An Overview of Heat Treatment in the Refining, Power, and Petrochemical Industry Part 1: A Primer on Heat Treating

Ben Osborne, Global Product & Service Line Director – Heat Treating Services

Introduction

Heat treatment has been used by mankind for centuries. While not as advanced as the controlled heat treatment we think of today in the refining, power, and petrochemical industries, the principles and philosophies of heat-treating metal dates back over 2000 years. It's an age-old practice that has been fine-tuned through years of science and technology to become one of the most essential processes during manufacturing, repair, and fabrication requirements.

There are numerous reasons to heat treat along with a few different methods of heat treating. The use spans across many industries, including oil and gas, power, chemical, automotive, aerospace, and consumer product manufacturing (glass, knives, utensils, etc.).

In this article, we're going to skip over the scientific foundations of heat treating. Instead, we'll cover the techniques commonly used in the refining, power and petrochemical industry at a high level. We'll focus on the basics, including the varying reasons to heat treat, the types of heat treating available, and methods of heat treating to achieve specific material properties. In addition, we'll focus on the role mechanical integrity plays in heat treating, including special considerations and the role of inspection during the process.

Figure 1. 40' combustion furnace located in Pasadena, Texas.

What is Heat Treating?

In short, heat treating is a process in which a product is heated and cooled with precise controls to improve its properties, performance, and durability while maintaining the product's shape. Depending on the desired outcome, the variables of temperature and time can be manipulated to alter the material's hardness, strength, toughness, ductility, and elasticity.

I used the term "product" because heat treating does not only apply to metals. Heat treating is also used to alter the properties of non-metallics, coatings, and even process fluids.

Temperatures may range as high as 2,400°F and the hold time at temperature may vary from only a few minutes to a few days or more, depending on the desired outcome and circumstances.

Equally, if not more important, than the temperature and hold time is the cooling time or cooling rate. Again, depending on the desired outcome, some products are cooled very slowly, some are cooled in ambient air, and some are quenched rapidly.

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Heat Treating Methods

There are four primary methods in which to heat treat that are commonly used for piping and equipment in the refining, power, and petrochemical industries. Each of them are introduced in the following sections.

Enclosed Combustion and Electrical Furnace

As an analogy, think of an enclosed combustion/electrical furnace as a giant oven. When you want your supper cooked evenly, you cook it in the oven. Just like the oven in your kitchen, heat treating furnaces allow the most control over time and temperature. There's minimal setup time since the furnace is typically in place already and ready to go.

Most reputable manufacturing facilities and fabrication shops will have a large furnace to accompany the majority of their work. Of course, as the asset being manufactured or fabricated grows in size, the number of shops with a furnace large enough to accommodate the asset gets fewer and fewer. This isn't typically an issue for piping, but it can be for larger pressure vessels.

For field work, there are portable furnaces which can be brought or built at the jobsite. However, the size of such furnaces are limited due to transportation and logistical considerations.

Internal Combustion

When an asset is far too large for a furnace and requires a large area of heat treatment, or if an asset cannot be removed from the field to be placed in a furnace, then internal combustion (also called gas-fired) is a commonly accepted option.

Think of this as a fireplace in a home. There's a single source of heat from a flame that's used to warm the entire house. Except, in this case, the fireplace is inside of a pressure vessel. Nevertheless, internal combustion heat treating is still a very controlled process.

Just as a home requires good insulation to retain the heat from the fireplace, so does a pressure vessel when performing internal combustion heat treatment. Unlike enclosed furnaces, attention must be paid to identify cold spots. Cold spots may not receive enough heat from the combustion process to achieve the desired result, so electrical resistance is installed and applied to run in conjunction with the combustion process. Internal combustion heat treating can be more labor intensive because of the insulation requirements. In some cases, an already insulated asset can utilize its existing insulation and may only need minor additions to the nozzles and other uninsulated projections that may act as a heat sink which is where the electrical resistance heat treating method will be applied and ran in conjunction with the combustion heating application.

Electrical Resistance

Electrical resistance is the most common form of heat treatment used in the field and in some manufacturing processes. It is common for both piping and pressure vessels in which specific isolated locations, such as welds, require heat treatment. You've likely noticed the bright pink ceramic flexible pads (CFPs) and cables at the jobsite.

With this method, the pads are attached to either the inside or outside of the area requiring heat treatment. The side chosen has minimal impact. Regardless of which side the pads are attached, the temperature is typically measured from the side that the CFPs are installed on with thermal couples that are spot welded to the material; so whichever side is more practical is typically the one chosen. Once set up, the power source is turned on, introducing an electrical current through the CFPs which generate the heat through the electrical resistance pads.

This method is ideal for the weld tie-ins, attachments, or closure welds that take place in the field. In most cases, it's not practical to build a large temporary furnace in the field for a smaller, focused scope.

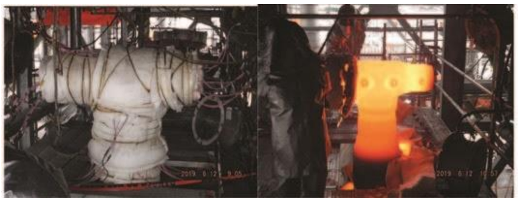

Figure 2. The effects of electrical resistance heat treating on a stainless steel header being annealed. Left: wrapped; right: unwrapped.

Induction

Induction heating systems employ non-contact heating. They induce heat electromagnetically rather than using a heating element in contact with a part to conduct heat, as is the case with resistance heating. Induction heating can be compared to a micro-wave oven. At home, the appliance remains cool while the food cooks from within. In an industrial example of induction heating, heat is induced in the part by placing it in a high-frequency magnetic field. The magnetic field creates eddy currents inside the part, exciting the part's atomic structure that consist of metal ions and generating heat. Because heating occurs slightly below the metal surface, no heat is wasted.

Induction heating is similar to resistance heating in that conduction is required to heat through the section or part. The differences between the two is the source and method of heat and the types of the equipment required. The induction process heats within the part and the resistance process heats from the surface through to the part.

The depth of heating depends on the frequency. High frequency (e.g., 50 khz) heats close to the surface, while low frequency (e.g., 60 hz) penetrates deeper into the part, placing the heating source up to 3 mm deep, allowing heating of thicker parts. The induction coil does not heat up because the conductor is larger than the cur-rent being carried. In other words, the coil does not need to heat up to heat the workpiece.

So Which One?

All of the above methods are industry proven and are suitable for heat treating. Of course, it really comes down to the size, geometry, and the desired result.

From a mechanical integrity perspective, ASME recommends heat treating in an enclosed combustion or electrical furnace, whenever possible. This is due to the amount of control and consistency during the heat-treating process, minimizing the potential uneven heating or cooling and the creation of localized hard zones.

Depending on the service conditions, hard zones from uneven heating or cooling can create high stresses and develop into cracks down the line. The potential for this is higher with internal combustion, electrical resistance, and induction; which is why more surface temperature monitoring is typically required. In addition, the temperature charts usually require a bit more scrutiny from the inspectors.

Reasons to Heat Treat

As stated before, there are numerous reasons to heat treat. In the refining, power and petrochemical industries, heat treating is commonly used to reduce residual stresses formed as a result of welding or forming a material. This is pretty typical for metallic piping and equipment subjected to environmental cracking. It's also not uncommon to heat treat a thick material after welding to allow it to "relax."

Non-metallics (plastics, fiberglass, refractories etc.) and even coatings often require heat treatment to fully cure the material to a finished state.

Although not ideal, some process fluids can become plugged or solidified and often require a controlled heat treatment to soften or liquify the product to allow the product to flow. This is a common practice in colder climates, where piping maybe subject to freezing up or in systems that may become stagnate and lose the expected and required flow rate.

Welding Preheat (PHT)

Preheat is added prior to the start of welding; and, in most cases, there is a minimum preheat requirement set forth based on the material and thickness. PHT elevates the temperature of the base metal surrounding the weld, minimizing the temperature differential between the base metal and the new weld metal. The goal of preheating is to reduce the cooling rate of the deposited weld metal, allowing time for it to fuse properly with the adjacent base metal.

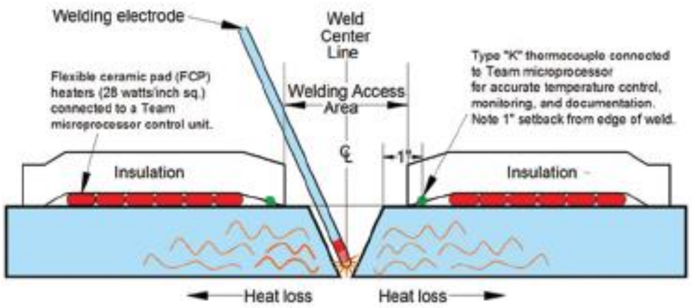

Figure 3. Typical example of a welding pre-heat set up.

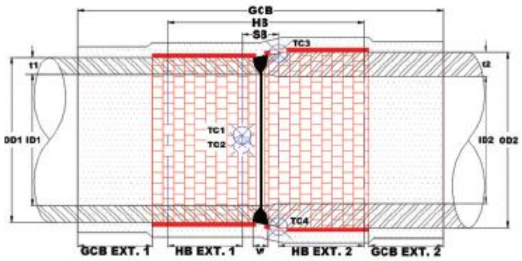

Figure 4. A Typical PWHT set up showing the Thermal Couple locations and heat band width.

Without PHT, the rapid cooling of the liquid weld pool results in residual tensile stresses and potential cracking as the pool rapidly contracts from the relatively rigid, lower-temperature base metal surroundings. Solidification of the weld pool also reduces weld ductility, with the resultant embrittlement causing a reduction in the fatigue life of the weldment assembly.

With PHT, the weld pool has time to fuse properly to the adjacent base metal.

In most cases, PHT is performed using electrical resistance. The ceramic pads are placed near the weld area, and the heat is maintained throughout the welding process.

Post Weld Heat Treatment (PWHT)

PWHT is a heat treatment process designed to relieve residual stresses caused by any such manufacturing processes. Bending, welding, grinding, rolling, cold working, quenching, stamping, and other operations can introduce new stresses into the structure of a metal part.

PWHT is the uniform heating of a structure to a suitable subcritical temperature below the austenitic transformation range. After the desired temperature is reached, it is held for a predetermined period, followed by uniform controlled cooling. Elimination of residual stresses can be an important step to ensure the manufacturability of parts to proper size, fit and function. The presence of excessive amounts of residual stresses in components can manifest into problems with size change, or undesirable mechanical properties during subsequent manufacturing operations or during use in service.

Figure 5. Holding sphere wrapped and set up for PWHT.

PWHT can be accomplished using any of the heat-treating methods mentioned above. Again, depending on the circumstances, the most practical method is the one that should be used.

PWHT can be used for a number of reasons, but it is primarily used to improve weld integrity. During welding, a couple things take place that affect the integrity of the weld. First, the rapid cooling of the liquid weld pool results in residual tensile stresses and a higher potential of cracking as the pool rapidly contracts from the relatively rigid, lower-temperature base metal surroundings. In addition, solidification of the weld pool reduces weld ductility, with the resultant embrittlement causing a reduction in the fatigue life of the weldment assembly.

This is where PWHT is beneficial. PWHT provides controlled slow heating, PWHT soak temperature and time, and controlled cooling, to reduce residual stresses and hydrogen content, and to restore ductility, corrosion resistance, and fatigue life to the weldment assembly.

Depending on the desired outcome of the material properties, the cooling rate after PWHT can be manipulated to affect the material's hardness, ductility, and elasticity.

Because of the metallurgical benefits of the PWHT process, there are oftentimes inspection benefits that follow. With regards to cracking susceptibility, PWHT reduces that susceptibility to the point that cracking inspection intervals are able to be increased or removed completely if the material is deemed no longer susceptible. One example is the PWHT of carbon steel piping and equipment in caustic service. The bottom line is that PWHT'ing carbon steel is much less likely to develop cracks in caustic service than non-PWHT'd carbon steel.

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Quenching is the process of heating a material above its transition temperature and rapidly cooling. Doing this forms martensite, creating a hard, brittle material that is able to withstand abrasion and vibrations. The downside to creating this harder, more brittle material is that the susceptibility to brittle fracture increases.

Normalizing is the process of heating a material above its transition temperature and allowing it to cool in the open atmosphere.

This process is similar to annealing, but the cooling process is not as controlled. This does allow for different areas of the material to cool at slightly different rates, depending on the geometry and complexity of the asset. This is not a big issue with piping, as the geometry and complexity are typically simple in nature.

Annealing is similar to normalizing, except that the cooling rate is more controlled. The material is heated above its transition temperature and is then cooled at a controlled rate. This typically involves a stepwise cooling process, where the material will cool to a temperature and hold for a few hours before cooling to the next temperature. This controlled heating and cooling improves strength, ductility, and elasticity.

Hydrogen Bake-Out

Hydrogen bake-out, also known as degassing, involves heating the steel to an elevated temperature and allowing time for the hydrogen or other contaminant to diffuse out of the material. This leaves the material contaminant-free and increases the desired quality for the welding process. The time and temperature used may vary depending on the thickness of the part being degassed. A typical rule of thumb suggests to bake-out the steel at 600°F (316°C) for at least one hour per inch. In some cases, a higher temperature may be substituted for a shorter duration. The end goal is to have a clean, contaminant-free, material to weld on.

Refractory Dry-Out (RDO)

This is a common need for most industry applications that use refractory linings to help protect the shell of equipment seeing high temperature gases and liquids. While the type of refractory materials differs greatly, the need to dry the water-based material is high. This is mostly due to the usually thick application ranging anywhere from 3" to upwards of 18" thick.

Cracking in refractory can render the lining useless. Controlled RDO minimizes and sometimes eliminates the potential for cracking in the refractory liner, thus extending its life. In addition, the controlled heating rate helps avoid thermal shocks to the refractory during startup.

Combustion heating is the more common method used for this application and can be used on anything from a small exchanger or refractory lined piping to providing an entire FCCU reactor lining dry out.

Coating Cure

Similar to RDO, coating cures is another common need in the refining and petrochemical industries. A controlled coating cure improves the coating integrity, keeping it to within the manufacturer's specifications, and reduces the risk of overheating or damaging a new coating.

Like many materials in the refining and petrochemical industries, coatings have been heavily engineered and scientifically manufactured to withstand many of the harshest conditions. With these highly engineered coatings comes stringent specifications for applying them. The curing process is one of them.

Just as with RDO, combustion heating is typically used for coating cures.

Product Thaw

Another common purpose of heat treating is to liquify solidified products which have plugged the piping system. This is a fairly common remedy in colder climates, where insulation and steam or hot oil tracing is very important to keep the process flowing. It is also a common remedy for heavy services such as crude vacuum tower bottoms and coker or asphaltene piping. A failed section of steam, flow or hot oil tracing can lead to the solidification of the product inside, especially when temperatures are at or below freezing.

The primary method of heating up and loosening the product is by way of electrical resistance. The ceramic pads are installed on the piping with the solidified product and heated up to the temperature needed to liquify the product. It sounds easy, but there are many steps and stringent monitoring of the metal temperatures during this process.

Role and Impact on Mechanical Integrity

Now that we've covered the basics of heat treating, we can begin to further explore to the role that mechanical integrity plays in heat treating. With the basic knowledge of this article, you can better understand the impact that heat treating has on your inspection programs.

In part two of this series, we'll dig deeper into the benefits that heat treating has on mechanical integrity as well as the quality control measures that take place during the heat-treating process. We will discuss the common damage mechanisms whose susceptibility can be greatly reduced with the heat treatment and how it's used to reduce risk in RBI programs. We will also cover the importance of the heat treatment plan, including the engineering that takes place which determines pad layouts, supports, etc. the Mega Rule, but also operators around the world with their integrity assessments, we have introduced a Material Verification Framework (Figure 1).

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