运用感应硬化进行紧固件热处理

Using the Induction Hardening Process for the Heat Treatment of Fasteners

感应加热是用来进行紧固件热处理的其中一种技术。这方法有高度多功能性，可符合高产量（连续式）与少量（批量）两种的生产需求。

Induction heating is one of the technologies that can be used to heat-treat fasteners. This method is highly versatile and can be used to meet the demands of either high production (continuous) or piece-by-piece (batch) production needs.

by Daniel H. Herring

什麼是感应加热？

感应加热（图一）是一种非接触性的加热方法，利用交流的磁场来对导电材料（通常是金属）加热。此导电材料被一个看不见力量线（环绕整个电气设备的力量）之磁场所环绕，这些力量是由一个线圈与通过这线圈的电流所创造，这个具有电流的线圈会产生一股电流通过该导电材料。加热是由於**焦耳效应**中所谓的电气阻力，以及较小程度由於磁性滞後（magnetic hysteresis，即除了磁场反转引起的磁性材料涡电流现象之外的其他电力损失）所产生。**焦耳定律（图二）**陈述，电气回路任一部份所产生的热量，其产生的速度是由电流（I）平方乘以该部分回路之电阻（R）的积来量测。

感应加热背後之科学原则，是以所谓法拉第效应为基础的科学原则。此法则是为了纪念法拉第而命名，法拉第是第一位成功从磁场产生出电流的物理科学家。

感应加热如何运作？

感应加热的运作是基於对感应电流阻力的原则。这些电流称为涡电流，与感应线圈（也称为感应器）产生的电流在大小上相似，在方向上则相反。

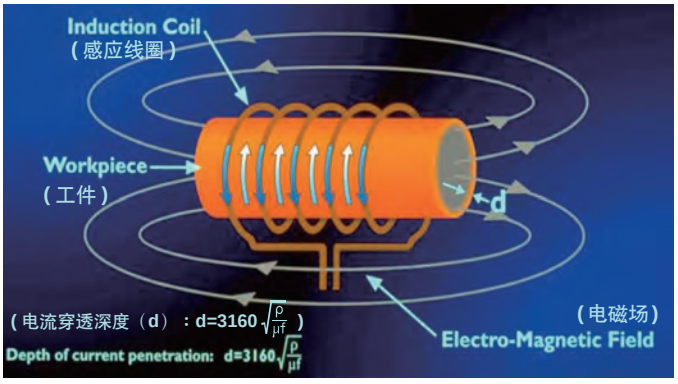

Figure 1 Principles of Induction Heating
图一 感应加热原则

What is Induction Heating?

Induction heating **(Fig. 1)** is a noncontact heating method; one in which an electrically conductive material (typically a metal) is heated by an alternating magnetic field. The conductive material is surrounded by a field of invisible lines of force (forces that surround all electrical apparatus) that are created by a work coil with a current flowing through it, inducing a current to flow in the conductive material. Heating results due to electrical resistance in the so-called **Joule effect** and, to smaller degree, magnetic hysteresis (i.e., power loss other than by eddy currents in a magnetic material caused by reversals of the magnetic field). **Joule's Law (Fig. 2)** states that the rate at which heat energy is produced in any part of an electric circuit is measured by the product of the square of the current (I) times the resistance (R) of that part of the circuit.

The scientific principle behind induction heating is based on a scientific principle called the "Faraday effect" named for the physicist Michael Faraday, who was the first to produce an electric current from a magnetic field.

How does Induction Heating Work?

Induction heating works on the principle of resistance to induced currents. These currents, called eddy currents, are similar in magnitude and opposite in direction to the current produced by the induction coil (also known as the inductor).

A number of other independent variables, including the work piece's

其他许多独立的变数，包括工件磁导率（关於一件材料磁性强度的量测）、气隙（air gap，即感应线圈与工件的耦合距离）以及频率等，都会影响感应处理与其效率（图二）。

应用实例

汽车紧固件的感应硬化是自攻螺丝、螺栓与类似组件广泛使用的方法。由於这些零件的大小，典型的材料搬运方法会被采用以使硬化处理具有经济性，在整个紧固件业界有若干不同的方法。其中一种是使用简单的震动送料器（图三），其在排整零件方向後，以一秒一个的速度，将零件运送到一个转轮，该转轮会将零件送到定位。该转轮依零件大小制成，有沟槽可悬挂零件的头部，将零件送经所需的加热区（一般是一个隧道式线圈），然後到喷洒区或掉入淬火溶液中（如水、聚合物、油）快速冷却。有些系统比较复杂，设有接收或拒收的闸门，利用光学仪器量测，把不合乎规定温度的工件分离出来。淬火液流量、压力、温度与电力都在线圈处量测，再输入监控硬化过程的电脑，以确保稳定可重复的结果。感应处理之後是炉内回火或应力消除。

汽车用紧固件品质要求极为严格，座位安全带的螺栓即是一例，以 AISI/SAE 4037 材质的 M8 紧固件为例，其典型的感应区规是 1~3 条全螺纹。由於滚制螺纹的性质、螺纹螺旋线，以及检查员对第一全成型螺纹的诠释等因素，确切尺寸通常是无详列的，这部分处理可由目视进行。该材料有预热（硬化及回火）至心部硬度达到 HRC28~34。感应硬化区的最小硬度值通常位於螺纹根部以下 0.008”。整体设置过程通常包含测试，包括加热线圈的调整（图五），以及透过安装、抛光与微硬度测试样品（图六）的品质检查。在这个案例中，非穿透硬化的螺纹区域让产品更有延展性，这在紧固件产业里是极为理想的特性。

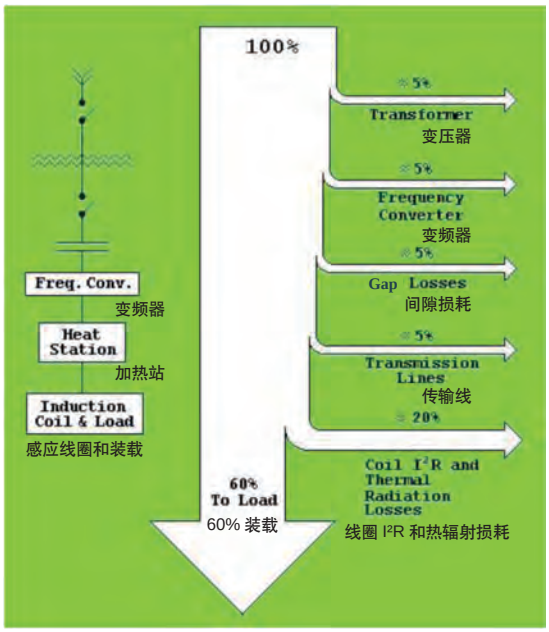

Figure 2 Energy Transferred to Work Piece
图二 转移至工件之能量

magnetic permeability (a measure of how magnetic the material is), the air gap (coupling distance between the induction coil and work piece) and the frequency influence the induction process and its efficiency **(Fig. 2)**.

Application Examples

Induction hardening of automotive fasteners is a widely used method for self-tapping screws, bolts and similar components. Due to their size, a method of material handling is typically used to make the process economical, and there are several different methods used throughout the fastener industry. One type is a simple vibratory feeding unit **(Fig. 3)** that orients the part and transfers them, at a rate of up to one piece per second, to a rotating wheel that positions the parts. The wheel is machined to size of part with notches that suspend them by the head so that they pass through the required heat zone (typically a channel coil) and then into a spray or dropped into a quench solution (e.g. water, polymer, oil) for rapid cooling. Some systems are more complex and utilize accept/reject gates that segregate pieces that do not meet the required temperature measured by an optical pyrometer. Quench flow, pressure, and temperature as well as kW are measured at the coil and inputted into a computer system that monitors the process for consistent and repeatable results. Oven tempering or stress relief follows the induction process.

Automotive fasteners have stringent quality requirements, an example of which is seat belt bolts. A typical induction zone specification for a M8 fastener of AISI/SAE 4037 material is one to three full threads. Exact dimensions are often not specified because of the nature of roll threading, the helix of the thread and the interpretation of the first full form thread by the inspector. This part of the process can be done visually. The material is pre-treated (hardened and tempered) to achieve a core hardness of 28 to 34 HRC. A minimum induction hardened zone hardness is typically 0.008” below the root of thread. Set-up often involves trial runs including adjustments to the heating coil **(Fig. 5)** and quality checks by mounting, polishing and microhardness testing sample parts **(Fig. 6)**. In this case a non-through hardened thread area gives the part more ductility, which is highly desirable in the fastener industry.

Induction heating tempering **(Fig. 5)** or conventional furnace/oven tempering **(Fig. 6)** can also be used to reduce (draw back) fasteners hardness at high production rates. For example, high frequency (10 – 50 kHz)

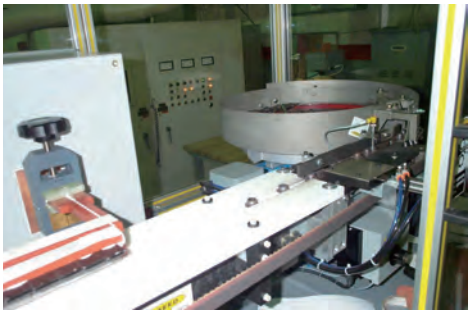

Figure 3 Vibratory Bowl Feeding Arrangement into Induction Coil
图三 震动盆送料处理进入感应线圈处

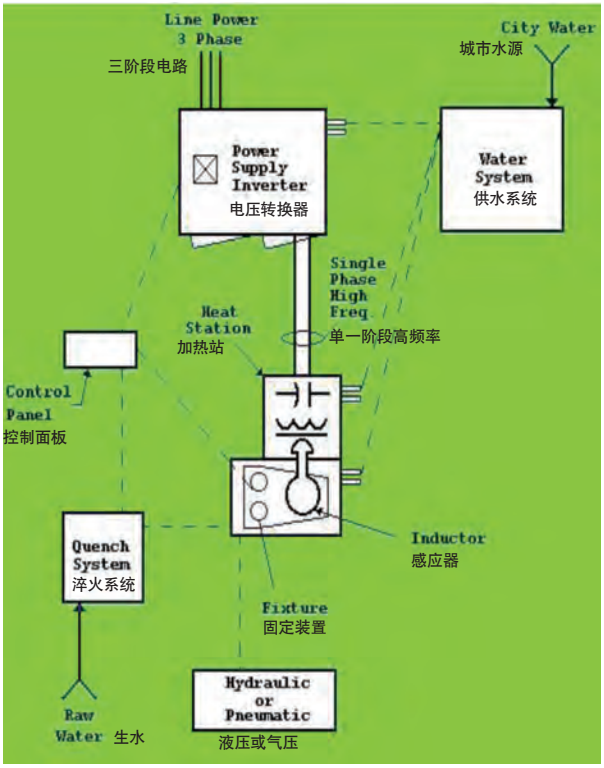

Figure 4 Typical Induction System Overview
图四 典型感应系统概述

感应加热回火（图五）或传统的熔炉 / 烤炉回火（图六），也可以高产量的速度来降低（拉回）紧固件硬度。例如，高周波系统（10-50KHz）在渗碳後，可以每秒 1~2½ 个的速度拉回 8620 螺栓头部，来改善韧性。同样地，4,140 颗座位螺栓和座位安全带固定螺栓，以头部朝下，螺纹在上，依 200KHz 频率进行表面硬化，深度达到 0.020”，之後感应回火至表面硬度达到 40~45HRc，以获得强度与韧性。

如何选择感应设备

选择感应设备时，对於应该要考虑的变数时常有许多误解。以下为影响设备设计的典型因素：

材料

- 预先微结构 · 零件几何形状 · （沃斯田铁化）回火
- 生产速率 · 电力要求 kW* · 频率选择 kHz*
- 形状 / 轮廓（加热区形状） · 线圈设计 *
- 硬化过程发展之需求
- 应用之特定标准（如水或聚合物）
- 装载或卸载工件的方法（如人工或机器人化）
- 热处理後之切削
- 回火形式（如熔炉 / 烤炉式或感应式）

* 一般是供应商根据所提供的资讯来选择。

systems can draw back 8620 bolt heads after carburizing to improve toughness at a rate of 1 – 2 ½ pieces/second. Similarly, 4140 seat & seat belt retention bolts, run head down, threads up at frequencies up to 200 kHz are case hardened to depths up to 0.020” and induction tempered to a surface hardness of 40 – 45 HRC to impart both strength and toughness.

How to Select Induction Equipment

There is often a great deal of misunderstanding as to what variables need to be considered when selecting induction equipment. The following factors typically influence equipment design:

- Material · Prior Microstructure · Part Geometry
- (Austenitizing) Temperature · Production Rate
- Power Requirements, kW* · Frequency Selection, kHz*
- Pattern/Profile (i.e. shape of heating area) · Coil Design*
- Process Development Requirements
- Application Specific Criteria (e.g. water versus polymer)
- Method of loading and unloading the work piece (e.g. manual or robotic)
- Stock removal after heat treatment
- Type of tempering (i.e. furnace/oven versus induction)

* Typically selected by vendor based on information provided.

Key process parameters for induction heating include:

- Type (i.e. single shot or scanning)
- Power Level
- Frequency
- Part Position (e.g. rotation)
- Quench Flow and Pressure
- Quench Temperature
- Quench Time
- Quench Concentration (if polymer)

Figure 5
Annealing Process with Submerged Bolt Head
图五
螺栓头浸没之退火过程

Figure 6
Rapid Oven Temper System
(Photograph Courtesy of Carter Manufacturing)
图六 快速炉回火系统
（此图由 Carter Manufacturing 提供）

感应加热的主要处理参数有：

- 形式（如单步骤或扫瞄）
- 电力水平
- 频率
- 零件位置（如旋转轮替）
- 淬火液流量与压力
- 淬火温度
- 淬火时间
- 淬火浓度（如为聚合物）

以下问题(及其答案)有助于读者选择正确的感应加热设备：

- 我们需要几千瓦（kW）来执行这项工作？
- 该硬化层深度所需的频率？
- 零件如何进入与从机器取出？
- 需要多少种不同的线圈规格(与类型)，才能涵盖零件范围？
- 控制系统如何运作？电脑萤幕易於使用吗？（电脑有读者需要的资讯类型吗？）
- 我们需要光学高温计作为控制系统的一部分吗？加热不够或过热的结果是什麼？我们如何利用温度标准来淘汰商品？
- 若有温度差异，从零件的一端到另一端、中心到表面，会有多少？
- 工厂电力来源有多少伏特？
- 工厂需要什麼类型的冷却系统？若已有，是否未实际发挥产能？
- 机器每个时间单位成本为何？有基本电费吗？（巅峰或离峰？）
- 安装设备要多少成本？
- 机器需要什麼保养？多久要进行一次保养？
- 需要多少地面与头上空间？什麼形状？
- 我们需要通风设备或排气系统吗？
- 感应加热之前，我们需要清洗零件吗？

成功之钥

紧固件感应作业的成功之钥包括：

- 稳定的电力（kW）与温度
- 稳定的零件移动 / 时间
- 一致的零件转动 / 位置
- 接收 / 拒收闸门

感应加热非常多样化，易於控制且技术简单，少量与多量的情况皆可应用，其优点有：

- 感应加热 / 淬火的硬化层周期 / 淬火，一般是短的
- 生产速率与周期时间可与机器配合
- 硬化过程中的零件数在目在任何订定的时间中，通常是少的
- 对制造组体（manufacturing cells）而言，是理想设置
- 能量集中於需要硬化的区域，因此对加热与淬火而言，能量成本最少
- 一般说来电力效率高（60~70%）
- 每个零件的可用资讯能正确监控（如能源消耗及淬火变数，像是温度、压力和流量），使品管更简易。 ◘

The following questions (and their answers) will help you select the right induction heating equipment:

- How many kilowatts do we need to do the job?
- What frequency is needed for the case depth required?
- How does the part get placed into and removed out of the machine?
- How many different coil sizes (and types) will we need to cover our range of parts?
- How does the control system work? Are the computer screens user-friendly (and do they have the type of information you need)?
- Do we need an optical pyrometer as part of the control system? What are the effects of over and under heating and how can we reject parts based on temperature criteria?
- What, if any temperature differential will there be, from one end of the part to the other, from center to surface?
- What input voltage do we have in the plant?
- What type of plant cooling system is needed, if existing, is there unused capacity?
- How much will the machine cost to operate per unit of time? Are there demand charges for electricity (on-peak or off-peak)?
- How much will it cost to install?
- What maintenance needs to be done on the equipment? How frequently does maintenance need to be performed?
- How much (floor) space and headroom is needed? And in what configuration?
- Do we need ventilation or an air exhaust system?
- Should we wash the parts prior to induction heat-treating?

Keys to Success

The keys to success of an induction operation for fasteners involves:

Constant power (kW) and temperature
Constant part movement/time
Consistent part rotation/position
Accept / Reject gate

Induction heating is a highly versatile, easily controlled, and simple technology that can be applied to both low and high volume applications. Typical advantages include:

- Case hardening cycle of induction heat/quench is generally short;
- The production rate and cycle time can be matched to machine;
- Number of parts in process at any given time is often small;
- Ideal set-up for manufacturing cells;
- Energy is focused on just the zone requiring hardening and thus the energy cost is minimized both for heating and quenching;
- Electrical efficiency is generally high (60 to 70%);
- Accurate monitoring of available information on each part (e.g. energy consumption, quench variables such as temperature, pressure, and flow) makes quality control simple. ◘

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