仿真电泳涂装：科技的艺术

E-coating Simulation: Art of Science

仿真技术已成功用于众多行业，它加快了研发速度并缩短交货时间，然而在电泳涂装领域，仿真技术应用还未普及。本文，全球电化学模具专家比利时Elsyca公司将从电化学的角度为您解释如何将仿真技术用于电泳涂覆工艺。

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汽车原始设备制造商（OEM）在将汽车送到喷漆车间利用机器人进行实际的着色和表面处理工艺前，会利用电泳涂覆工艺在汽车上涂第一层防腐层。仿真技术普遍用于喷涂车间的着色及表面处理，而电泳涂覆工艺的仿真解决方案还未标准化。

本文将从电化学的角度解释如何将仿真技术用于电泳涂覆工艺。仿真技术可用于需在基材上沉积或移除金属的电化学过程。当沉积层厚度增加时，镀层的电阻率会随着时间的变化而变化，所以电泳涂覆工艺具有不同的性能。本文将解释Elsyca公司如何成功开发并验证一种能对电泳涂层厚度和电流密度设计改变后的效果进行仿真的解决方案，并在几天内获得结果。

引言

电喷涂（也称为电泳、电泳涂装、电泳涂料）从根本上说是一种将涂层沉积到基材上的电泳工艺。然而，与电镀不同的是，电泳涂层是由导电性低的涂料组成。由于电泳涂层具有极好的防腐性、成本低，以及良好的自流平效果，所以该工艺广泛应用于汽车等工业领域。电泳主要用于涂覆基材底漆，尽管它也可用于涂覆表面精饰层。

由于电泳涂层具有较好的电阻性，因此流平效应会将电流直接导向未被完全喷涂的表面区域。工艺时间是生产率和涂层厚度分布的一个关键参数。汽车电泳工艺时间一般为几分钟。另一个关键参数是

Automotive OEM use e-coating processes to build the first (primer) corrosion protection layer before the vehicle is sent to the paint shop where robots will take care of the actual coloring and finishing steps. Simulation technology is commonly available and used for the latter, simulation solutions for the e-coating process is not yet standard.

This paper will explain how the e-coating process can be approached from an electrochemical point of view. Simulation technologies are available for those electrochemical processes where metal is deposited or removed from a substrate. E-coating processes have a different behaviour since the resistivity of the deposited layer changes over time when the paint deposit layer thickness increases. This document will explain how Elsyca successfully developed and validated a solution that allows simulating the effect of design changes to the e-coating layer thickness and current density, thereby delivering results within a time frame of a few days.

Introduction

E-coating (aka electrocoating or electropainting or electrophoretic lacquering) is basically an electrophoretic process by which a paint layer is deposited on a substrate. However, unlike electroplating, electrocoating layers are composed of low-conductive paint. This process is widely used for industrial applications, mainly in the automotive industry, due to its excellent corrosion protection properties, low cost and self-leveling effect. E-coatings are mainly used for applying the primer paint layer on a substrate, although it might also be used for the finishing paint layer.

The leveling effect is, due to the highly resistive properties of the electrocoated paint layer, thereby directing the electrical current to surface areas that have

基材上的局部电流密度：涂层厚度值低于标准——一般出现在凹陷区域，如B柱形结构——这些区域与极低的电流密度值有关。

电泳是尚未普及电脑仿真的工程领域之一，目前主要的汽车OEM正在该领域寻求解决方案。在第一个原型建立之前需完成电泳相关工程。今天，这项工作仍需靠经验进行。该仿真技术不仅能识别出问题所在还能评估设计变化后的效果，这大大缩短了腐蚀工程师的交货时间，还可以使用其同事用于撞击、耐久性、NVH等测试的类似工具进行工作。

成功仿真这些工艺需要什么条件？

关键因素

从不同的角度来看，电泳涂覆工艺由以下几个因素决定：

- 电泳浴：使用不同基材的白色车身（BIW）的浴的特性;
- 电泳生产线：配置：电泳池的尺寸、阳极、车辆轨道;
- 工艺参数：电压施加方案、线速度;
- 车辆特性，一般为BIW（白色车身）的CAD几何尺寸。

电泳浴

化学供应商可提供由基础涂漆化学物和添加剂组成的不同类型的电泳浴。在生产过程中需监控这些浴的品质，以保证浴的成分维持在一定预定值内。Elsyca公司会提取几升正在操作的浴，并在实验室内对其进行分析。需结合材料来了解浴的特性，因为它们决定了电泳工艺的效率。在这种情况下，分析的重点不是化学成分，而是浴的性状：

- 电解质（和阳极液）的导电性；
- 阳极过电压（析氧）；
- 阴极过电压（析氢）；
- 涂料的电阻和涂层生成参数。

针对不同的基材需采用一致的DoE（实验设计法）来确定电泳浴的特性。电泳浴的寿命有限，因此需进行特定的处理和操作（如温度、搅动等）。还需准备基材样品来模拟生产环境中相同的工艺，包括前处理工序，如漂洗、清洗和磷酸盐处理，同时还包括后处理工序（烤箱）。利用电泳浴的特性作为仿真模型的输入参数。该信息可用于使用相同基材制造的所有车辆，因为电泳浴的特性与车辆本身无关。

还有一种特殊情况是确定新电泳浴的特性。这为比较两种或两种以上不同的电泳浴提供了客观信息，并可了解使用不同基材制造的车在浴中是如何工作的。在这种情况下样品是全新的，因为在生产槽中无法获取这些电泳样品。要明白涂层厚度将会变厚的重要性——因为该样品仅包含新的电泳漆。（在实际生产环境中还包括新

not yet received full paint coverage. The process time is a critical parameter in a compromise between productivity and paint layer thickness distribution. A typical automotive paint process time takes a few minutes. Another critical parameter is the local current density on the substrate: layer thickness values below specifications – typically in recessed areas like e.g. a B-pillar - areas are related to the occurrence of very low current density values.

E-coating is one of the last engineering areas where computer simulations are not commonly used, and mainly automotive OEMs are looking for solutions in this domain. E-coating related engineering has to be completed preferably before the first prototype is built. Today, this is still done based on experience. Being able to not only identify problem areas but also to demonstrate the effect of proposed design changes enables corrosion engineers to drastically reduce the lead time and to work with similar tools as their colleagues working on crash testing, durability, NVH etc.

What is required to successfully simulate these processes?

Key influencers

Looking at the e-coating process from a different perspective, one can say that the process is defined by

- The e-coat bath: characteristics in combination with the different substrates used in a BIW;
- The e-coat line: configuration: tank dimensions, anodes, vehicle trajectory etc.;
- Process parameters: imposed voltage program, line speed
- The vehicle characteristics, typically the BIW (body in white) CAD geometry.

The E-coat bath

Chemical suppliers provide different types of e-coat baths, composed of different type of base paint chemicals and additives. The quality of these baths is monitored in the production process to guarantee the composition of the bath remains within certain predefined limits. Elsyca will take a few litre of the operational paint bath, and analyse this in its laboratory. Characteristics of paint bath in combination with materials are required since they determine the efficiency of the e-coating process. The focus of the analysis is in this case not on the chemical composition, but on the bath behaviour:

- Electrolyte (and anolyte) conductivity;
- Anodic overpotential (oxygen evolution);
- Cathodic overpotential (hydrogen evolution);
- Paint resistance and paint growth parameters.

A consistent DoE must be applied to characterise the e-coat bath for the different substrates. The e-coat bath has a limited life-time and requires a specific treatment and operational conditions (like temperature, stirring etc.). The substrate samples must be prepared to mimic the same process as the one used in the production environment. This includes pre-treatment steps like rinsing, cleaning and phosphate, but also the post-treatment step (bake oven). The bath characteristics are used as input parameters the simulation model. The same information can be used for all vehicles built using the same substrates, since the bath characteristics are independent of the vehicle itself.

漆、几乎新的及旧漆）因此，需从新电泳漆开始确保现用电泳浴的特性，以便在相同条件下进行比较。

电泳涂装生产线

针对仿真，仅考虑前处理生产线中的电泳涂装环节。还需建立完整的数字模型，包括阳极的规模、大小和位置以及车辆轨道。所有车的轨道可以固定，或随车的类型改变。旧的系统会沿着车道将车拖进电泳浴，这与在地下停车场行驶的车类似。一旦车被浸没，在移至电泳池末端时会一直保持相同的水平位置，或沿着“驼峰线路”操作。更先进的系统是可以翻转车，还可将车移至任何旋转位置。这些旋转有助于排出气泡及附带涂料。可从电泳池的技术图纸中推导出车辆轨道，在某些情况下，可直接获取轨道档（如.wrl档）。

工艺参数

工艺参数描述了电泳浴和电泳生产线在实际操作中是如何工作的。这些参数决定了生产线速度、电泳浴温度、电压上升计划、车辆轨道（在连续系统的情况下）、浴的水平线等。理解这些参数对整个工艺的影响十分重要，因为在车辆设计确定后只有参数还可以改变。

车辆

车的设计对电泳涂覆的性能影响很大。新车开发过程中不同的工程部门对车的设计有不同的观点：撞击部门的人员可能希望增加一些增强型结构；噪音部门则想关闭一些开孔；而腐蚀部门正在寻找其它开孔用于排气并为内部结构中生成最小的涂层厚度提供足够空间。然而，在许多情况下，后者依靠的是经验来操作，而其它部门都有电脑仿真包。利用电泳仿真技术可以更好地理解并评估设计改变所产生的影响：例如，新的增强型结构是否会对电泳涂层厚度或邻近区域产生不利影响？是否可以取消某个孔及扩大另一个孔？现在可以在第一个原型制造出来前评估这些改变。

然而，一辆车完整的CAD设计非常复杂，这使其难以操作。若不采用智能的方式，那么在个人电脑上处理这样复杂的结构将会很慢。回应时间是成功的关键：工程师不可能等数周才能看设计改变的效果。车的CAD设计一般是在标准的CAD系统（如Catia V5）中创建。CAD可对撞击或可视化进行优化，但电泳仿真还有其它要求。如：

- 边缘必须连接完好；
- CAD需做好生成实体的准备；
- 不计“废弃的”内含物，因涂料不会进入该区域；
- 去掉微小细节和沟槽，因它们会使网格生成过程极端复杂。

有些工具可在一定程度上使该过程自动化，但这些任务仍需大量人力。在车辆计划的早期阶段可对此进行管理，因此，回应时间对最终设计十分重要。

A special case is the characterisation of new baths. This provides objective information to compare two or more different paint baths and understand how these baths behave in combination with the different substrates used for the vehicle. The samples are in this case brand new since these e-coat samples are not available in a production tank. It is important to realise that the layer thickness will be higher – since the sample only contains new e-coat paint. (In the production environment, one will have a combination of new paint, almost new paint, older paint etc.) Hence, one must make sure to also characterise the currently used e-coat bath starting from new e-coat paint in order to make the comparison in the same conditions.

The E-coat line

For the simulations, only the e-coat section of the pre-treatment line will be considered. A full digital model will be build, including dimensions, size and position of the anodes and the vehicle trajectory. The vehicle trajectory can either be fixed for all vehicles, or may very depending on the vehicle type. Older systems will drag the vehicle in the bath, following a trajectory that can best be compared with a car driving in an underground parking. Once the car is submerged, it remains in the same horizontal position while moving to the end of the tank, or follow a 'camelback' route. More advanced systems will allow flipping over the vehicle and moving it any wanted rotation position. These rotations help to remove gas bubbles and paint drag over. The vehicle trajectory can be deducted from the technical drawing of the tank, in some cases a direct trajectory file is available (e.g. a .wrl file).

Process parameters

Process parameters describe how the e-coat bath and e-coat line are actually operated. These parameters define amongst others, the line speed, the bath temperature, the voltage ramp up programs, the vehicle trajectory (in case of a continuous system), bath level, etc. It is very important to understand the impact of these individual parameters on the entire process, since these are the only parameters that can still be changed once the vehicle design is fixed.

Vehicle

The vehicle design has a big impact on the e-coat behaviour. The different engineering departments involved in the development of a new vehicle have different views on the design of a vehicle: people from the crash department may want to add some reinforcement structures, the acoustics department wants to close some holes, while the corrosion department is looking for extra holes to remove gas bubbles and provide sufficient space to build a minimum layer thickness in internal structures. The latter was (is?) however in many cases an activity based on experience, while the other departments have computer simulation packages available. Using e-coat simulation technology allows understanding and validating the impact of a design change: will e.g. a new reinforcement structure have a negative impact on the e-coat layer thickness or neighbour? Can a hole be removed if another one is made bigger? These changes can now be validated before a first prototype is build.

仿真解决方案

电泳仿真解决方案需具有包含浴的特性、电泳结构、工艺参数和汽车设计的能力。电化学工艺仿真法将计算出电流密度分布，因此在前面提到的输入参数的基础上可以得到白色车身 (BIM) 的涂层厚度 (**图1**)。

仿真解决方案需考虑电化学状态会随时间发生变化这一事实。整个工艺含大量步骤，一般有数百个，还需精确计算每个步骤的涂层厚度和电流密度值。这意味着第n个步骤都是从第n-1个步骤的涂层厚度和电流密度开始。这些步骤可在每个时刻应用正确的工作条件，包括车的方向，哪个阳极群在起作用，电压值是多少，车辆至各阳极的距离是多少，车辆与电泳浴表面的距离是多少，不同车身表面的涂层厚度是多少等。

有趣的是观察到电流密度和涂层厚度分布随时间的变化而变化。电流以最短的路径流动，靠阳极侧边最近的车身会最先生成涂层。涂层的电阻率随着涂层厚度的变化而增加，电流会改变方向，改走不同路径（**图2**）。

图2是电泳工艺开始不久后在同一时刻显现的电流密度分布 (左图) 和涂层厚度 (右图)：门和引擎盖上的浅蓝色部分表示最初的涂层。它使电流密度改变方向并流向红色的车顶和引擎盖区域。你还可以看到聚集在车辆外部较高的电流密度值，这意味着内部不会沉积涂层（右图较深颜色区域）。

一旦外部初始涂层形成，就会有足够的电阻率改变较高的电流密度值并导向车的内部。**图3**显示了涂层 (右

A full CAD of a vehicle is however very complex, and makes it hard to handle. Processing such a complex structure on a PC will be slow if not handled in an intelligent way. Response times are a crucial key to success: an engineer cannot wait for weeks to see the effect of design change.

The CAD of the vehicle is typically created in a standard CAD system like e.g. Catia V5. The CAD may be optimised for e.g. crash or visualisation, but e-coat simulations have additional requirements. Some examples:

- The edges must be perfectly joined ;
- The CAD must be prepared to generate a solid body;
- 'Dead' inclusions must not be taken into account, since no paint will enter this area;
- Small details and trenches should be deleted, since they will make the mesh generation process extremely complex.

Some tools exist to automate this process to a certain extent, but these tasks still require a lot of man-effort. This can be managed in the early stages of the vehicle program, response times become more and more critical towards the design freeze.

Simulation solution

E-coating simulation solutions must incorporate the capability to include the bath characteristics, the e-coat infrastructure, the processing parameters and the vehicle design. The electrochemical process simulation approach will compute the current density distribution, hence the layer thickness over the BIW based on afore mentioned input parameters. The simulation solution must account for the fact that the electrochemical conditions change over time (**Figure 1**).

The entire process is split into a number of steps, typically a few hundred, and for each of the steps, the exact layer

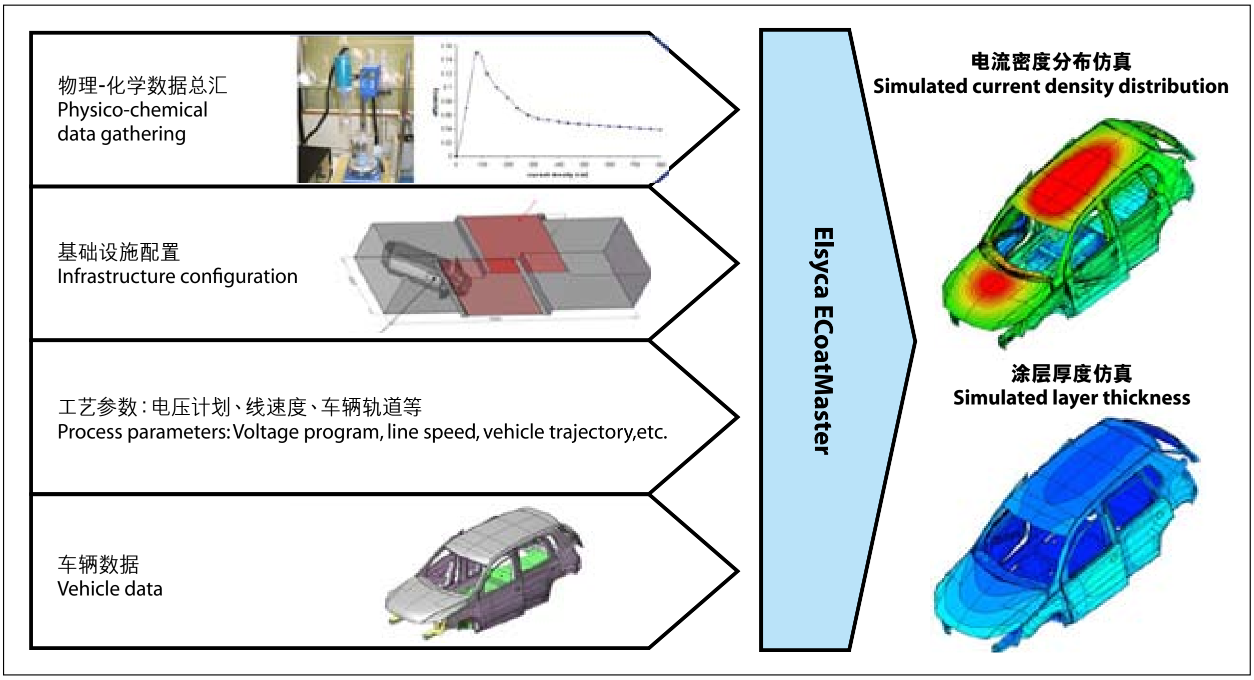

图1：仿真过程所需的输入参数概览
Figure 1: Overview of input parameters required for the simulation process

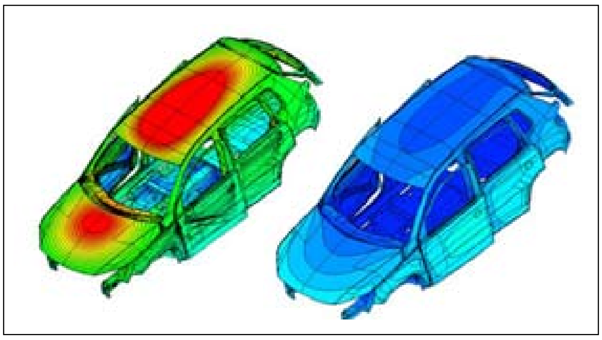

图2：电泳工艺开始不久后的电流密度（左图）和涂层厚度（右图）
Figure 2: Current density (left) and layer thickness (right) near beginning of the e-coat process

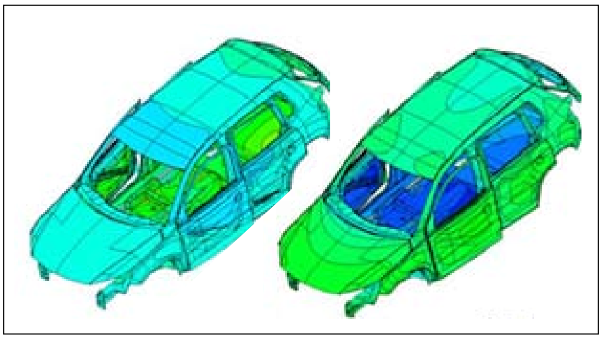

图3：涂层覆盖车辆外部时的电流密度（左图）和涂层厚度（右图）
Figure 3: Current density (left) and layer thickness (right) when paint layer covers the outside of the vehicle

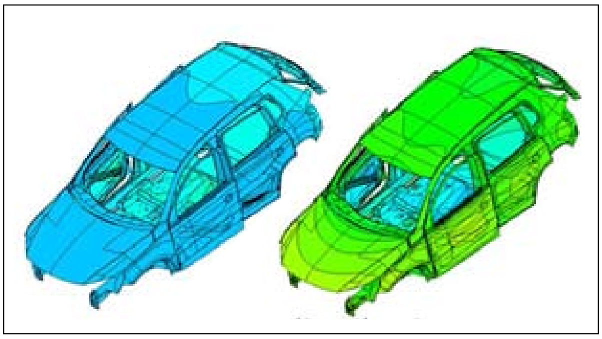

图4：工艺趋于结束时的电流密度（左图）和涂层厚度（右图）
Figure 4: Current density (left) and layer thickness (right) towards end of the process

图中绿色）覆盖了车的外部，但车的内部却无变化。左图中的电流密度显示较高（=绿色）的电流密度值，说明它是涂层厚度沉积最快的区域。我们还注意到车的外部是不完全阻抗的，意味着车身在继续生成涂层。

片刻后，车的内部区域也被涂覆了。涂层仍需不断生成，电阻率增加到某一水准后会使电流密度进入腔中。这意味着只有在电泳工艺的后期阶段，外部和内部区域都已产生足够的电阻率后（由于涂层的原因），（例如）内部B柱形结构区域才会被涂覆（**图4**）。

仿真的优势在于工程师可以看到整个工艺在每个时刻的情况，这为进一步理解工艺提供了非常宝贵的信

thickness and current density values are computed. This implies that each step n will start from the layer thickness and current density values from step n-1. These steps allow the application of the correct operational conditions at each moment in time, including the orientation of the vehicle, which anode group is active, what is the voltage value, what is the distance from the vehicle to the various anodes, what is the distance between the vehicle and the top of the e-coat bath, what is the layer thickness on the different surfaces and so forth.

It is interesting to observe the evolution of the current density and layer thickness distribution over time. The current will follow the shortest path, and the paint layer will first be built on the surfaces of the vehicle that are closest to the side anodes. The resistivity of this paint will increase as the paint layer thickness changes, and the current will redirect to follow different paths. This is illustrated in **Figure 2**.

The current density distribution (left) and the layer thickness (right) are plotted at the same moment in time near the beginning of the e-coat process: the light blue colours on the doors and engine hood show an initial paint layer. This redirects the current density to the roof and engine hood area, which are red coloured.

One can also see that the higher current density values are mainly on outside of the vehicle. This implies that no paint layer will be deposited on the inside (as can be seen by the dark colour zone on the right)

Once the initial outside layer has been formed, sufficient resistivity will be available to redirect the higher current density values to the inside of the vehicle. This is illustrated in **Figure 3**: the paint layer (green on right image) covers the outside of the vehicle, but nothing happened at the inside. The current density on the left now shows higher (= green) current density values, indicating the areas where the layer thickness will start depositing the fastest. Note that the outside of the vehicle is not fully resistive, implying the paint layer will still grow on the outside as well.

After a while, also the inside area of the vehicle also becomes coated. The layer still needs to grow, but the resistivity is up to a level that will force current density into the cavities. This implies that only at a rather late stage in the e-coating process, after the outside and inside area have developed sufficient resistivity (due to the paint layer) , will the inside of a B-pillar, for example, be coated (**Figure 4**).

The advantage of the simulations is that the engineers can see the entire process at each moment in time, providing very valuable information in further understanding the process. This is not possible without simulations, since the paint bath is not transparent and the process cannot be interrupted in a real tank.

Internal structures

Structures like a B-pillar are typically composed of different metal sheets, consisting of the outside/inside cover, but also including the reinforcement structures. These structures are positioned very close to each other, leaving little room for current to pass. The position and size of the holes in these structures are crucial in attaining the minimum layer thickness

The internal structures are the most challenging areas in the context of e-coating. It takes a long time before these areas show some paint growth activity. The worst part

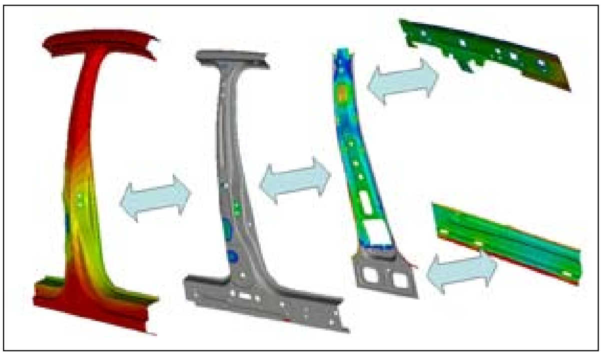

图5：B型结构部件
Figure 5: Example of B-pillar components

息。若无仿真，这些都将不可能，因为电泳浴是不透明的，而且在实际的电浴池中也不可能中断工艺。

内部结构

B柱形结构一般由不同的金属板制成，含外部/内部盖及增强型结构。这些结构的位置较为接近，电流通过的空间极小。因此这些结构中的孔的位置和大小对于获得最小涂层厚度非常关键（**图5**）。

内部结构是电泳涂覆最有挑战的区域。这些区域需很长时间才能显现出涂层生成的迹象。最糟糕的情况可能是错误难以修正，验证也相当困难。正确验证涂层厚度的唯一方式是在昂贵的车的原型上进行破坏性试验。除了车辆的成本外，测量实际数据也非常耗时。虽然可以对涂层厚度以及设计改变对涂层的影响进行仿真，但这并不能完全取代实物试验，不过可以大大减少实物试验的数量。这意味着工程师可以自由修改BIW设计，并通过仿真来验证所改变的设计。您可能仅是仿真B型柱结构来加快仿真的回应时间，而非利用整个车辆CAD。仅仿真B型柱结构可大大降低复杂性及处理的数据量，但会导致涂层厚度值远高于真实值。为此，需考虑车的其它部分。

Elsyca已开发出一种多层面方法，利用这种方法仅用几天就可以评估增强型结构区域（如B型柱）的改变，同时仍会考虑BIW其它部分产生的影响。

总结

仿真工具常用于缩短新车的开发周期。这些工具的优势毋庸置疑。它为不同开发阶段的工作人员评估新的或改性产品的不同特性（如NVH、耐久性、噪音等）提供了方法。

防腐的工作人员不再仅靠经验或利用一些不适宜的仿真工具（不能以合理的工艺时间提供精确的结果）进行工作。电化学工艺的仿真方案现已是新车开发不可缺少的工具。

probably is the fact that errors are very difficult to correct and validation is extremely difficult. The only way to properly verify the layer thickness properly is by performing destructive tests on expensive prototypes. Apart from the cost of the vehicle, it is also very time consuming to measure the actual values (**Figure 5**). Being able to simulate the layer thickness and the effect of design changes on this layer will not completely remove the need for physical testing, but the amount of physical tests can drastically be reduced. This implies the engineer can freely modify the BIW design and validate the change via simulations.

One may be tempted to run a simulation on the B-pillar only instead of using the entire vehicle CAD to speed up the simulation response time. Limiting the simulation to the B-pillar only would drastically reduce the complexity and amount of data to be handled, but would result in layer thickness values that are far above reality. For this reason, the remainder of the vehicle must be taken into account as well.

Elsyca has developed a multi-level approach where changes to a reinforcement structure zone like a B-pillar can be evaluated with a time frame of a few days, while still taking into account the effect that is caused by the remainder of the BIW.

Summary

Simulation tools are commonly used to shorten the development cycle of new vehicles. The advantages of these tools are unquestioned. They provide the people involved in the different development stages with the means to validate new or modified products for many different domains (NVH, durability, acoustics, etc.).

The people involved in corrosion protection are no longer limited to working either based only on experience, or by using some sub-optimal simulation tools that do not provide accurate results in a reasonable process time. Solutions based on electrochemical process simulation have now reached a level that these solutions are indispensible to the development of new vehicles.

作者简介 Biography

Robrecht Belis曾在比利时鲁汶学习信息技术和市场推广。他于1986年在鲁汶测量系统（LMS）公司负责软件工程开发，并创建了NVH领域新型高科技解决方案体系，后担任多个全球业务项目管理职位。自2008年以来，他负责Elsyca公司表面精饰业务部全球活动。

ELSYCA是电化学智能公司，总部位于比利时Wijgmaal，并在美国亚特兰大设有办事处，该公司为表面精饰和阴极保护工业提供电化学工艺工程服务和软件解决方案。

Robrecht Belis studied Information Technology and Marketing in Leuven (Belgium). He started at Leuven Measurement Systems (LMS) in 1986 with an initial focus on software engineering creating the framework of a new high-tech solution for the NVH industry, later on moving towards several project management positions with global business responsibilities. Since 2008, he manages the worldwide activities of the Surface Finishing Business Unit at Elsyca.

ELSYCA, the electrochemical intelligence company with HQ in Belgium (Wijgmaal) and an office in the US (Atlanta), offers Engineering services and software solution in the context of electrochemical processes for the surface finishing and cathodic protection industries.