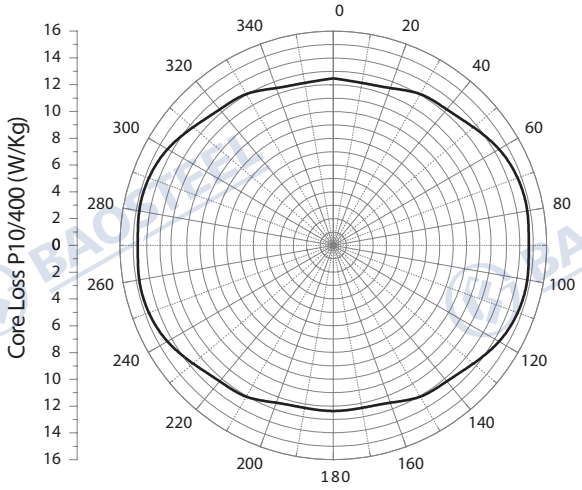


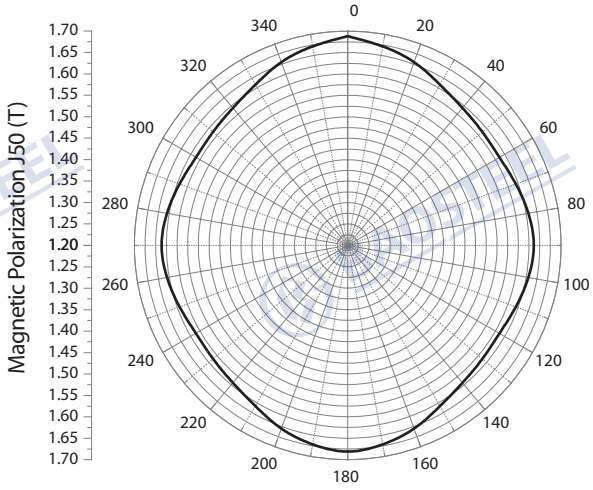
■ **B30AHV1500在不同温度下的屈服和抗拉强度** B30AHV1500 yield strengths and tensile strengths at various temperatures



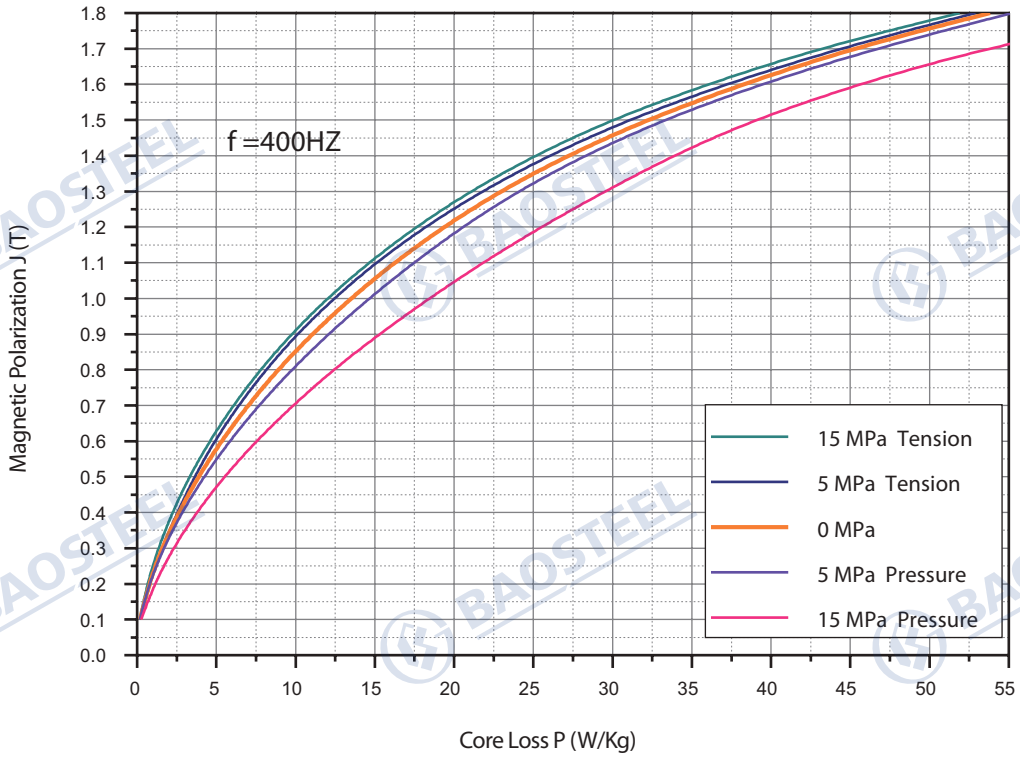
5.1.5 特殊条件下的磁性曲线 Magnetic Property Curves Under Special Condition

■ **B30AHV1500在不同方向下的磁性** B30AHV1500 magnetic properties along various directions

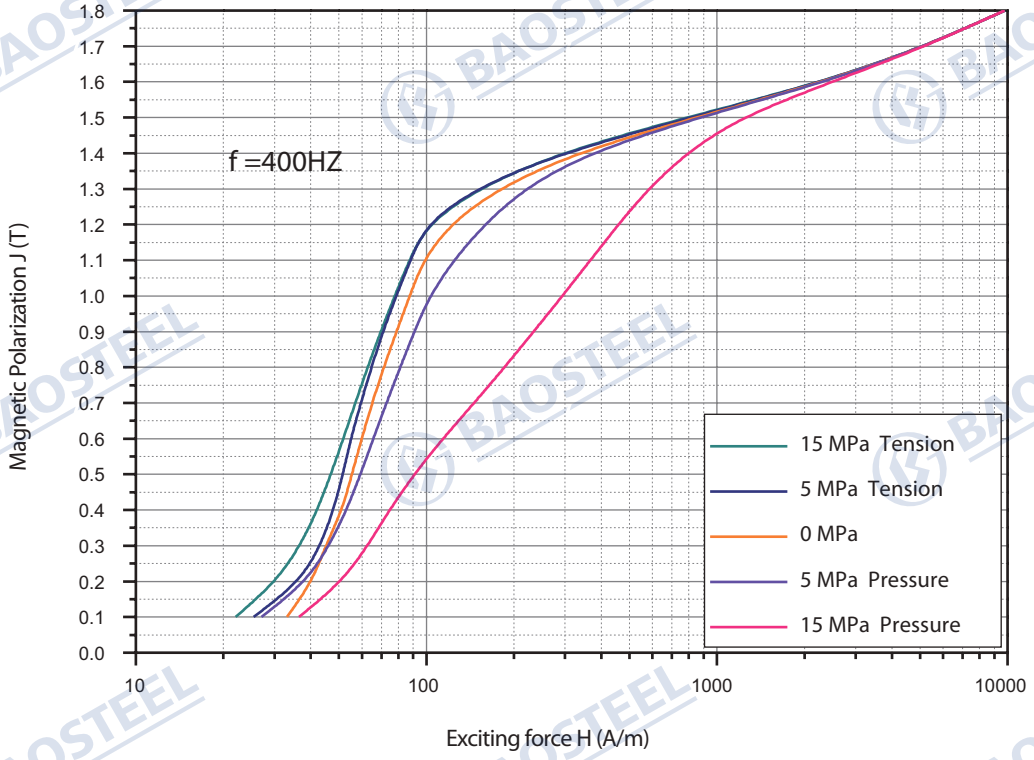




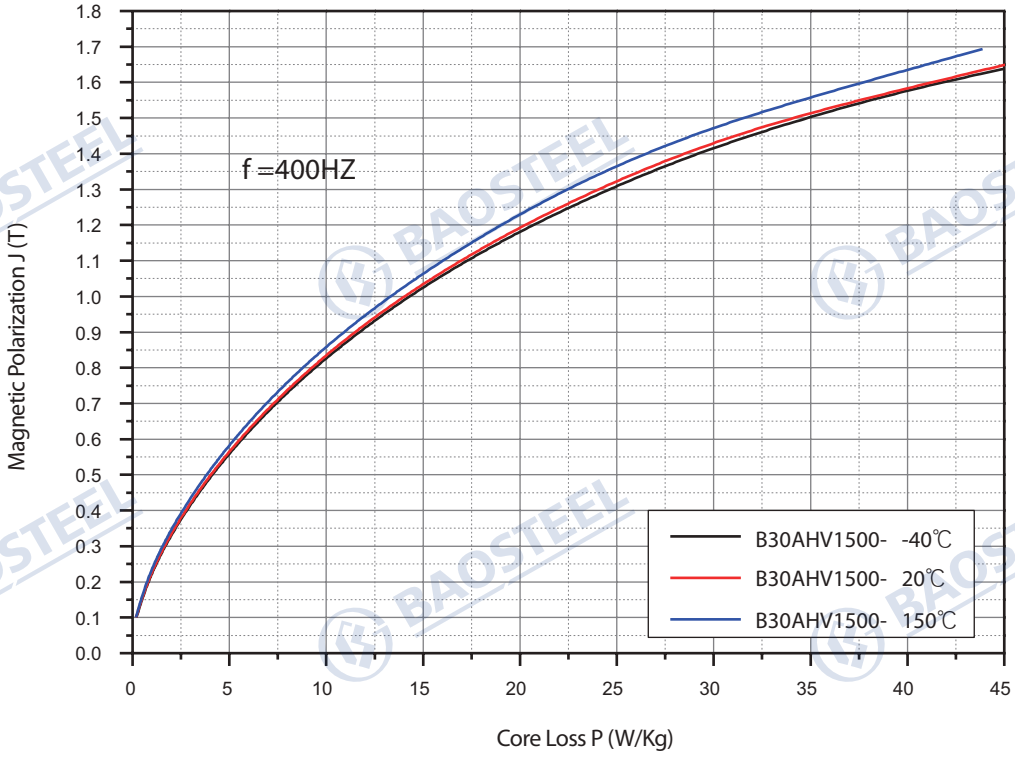
B30AHV1500在轧向不同应力下的铁损曲线 B30AHV1500 iron loss under various stress along rolling direction



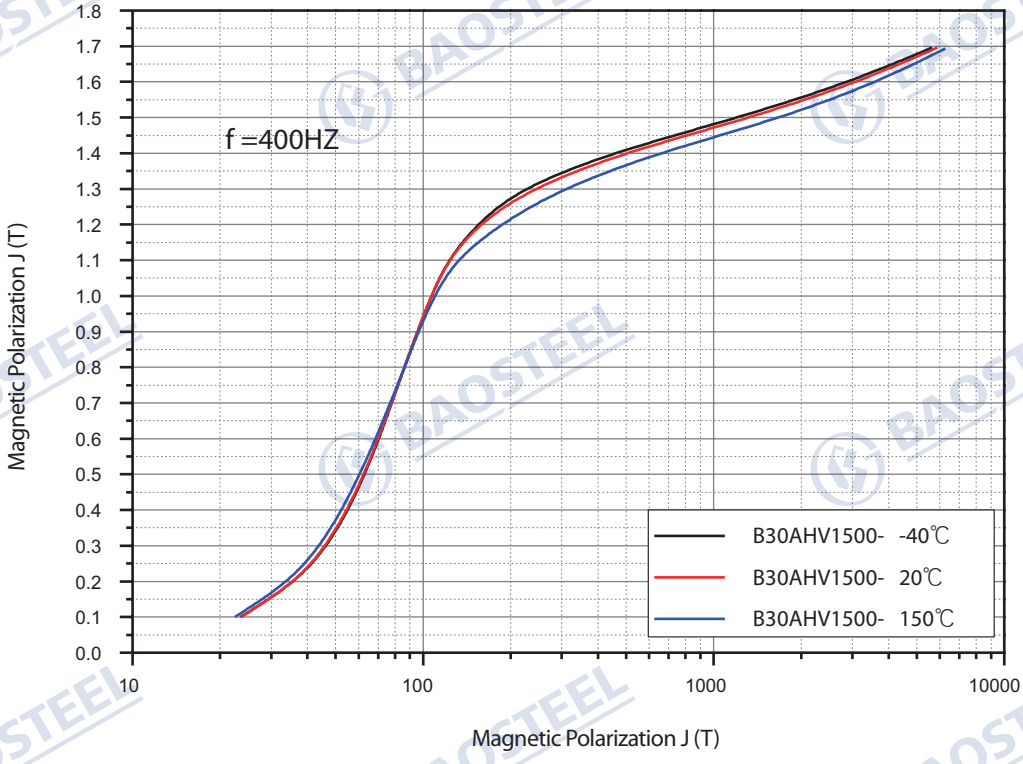
B30AHV1500在轧向不同应力下的交流磁化曲线 B30AHV1500 AC magnetization curves under various stress along rolling direction



B30AHV1500在不同温度条件下的铁损曲线 B30AHV1500 iron loss curves under various temperatures



B30AHV1500在不同温度条件下的交流磁极化曲线 B30AHV1500 AC magnetization curves under various temperatures



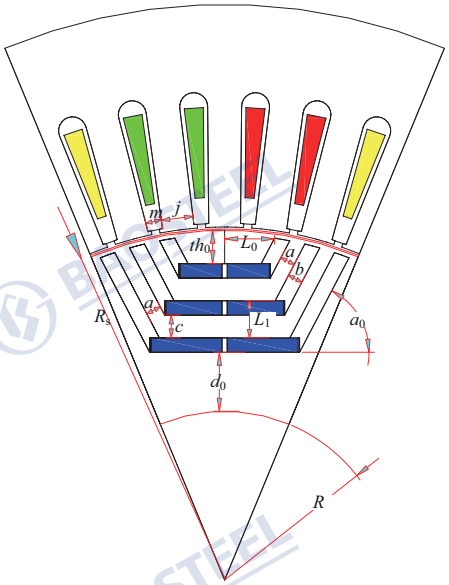
5.1.6 涂层性能 Coating Properties

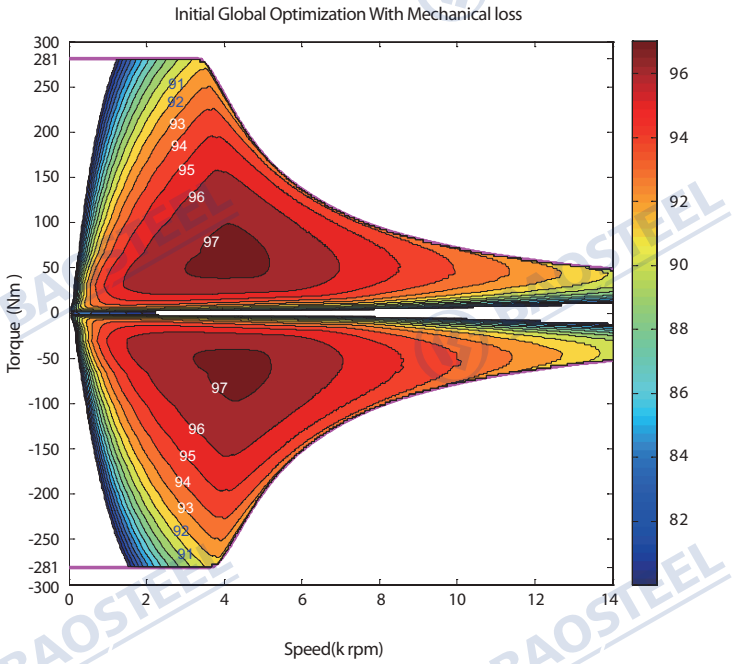
涂层种类 Coating type	H	M	Z
组分 Composition	半有机 Semi-organic	半有机（无Cr） Semi-organic (Cr free)	有机（无Cr） Organic(Cr free)
国际分类标准 International standard (DIN EN 10342)	EC-5	EC-5	EC-3
叠片系数 Stacking factor	高 Excellent	高 Excellent	高 Excellent
层间电阻 Interlamination resistance	≥3Ω·cm²/片 ≥3Ω·cm²/lamination	≥3Ω·cm²/片 ≥3Ω·cm²/lamination	≥50Ω·cm²/片 ≥50Ω·cm²/lamination
附着性 Adhesiveness	很好 Excellent	很好 Excellent	粘接强度≥2N/mm （T剥离测试） Bonding strength≥ 2N/mm（T-Peel test）
耐热等级 Thermal rating	H	H	H
耐腐蚀性 Corrosion resistance	很好 Excellent	很好 Excellent	很好 Excellent
冲片性 Punching ability	很好 Excellent	好 Good	好 Good
焊接性 Weldability	好 Good	好 Good	—
特点 Feature	普适性 Universal	普适性，无Cr，极好环保性 Universal , Cr Free Environment friendly	自粘结 Self-bonding 低噪音、高刚度 Low noise, high stiffness

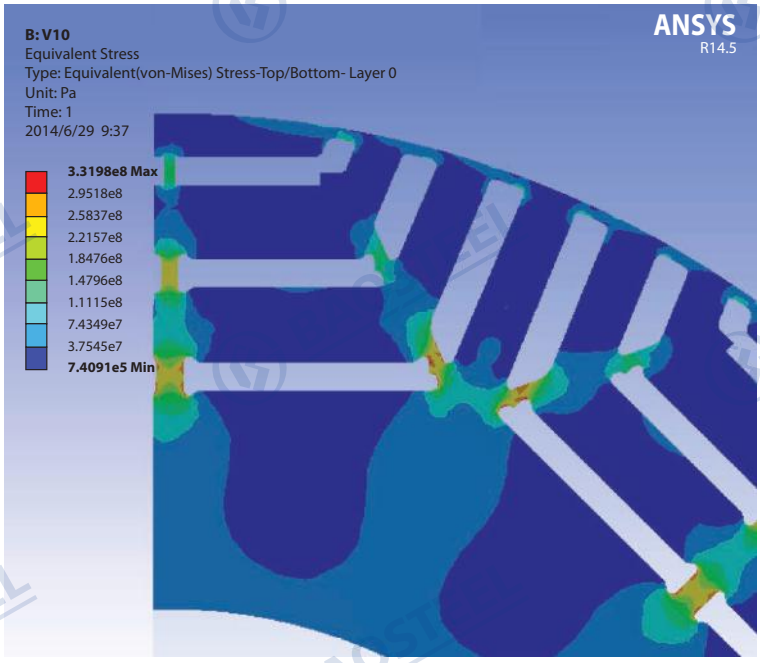
5.2 仿真能力 Simulation Analysis Capability

- 分析铁芯磁路，选取更优磁感材料
- 分析电机效率云图，选择更优铁损材料
- 分析转子铁芯应力分布，选择更安全的材料

- Magnetic path analysis for material selection
- Motor efficiency cloud map analysis for material selection;
- Stress distribution analysis for safety







5.3 材料冲压加工技术支持 Punching And Lamination Process Support

5.4 实验样机及测试平台 Prototype Iron Core Build & Test Platform

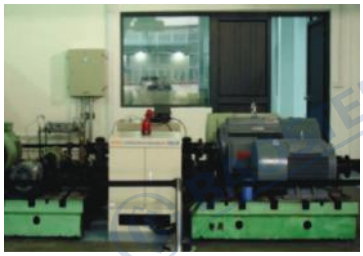
电工钢使用技术服务平台：铁心样机切割与检测

Technical service platform for electrical steel application technology: prototype iron core cutting and testing.

激光切割 Laser cutting

线切割 Wire-electrode cutting

电机铁芯 Motor core



整机测试 Motor testing

铁芯测试 Core testing

- 样机铁芯切割服务：在新品开发早期为用户提供样机材料、铁芯加工一揽子服务，减少样机冲片模具制作投资、缩短开发周期。
- 性能测试：铁芯损耗测试，电机效率测试。

- Prototype iron core cutting service: To provide our customer with electrical steel material, iron core cutting service to avoid prototype punching die building investment in early stage of new product development to shorten the R & D cycle.
- Properties testing: Iron core testing, motor testing.

5.5 选材推荐 Material Selection

综合考量材料性能、价格等因素，为新能源汽车驱动电机铁芯设计进行选材支持。根据铁芯设计、加工以及性能检测，对比不同材料的使用效果，以实现性价比最优。

To support customers for electrical steel selection for design of traction motor of clean-energy vehicle considering cost and performance, comparison would be done according to core design, manufacturing process design by simulation and experiments to realize an optimized performance price ratio.

案例一：电工钢材料厚度选择

Case 1: Thickness selection of electrical steel

(1)、电机转速和频率 Motor Speed And Frequency

要提高功率密度，需要进一步提升电机的转速，其相关参数可见下表：

It needs to increase motor speed in order to increase motor's power density, the relevant parameters are listed in the following table

电机转速（rpm–4p） Motor speed (rpm-4p)	电频率（Hz） Working frequency(Hz)
9000	600
10500	700
12000	800
15000	1000

(2)、电工钢材料的频率–损耗特性 Frequency-loss Relationship of Electrical Steel Material

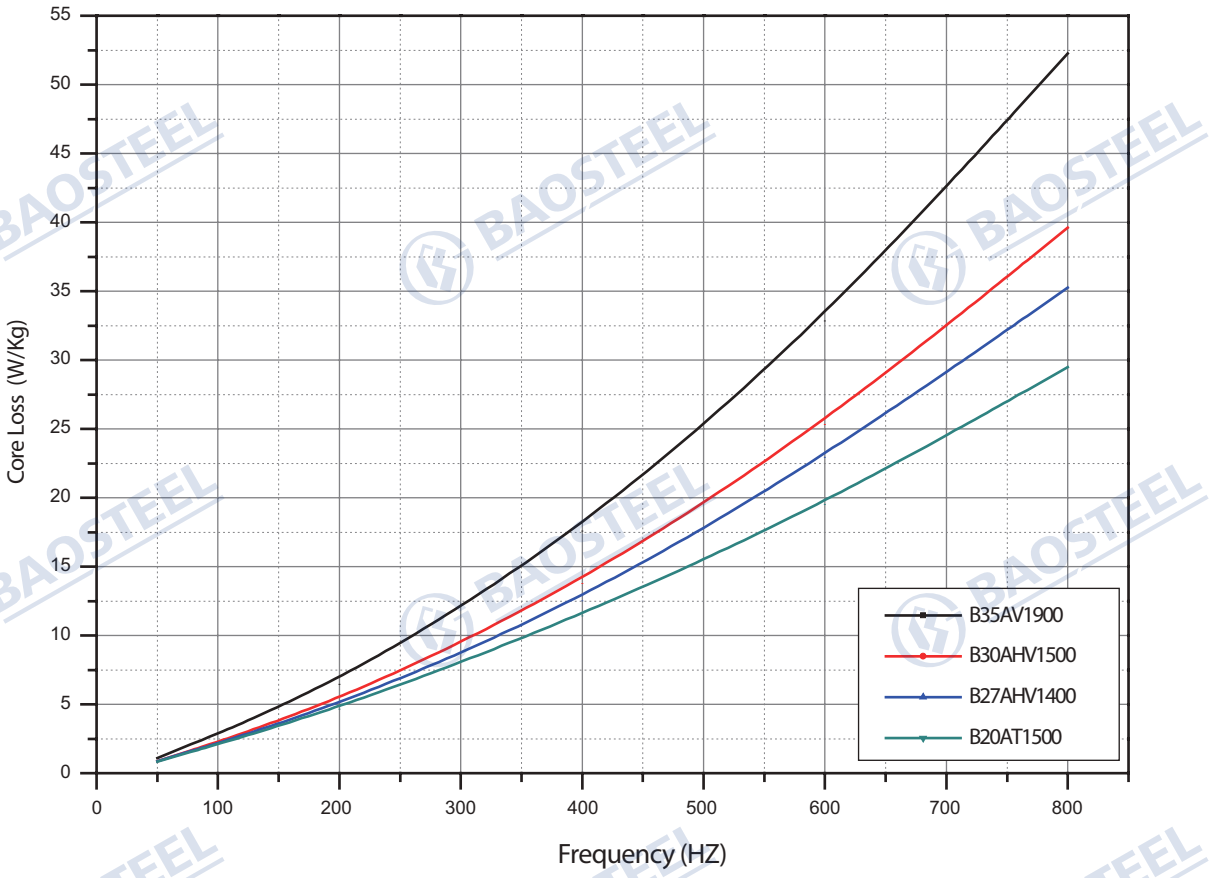
电工钢材料的损耗（Ph、Pe）同频率(f)密切相关，其中磁滞损耗（Ph）与频率（f）成正比，而涡流损耗(Pe)与频率(f)的平方成正比(如下式所示):

Loss of electrical steel is closely related to frequency(f), where hysteresis loss Ph is proportional to frequency f, while eddy current loss Pe is proportional to frequency f square (shown as following equation):

$$P_h = k\ Vol\ f\ (B_{\max})^n\ [W] \qquad P_e = \frac{Vol\pi^2 f^2 t^2 (B_{\max})^2}{6\rho}\ [W]$$

为了提高电机效率，需要大幅度降低电工钢材料本身的损耗特性，其中最直接的方法就是减薄。不同厚度电工钢材料在不同频率下处于磁感应强度1.0T时的损耗变化如下图:

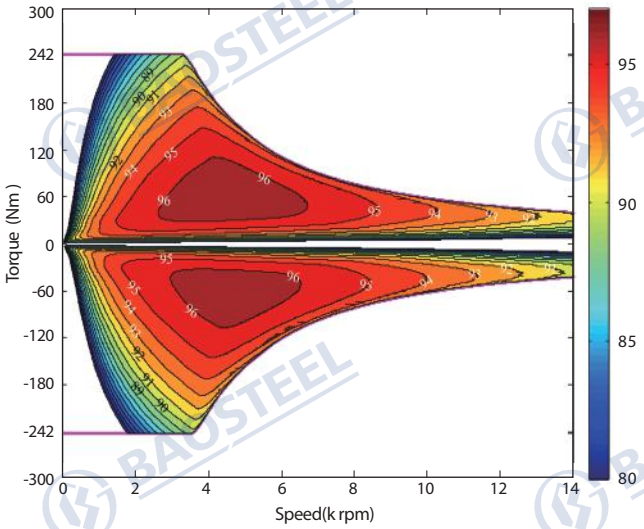
In order to increase motor efficiency, it's necessary to decrease iron loss of electrical steel greatly. The effective way is to reduce the thickness of electrical steel sheet. The iron losses of various thicknesses at magnetic induction density 1.0T under various frequencies are shown in following figure:

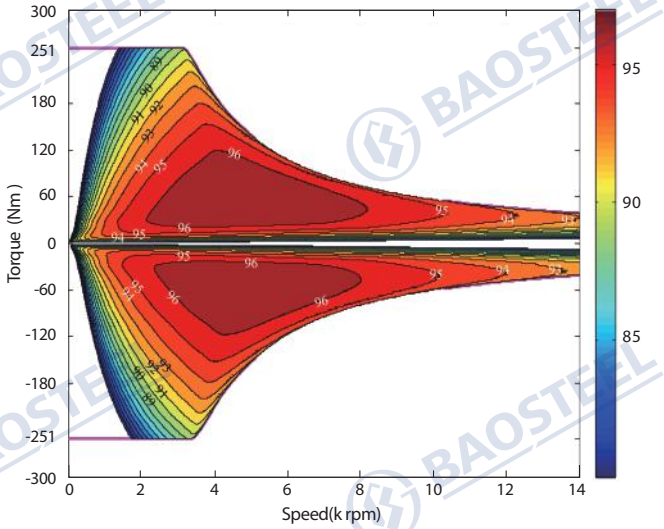


(3)、不同厚度材料的效率云图的变化 Changes of Efficiency Map with Various Thickness of Electrical Steels

选择了若干个牌号电工钢进行仿真计算，得到效率图: (0.35/0.30)

Simulation has been done with various electrical steel grades to obtain efficiency maps:(0.35mm/0.30mm)

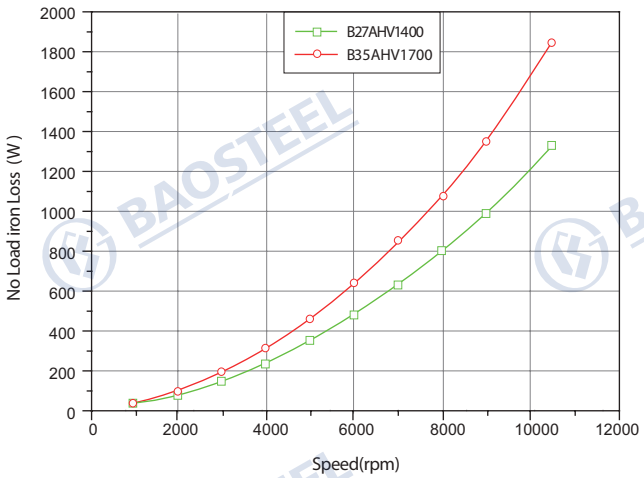




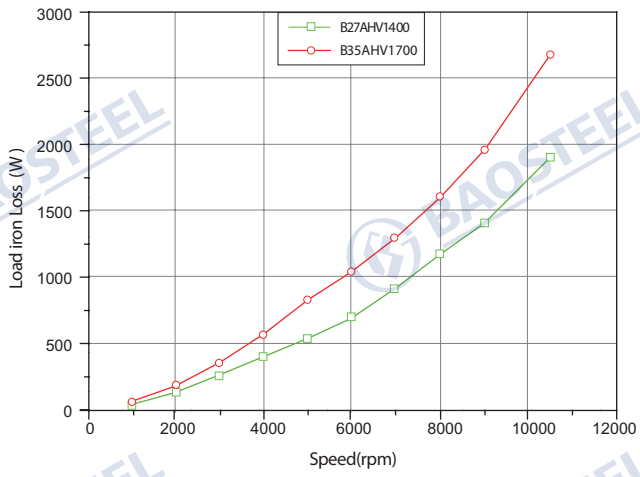
(4)、不同频率下的效率仿真和实测 Motor Efficiency Simulation and Testing Under Various Frequencies Electrical Steels

为实际验证不同厚度材料对效率的影响，利用另外一个设计方案，分别进行了仿真和实测。铁耗的计算值如图所示:

In order to verify the effect of thickness of electrical steel, a design model has been used to do simulation analysis and experimental testing. Iron loss calculation results are shown in following figures.



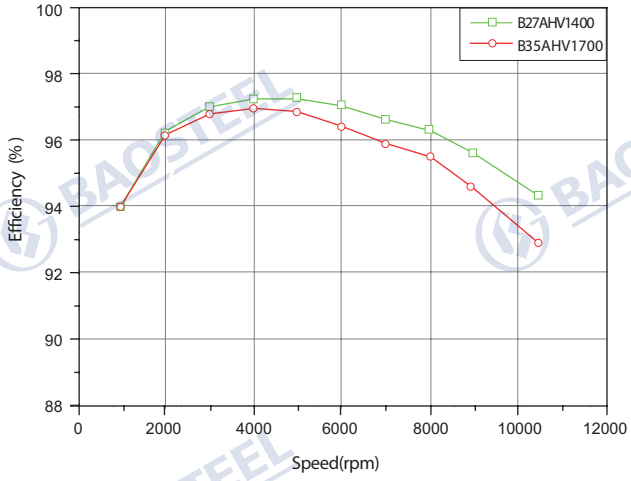
空载铁耗（额定） No load iron loss(rated)



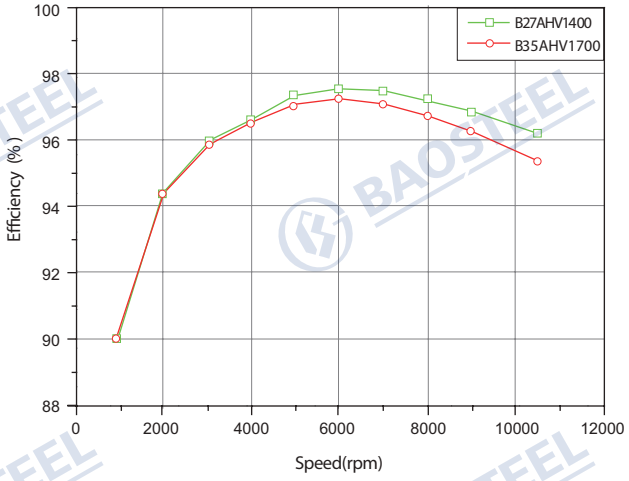
负载铁耗（峰值） Load iron loss (peak)

效率计算值如图所示：

Efficiency calculation results are shown in following figures



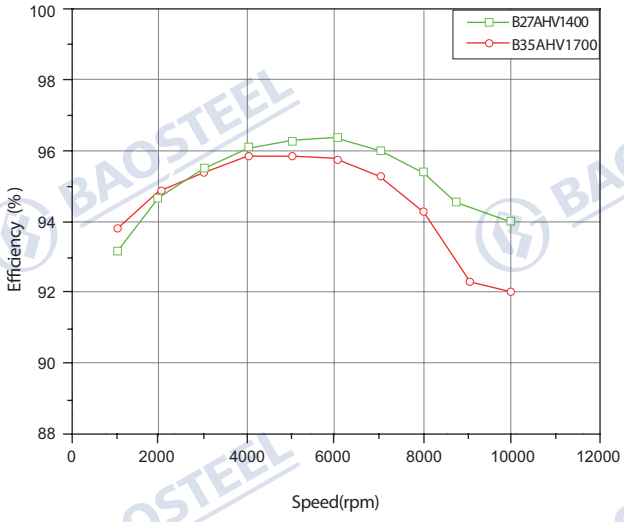
效率曲线（额定） Efficiency curve(rated)



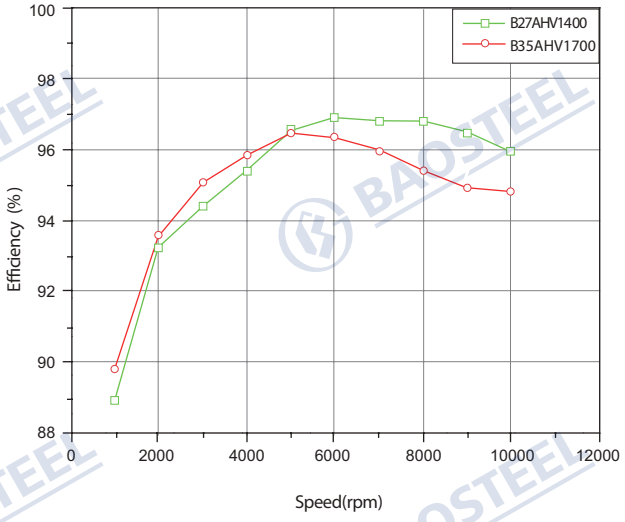
效率曲线（峰值） Efficiency(peak)

实测效率曲线如图：

Measured efficiency curves are shown in the following figures



效率曲线（额定） Efficiency curve(rated)



效率曲线（峰值） Efficiency(peak)

(5)、结论 Conclusions

采用薄规格无取向硅钢材料，有助于降低高速区负载损耗，提升电机效率。根据电机的最高转速（频率）、额定转速（频率）、高效区间等性能因素以及成本来选择电工钢的厚度和牌号。

The thickness and grade of electrical steel should be determined by maximum speed (frequency), rated speed(frequency), high efficiency region, and other factor regarding motor performance and cost. Thin gauge non-oriented electrical steels are good in reducing load loss in high speed region therefore improving motor efficiency.

案例二：电工钢材料强度选择

Case 2: Selection of strength of electrical steel

(1)、电工钢材料的强度 Strength of Electrical Steel

随着电机功率密度的提高，其频率和转速都呈增长的趋势。磁桥是整个电机（转子）受力最为集中的区域，是整台电机结构上的薄弱点。因此电工钢材料的强度选择是十分重要的。

With increasing motor power density, the working frequency and motor speed are increasing. High strength is needed for electrical steel at the magnetic bridge area of rotor because the stress concentration in this area makes it the weakest point of motor in structure.

(2)、转子磁桥应力分析 Stress Analysis in Magnetic Bridge Area of Rotor

对电机转子应力分析，基本数据如下表：（电工钢材料屈服强度按403MPa计）

Basic data for stress analysis in rotor is shown in the following table: (yield strength of electrical steel is taken as 403MPa)

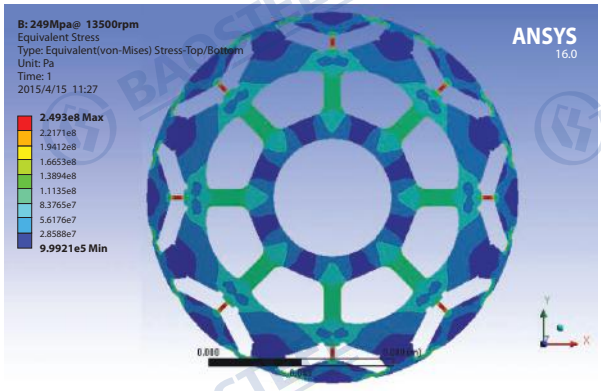
电机设计 Motor design			等效应力(MPa) Equivalent stress	安全系数 Safety coefficient
Tmax(Nm)	隔磁桥 Magnetic bridge	宽度 Width(mm)		
250.9	一处 One place	1.87	249	1.62

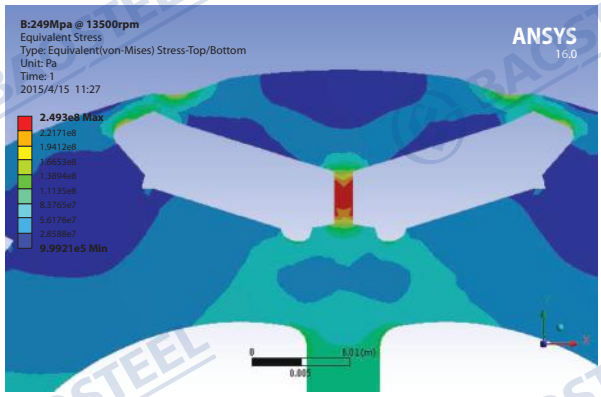
其中系数1.62是包括了各种不确定因素在内的安全系数，不确定因数包括但不仅限于：磁桥实际尺寸变化、材料强度的波动、温度的影响、加工应力、超速、装配公差、单边磁拉力等。

Safety coefficient 1.62 is the safety factor considering all uncertain factors, which includes but not be limited to: actual size change of magnetic bridge, variation of material strength, effect of temperature, manufacture resulted stress, speed excess, assembly tolerance, one side magnetic pulling force, etc.

应力分布如图所示

Stress distribution is shown as following figures





(3)、转子的转速–应力特性 Stress Dependence of Speed in Rotor

转子受力主要由如下几部分组成：

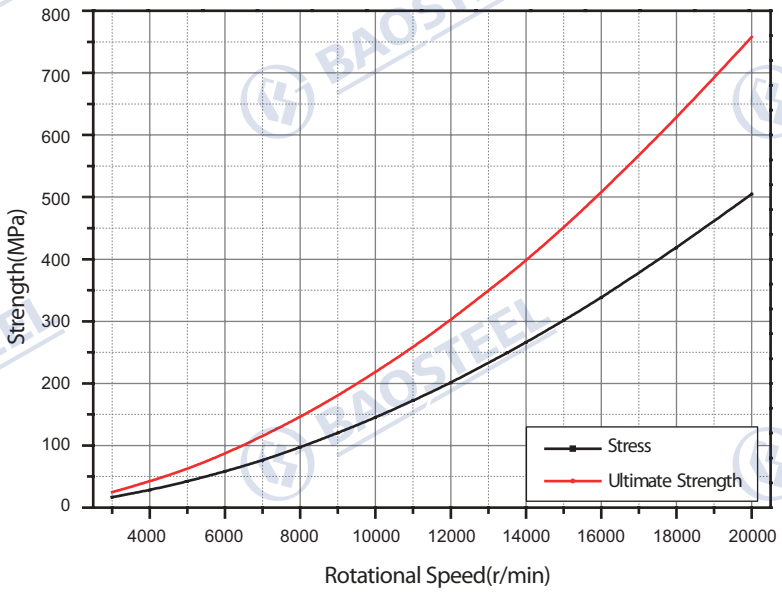
- 外圆（即由磁桥围成的部分）和磁钢的离心力，与转速成平方关系。
- 电机运行时的定转子之间的电磁力，然后传递到铁心并且主要由磁桥承担受力，在额定转速以上大体上同转速成反比关系。
- 由于磁场分布不均匀和装配间隙等因素产生的单边磁拉力，基本是固定值，与转速无关。

磁桥的应力是由上述三部分力共同组成。总体上同转速的关系介于正比和平方之间。此处暂按应力–转速成1.8次方估算。

Stress in rotor mainly composes of following parts:

- Centrifugal force of outer circle (i.e., surrounding bridges) and steel magnet, being proportional to speed square.
- Magnetic force between rotor and stator when motor is running, passing on to iron core mainly at bridge, being roughly in inverse proportion to speed above rated speed range.
- One side pulling force due to uneven magnetic field, assembly gap, etc, being a fixed value basically and irrelevant to speed.

Stress in magnetic bridge composes mainly of above three parts, being generally proportional to speed by power between1 to 2, where taking power 1.8.



(4)、转速提高的应对方案 Solution to Speed Rise

当电机转速在1.2万转以下时，当前普遍使用的材料（屈服强度400Mpa左右）可以放心使用。当电机转速达到1.5万转时，对电工钢屈服强度的要求会增加到450Mpa左右，需要采用更高强度转子专用材料。如果转速进一步提升，强度超出了现有电工钢的极限，则必须采取其他方面的措施。

It can been seen that normal electrical steel grades (yield strength around 400MPa) could be used without any problem when motor speed is lower than 12krpm, but electrical steel with higher strength (yield strength above 450MPa) are necessary when motor speed reaches 15krpm.

Other measures should be taken if strength requirement exceeds the strength limit of electrical steel.

新能源汽车驱动电机用无取向电工钢推荐 | Recommendation About Non-oriented Electrical Steel Grades for Traction Motor of Clean-energy Vehicles

根据电机的转速（频率）来选择无取向电工钢材料，基于宝钢EVI工作，推荐产品如下:

Recommended electrical steel grades in Baosteel are listed in following table according to motor speeds based on our EVI research results

类别 Type	电机最高转速，rpm Maximum motor speed, rpm	无取向电工钢产品推荐 Recommended electrical steel grades
乘用车 Passenger cars	10500以下 Below 10500	0.35mm厚度产品，典型牌号 B35AV1900、B35AV1700 0.35mm gauge, typical grades:B35AV1900, B35AV1700
	12000	0.30mm厚度产品，典型牌号 B30AV1500、B35AHV1500 0.30mm gauge, typical grades:B30AV1500、B35AHV1500
	13500	0.27mm厚度产品，典型牌号B27AV1400、B27AHV1400 0.27mm gauge, typical grades:B27AV1400、B27AHV1400
	15000	0.27mm以下厚度产品 Gauge below 0.27mm
	15000以上 Above 15000	定子采用0.20mm厚度产品，转子采用500MPa或以上强度产品 Stator: 0.20mm gauge；rotor: high strength one (500MPa and above)
商用车 Commercial cars	3000	0.35mm厚度产品，典型牌号B35AV2100 0.35mm gauge, typical grades:B35AV2100
	4000	0.35mm厚度产品，典型牌号B35AV2000，B353AV1900 0.35mm gauge, typical grades:B35AV2000，B353AV1900
	5000	0.35mm厚度产品，典型牌号B35AV1900，B353AV1800 0.35mm gauge, typical grades:B35AV1900，B353AV1800
	6000	0.35mm或 0.30mm厚度产品，典型牌号B35A(H)V1700、B30A（H）V1500 0.35mm or 0.30mm gauge, typical grades:B35A(H)V1700、B30A（H）V1500

注: 乘用车以8极永磁同步为准，商用车以12极永磁同步为准

Note: 8 poles PMSM in passenger car while 12 poles PMSM in commercial cars

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