Fastener Failures Due to Heat Treatment: A Case Study

案例研究：熱處理導致的扣件失效

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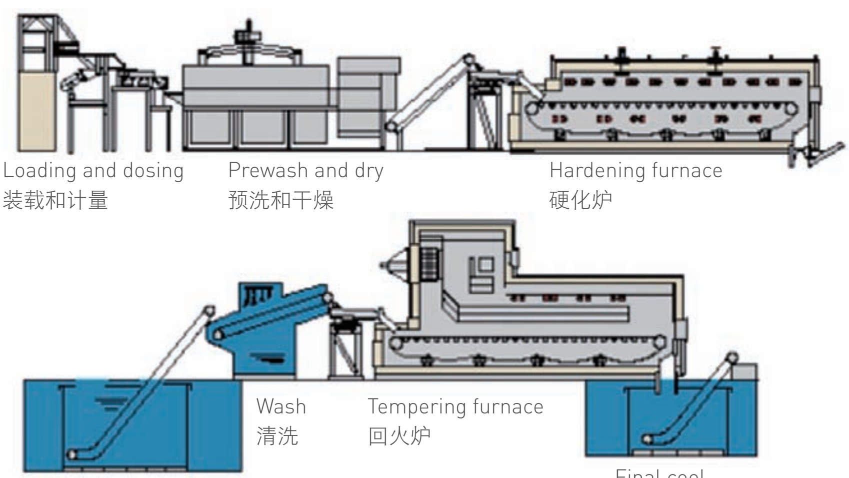
When a component part fails, it is only natural to ask why and then strive to determine the root cause. Gathering all possible information about the circumstances surrounding the event and performing a thorough failure analysis is a critical first step in the process. For the Heat Treater this type of information helps us create a set of do's and don'ts, which are invaluable in avoiding a repetition of the problem.

Finding the root cause of a failure is an important part of corrective actions required when a fastener system fails. There are many contributory factors as to why a fastener may fail. Here is an example of one instance where faulty heat treatment was responsible. It will serve as a valuable addition of our knowledge base and falls in the category of "lessons learned".

Failures can be traced to deficiencies in design, materials, processing, product characteristics and quality, known and unknown application factors and to human error. Examples include excessive distortion, buckling, ductile or brittle fracture, creep, rupture, cracking, fatigue, shock, wear, corrosion, misalignment, poor geometrical design and literally

Figure 1. Typical Mesh Belt Furnace System with Oil Quench Capability
图例 1典型具油淬火性能的网带炉系统



零组件故障的时候，很自然地大家都会先问为什么，然后努力厘清问题的根源。过程中关键的第一步便是：收集所有事件前因后果以及相关的资讯，并进行彻底的故障分析。对专业热处理厂而言，此类资讯可以帮助我们建立一套该做和不该做的规则，这对于避免重复问题是非常有价值的。

吾人可借由故障追溯设计、材料、加工、产品特性和品质、已知和未知的使用条件以及人为错误等的缺失。故障实例包括过度的变形、屈曲、延性或脆性断裂、潜变、断裂、龟裂、疲劳、冲击、磨损、腐蚀、对齐不良、几何设计粗劣，以及其它数以百计的因素。无论故障根本原因为何，最重要的就是要认知不可能将产品和过程分离；同理，**材料 - 設計 - 處理 - 使用**彼此间皆有相互关联。

思考如何避免故障发生，「辨识相关因素」为首要步骤，接着厘清是独立产生效应，或是彼此关连导致故障。好比说，我们问自己「主要导致此类故障之因为为何？」或者「设计是否够扎实稳当，安全系数选择是否正确，足够应付使用期间严苛的应用需求？」**完善的工程設計，加上對實際應用、負載和設計需求的了解，是避免故障的關鍵。**

扣件系统出现故障的时候，寻找故障的根本原因，是矫正措施很重要

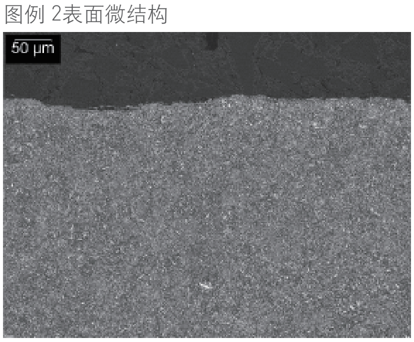
hundreds of other factors. Whatever the source, it is important to recognize that it is impossible to separate the product from the process and as such material – design – processing – applications are all interrelated.

When considering ways to prevent failures from occurring, one determines the factors involved and whether they acted alone or in combination with one another. We ask ourselves questions such as "Which of the various failure classifications were the most important contributors?" and "Was the design robust enough and the safety factors properly chosen to meet the application rigors imposed in service?" Having a solid engineering design coupled with understanding the application, loading and design requirements is key to avoiding failures. If failures do happen, we must know what contributed to the damage.

Case Study – Root Cause: Bad Heat Treatment

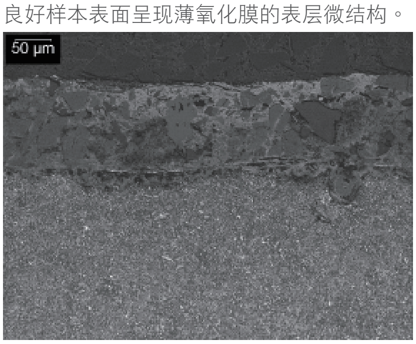
Ten out of sixty SAE 1045 fasteners were found to be cracked after heat treating in a continuous mesh belt furnace line (Fig. 1). The heat treatment called for austenitizing at 870˚C (1600˚F) for 30 minutes, oil quenching and tempering at 370˚C (700˚F) for two (2) hours.

Figure 2. Surface Microstructure
图例 2表面微结构



200X, 2% Nital
200X，2% 硝酸酒精

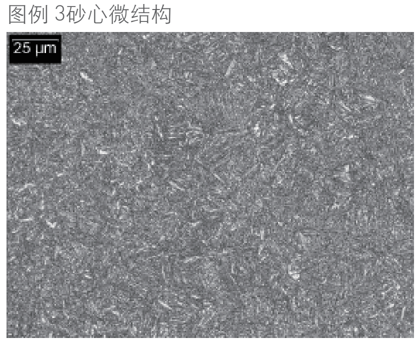
(a) Surface microstructure of "good" sample revealing thin oxide film at the surface.
良好样本表面呈现薄氧化膜的表层微结构。



200X, 2% Nital
200X，2% 硝酸酒精

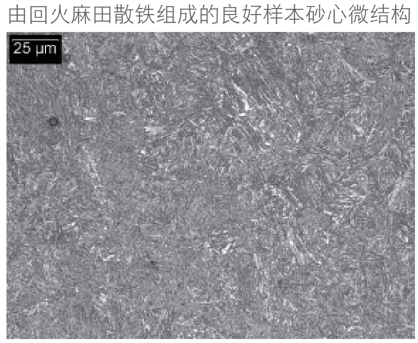
(b) Surface microstructure of "bad" sample revealing thick oxide film at the surface.
不良样本表面呈现厚氧化膜的表层微结构。

Figure 3. Core Microstructure
图例 3砂心微结构



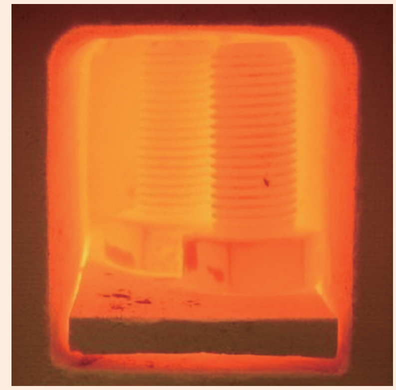
500X, 2% Nital
500X，2% 硝酸酒精

(a) Core microstructure of "good" sample consisting of tempered martensite.
由回火麻田散铁组成的良好样本砂心微结构。



500X, 2% Nital
500X，2% 硝酸酒精

(b) Core microstructure of "bad" sample consisting of tempered martensite.
由回火麻田散铁组成的不良样本砂心微结构。



的一部分。导致扣件故障的因素有很多，以下将说明一个因热处理不良所致的扣件故障实例。

案例研究

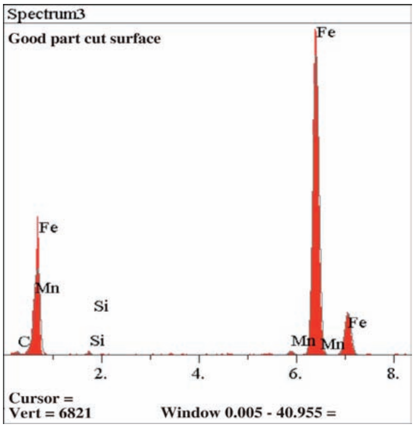
根本原因：熱處理不良

六十个SAE 1045扣件中，发现有十个在连续式网带高温炉线上热处理后破裂（图例 1）。热处理要求以870℃（1600℉）沃斯田铁化30分钟，之后，以370℃（700℉）油淬火和回火两小时。

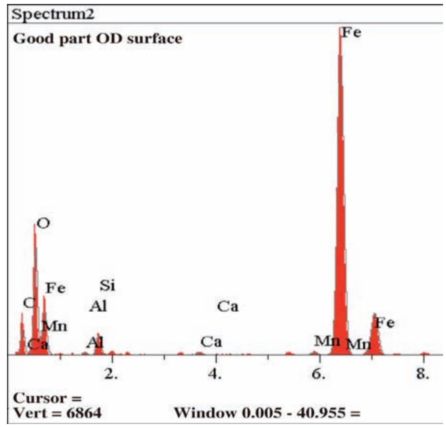
调查过程中，专业热处理厂商报告，因雷电暴风雨使的闪电击中当地变电所，导致该地区停电，电力中断期间发生问题的部件正进行热处理，结果造成炉内气压和温度减损。部件随后自生产线卸下，进行硬度测试后发现硬度过低，部件于是重新硬化处理，试图补救。随后的硬度测试指示规格在正常范围内。

一支龟裂的扣件和一支生产批次稍早，但已知是良好的部件两者同时递送并进行冶金分析。首先以目测观察两支部件的差异，「不良」的扣件上出现严重的鳞片，特别是在螺纹区域；而「良好」的部件则呈现光滑表面。

Figure 4. SEM/EDX Investigations/图例 4扫描式电子显微镜/能量散射光谱仪（SEM/EDX）调查研究

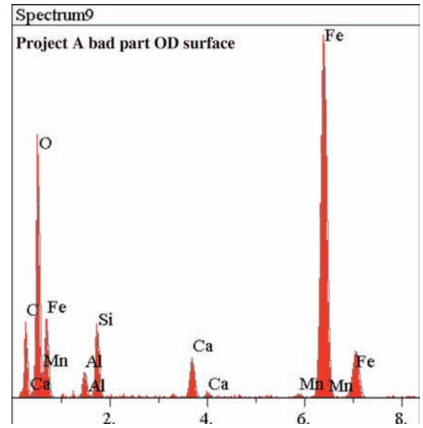


(a) Baseline EDX results
基线能量散射光谱仪结果。



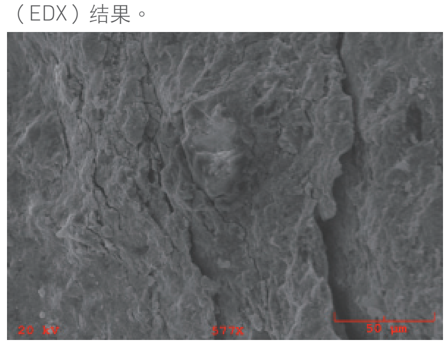
(b) EDX results on the OD surface of the "good" sample.

良好样本外径表面的能量散射光谱仪（EDX）结果。

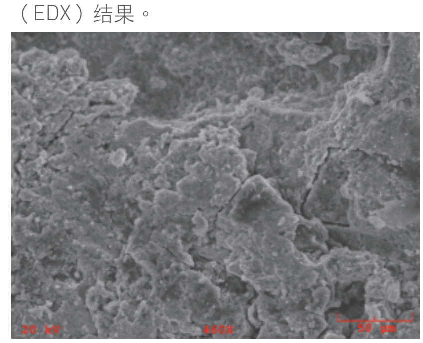


(d) EDX results on the OD surface of the "bad" sample.

不良样本外径表面的能量散射光谱仪（EDX）结果。



(c) SEM view of surface of "good" sample.
良好样本表面的扫描电子显微镜（SEM）视图。



(e) SEM view of surface of "bad" sample.
不良样本表面的扫描电子显微镜（SEM）视图。

During the investigation the commercial heat treater running the job reported a power outage (due to a lightning strike during an electrical storm on a local substation) that occurred while the parts in question were being heat treated, resulting in a loss of furnace atmosphere and temperature. Parts were subsequently unloaded, hardness tested and found to be low in hardness and re-run in an attempt to salvage them. Subsequent hardness testing indicated they were within specification.

Both a cracked fastener and a known good part from a previous production lot were sent for metallurgical analysis. Visually, the difference between the two parts was the presence of heavy scale on the "bad" fasteners; especially in the thread areas while the "good" parts were clean.

The fracture surface of the "bad" fastener appeared uniformly black - the same color as the exposed surfaces on the "bad" part. SEM / EDX analysis was performed on both the fracture surface and the exposed OD surface for comparison. Both of the analyzed "bad" fastener surfaces revealed continuous coverage with the oxide film with identical elemental composition.

Using a SEM/EDX, the outer diameter surface of the "good" fastener

「不良」扣件的断裂表面呈现均匀的黑色，和其外露表面的颜色相同。断裂面和外露的外径表面两者以扫描式电子显微镜/能量散射光谱仪（SEM/ EDX）分析比较。两个「不良」的扣件表面经由分析显示连续的氧化膜披复，且膜层组成元素相同。

以SEM/EDX 分析「良好」的扣件外径表面和基线材料，与「不良」部件作比较。分析发现「良好」之扣件外径表面氧化较少，该材料经由嵌入壁剖面分析确定为SAE1045钢。

将「良好」及「不良」扣件的横截面另外进行分析，可得知分析结果是回火的麻田散铁微结构。「不良」扣件外露的表面和断裂的横截面上观察到约100微米厚连续的膜；相较之

and the baseline material were analyzed for comparison with the "bad" part. Less oxidation on the "good" fastener outer diameter surface was determined in the analysis. The material was identified as SAE 1045 steel based of analysis the sectioned insert wall.

In addition, an examination of the cross section of both the "good" and "bad" fasteners was also performed. The result of the analysis was a microstructure of tempered martensite. A continuous film that is approximately 100 microns thick was observed on the exposed surfaces and fracture cross sections of "bad" fastener. In contrast, the surface film on the "good" fastener was approximately 2 microns thick.

Hardness was measured on the fastener cross sections using microhardness methods (Vickers, 500 gf) and converted into Rockwell "C". Enough microhardness indentations were placed in the middle of the insert wall to be statistically meaningful.

After metallurgical and failure analysis, the following conclusions were reached:

The "good" fasteners exhibited a surface and core microstructure of tempered martensite, the result of proper heat-treating. A thin oxide layer was observed on the part surface indicative of tempering at elevated temperature in air.

The "bad" fasteners were cracked during the heat treatment process, either the result of thermal or quenching stresses.

The fracture surface and the outside diameter of the fastener both yielded the same composition and oxide layer thickness.

Hardness values (converted from microhardness measurements) on the "bad" fasteners found were out of specification (high) indicating an inconsistency in response after the re-hardening operation.

These measurements are considered more accurate than attempting to hardness test the surface using conventional Rockwell "C" measurements with scale present.

Corrective action, in this instance, consisted of instructing the commercial heat treater to not rework but quarantining any fasteners that were subjected to an abnormal heat treatment cycle until a thorough metallurgical analysis could be performed. Furthermore, using a dye penetrant or similar method for determining the presence of cracks after heat treatment was also suggested. Using an independent source, routine (per batch) quality checks could be performed by an independent third party. Finally, in-house heat-treating is an alternative that might be considered if the problem is found to persist despite the quality control measures suggested.

下，「良好」扣件表面膜的厚度仅约2微米。

扣件横截面的硬度以微硬度方法（维氏（Vickers），500 gf）测量，然后转换成洛氏（Rockwell）「C」。嵌入壁中间位置预留足够的微硬度空间，以便统计分析呈现意义。

冶金和故障分析后，得出以下结论：

「良好」的扣件表面和砂心具有回火麻田散铁的微结构，这是热处理适当的结果；若部件表面有一层薄氧化层，这表示回火在提高的温度中进行。

「不良」扣件的龟裂发生在热处理过程中，因热应力就是淬火应力。

断裂面和扣件外径都可测出相同的组成元素和氧化层厚度。

「不良」扣件（转换自微硬度值）的硬度值超出规格，与重新硬化后测出值不一致。

这样测出的量值比使用传统洛氏 「C」测量表面鳞状补救性的硬度测试更准确。

此实例的矫正措施包含专业热处理厂不可重新加工，且必须将任何需作异常热处理的扣件隔离，直到彻底执行冶金分析为止。同时，热处理后也建议使用染料渗透剂或类似方法，检测是否存在龟裂。若使用自主的供料来源，可由独立的第三方进行常态（批次别）质量检查。最后，如果已施行所建议的品管措施，而问题仍存在，厂内热处理是另一种可考虑的替代方案。