Oil Quenching of Fasteners - Part One

by Daniel H. Herring

For the hardening of most steel fasteners, oil quenching is a logical and popular choice among manufacturers looking to achieve consistent mechanical properties and acceptable distortion levels **(Fig. 1)**. A wide variety of equipment is used, either batch or continuous **(Fig. 2)**, atmosphere or vacuum case hardening (i.e.carburizing/carbonitriding) followed by oil quenching. The reason oil quenching is so popular is due to its excellent performance results and stability over a broad range of operating conditions.

For many the choice of oil as the best quenchant is due to an evaluation of a number of factors, including[1]:

- **Economics/cost** (initial investment, maintenance, upkeep, life)
- **Performance** (cooling rate/quench severity)
- **Minimization of distortion** (quench system)
- **Variability** (controllable cooling rates)
- **Environmental concerns** (recycling, waste disposal, etc.)

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Figure 1

Typical Production Run of Fasteners

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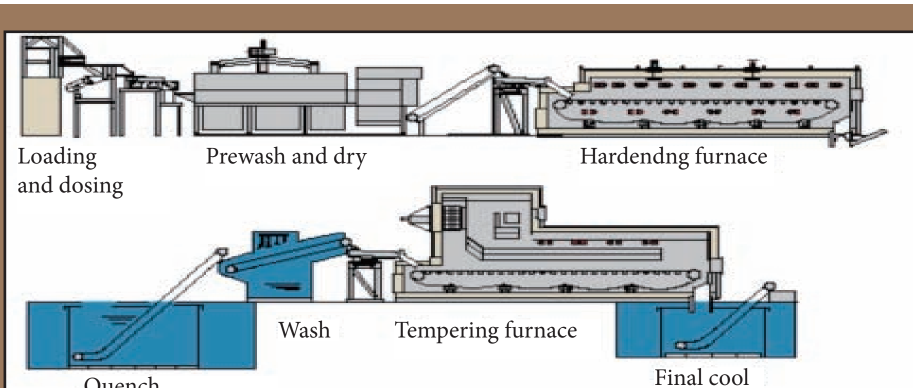
Figure 2

(a) Typical Fastener Heat Treatment System with Oil Quench Capability



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(b) Schematic Layout of Typical Fastener System Layout

Stages of Cooling

Fastener geometry and size (for the given material) often dictates the type of quench media, which in turn dictates the requirements of the quench system. Many components use oil quenching to achieve consistent and repeatable mechanical and metallurgical properties and predictable distortion patterns. Oil quenching facilitates hardening of steel by controlling heat transfer during quenching, and it enhances wetting of steel during quenching to minimize the formation of undesirable thermal and transformational gradients which may lead to increased distortion and cracking.

There are three distinct stages of cooling (Fig. 3)

Stage 1 is called the "vapor blanket" (or "film boiling") stage. It is characterized by the Leidenfrost phenomenon, which is the formation of an unbroken vapor blanket that surrounds and insulates the work piece. It forms when the supply of heat from the surface of the part exceeds the amount of heat that can be carried away by the cooling medium. In this stage the cooling rate is relatively slow, in that the vapor envelope acts as an insulator and cooling is a function of conduction through the vapor envelope.

Stage 2 is the second stage of cooling, known as the "vapor transport" (or "nucleate boiling" or "bubble boiling") stage. It is during this portion of the cooling cycle that the highest heat transfer rates are produced. It begins when the surface temperature of the part has cooled enough so that the vapor envelope formed in Stage 1 collapses. Violent boiling of the quenching liquid results, and heat is removed from the metal at a very rapid rate. The boiling point of the quenchant determines the conclusion of this stage. Size and shape of the vapor bubbles are important in controlling the duration of this stage. The majority of fastener distortion occurs during this stage.

Stage 3 is the third stage of cooling, called the "liquid" (or "convection") cooling stage. The cooling rate during this stage is slower than that developed in the second stage. This final stage begins when the temperature of the metal surface is reduced to the boiling point (or boiling range) of the quenching liquid. Below this temperature, boiling stops and slow cooling takes place by conduction and convection. The difference in temperature between the boiling point of the liquid and the bath temperature influences the rate of heat transfer in liquid quenching as does viscosity.

These stages of cooling may not occur at all points on a fastener geometry at the same time. As the internal heat moves to the surface, differences in heat rejection may vary based on the surface configuration. Consequently, there is a need for a uniform and controlled agitation of liquid over the part surface. Controlled movement of the quenching liquid is important as it causes an earlier mechanical disruption of the vapor blanket in the first stage and produces smaller, more easily detached vapor bubbles during the second stage. Agitation allows the heat generated by the part to be swept away from the surface improving the heat rejection and transformation of the part.

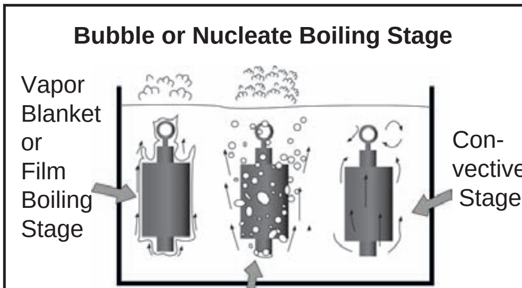

Figure 3

An Ideal Quenching Medium

The ideal quenching medium is one that would exhibit high initial quenching speed in the critical hardening range (through Stage 1 and 2) and a slow final quenching speed through the lower temperature range (Stage 3). **Thus the ideal quenchant is one that exhibits little or no vapor stage, a rapid nucleated boiling stage, and a slow rate during convective cooling.** The high initial cooling rates allow for the development of full hardness by getting the steel past the "nose" of the isothermal transformation diagram (quenching faster than the so–called critical transformation rate) and then cooling at a slower rate beginning at the time the steel is forming martensite. This allows stress equalization; thus distortion and cracking are reduced.

The first criterion that any quenchant must meet is its ability to approach this ideal quenching mechanism. When conventional quenching oils are used the duration of Stage 1 is longer, the cooling rate in Stage 2 is considerably slower, and the duration of Stage 3 is shorter. As such, the "quenching power" of oil is far less severe than that of water. Water and water solutions exhibit high initial cooling rates. Due to the low boiling point of water, fast cooling persists until the steel is cooled to below 150°C (300°F). The internal stresses of the part are given very little time to equalize, and by this point most steels have formed or are already forming martensite.

Oil has a major advantage over water due to its higher boiling range. A typical oil has a boiling range between 230°C (450°F) and 480°C (900°F). This causes the slower convective cooling stage to start sooner, enabling the release of transformation stresses. Oil, therefore, is able to quench intricate shapes and high hardenability alloys successfully. As it is heated, oil has a proportional drop in viscosity. This allows the quenchant to move more freely, increasing the tendency to break apart the vapor blanket layer. The nucleate boiling stage is not significantly altered by changes in bath temperature. The cooling rate in the convection stage of an oil quench will slow as the bath temperature increases. This is advantageous for obtaining a slower rate of cooling through the austenite–to–martensite transformation range.

In general, as the temperature of quenching oil increases, the overall quenching rate increases. Practical heat transfer coefficient (α) values in the 1000 to 2500 W/m2-°K range can be achieved depending on oil characteristics and degree of agitation. Peak values of ‘± in the cooling range of oil are 4000 to 6000 W/m2-°K, or a cooling rate greater than 100°C/s (180°F/sec).

Effect of Oil Speed

The "speed" of the particular quenchant is one of the factors involved in the choice of quench oil. This is typically measured in one of two ways: by measuring the oil's hardening power, that is, its ability to harden steel, or by measuring its cooling ability (i.e. its ability to remove heat from the surface). Since cooling ability and steel selection (i.e. composition and grain size) are independent of each another, this method is the most popular because it provides information about the oil itself, independent of its end use application.

The preferred test method today is cooling curve analysis (ISO 9950 / ASTM D6200), which involves a laboratory test using a nickel–alloy probe for the determination of the cooling characteristics of industrial quenching oils. The test is conducted in non–agitated oils, and thus is able to rank the cooling characteristics of the different oils under standard conditions, providing information on the cooling pathway, which must be known if the ability of quench oil to harden steel is to be determined.

Older methods such as the GM Quenchometer (ASTM D3520) or the hot wire test are still in common use. The GM Quenchometer method, for example, measures the overall time to cool a 22 mm (7/8") nickel ball from 885°C (1625°F) to 355°C (670°F), while the hot wire test is influenced by the heat extraction rate of the oil at temperatures close to the melting point of Nichrome, about 1510°C (2750°F).

Oils are generally classified as fast, medium, or slow speed oils. A class of oils known as marquench oil is usually considered separately. Fast (8–10 second) oils are used for low hardenability alloys such as carburized and carbonitrided low carbon or low alloy fasteners, and large cross sections that require high cooling rates to produce maximum properties. Medium (11–14 second) oils are typically used to quench medium to high hardenability steels, and slow (15–20 second) or marquench (18–25 second) oils are used where hardenability of a steel is high enough to compensate for the slow cooling aspects of this medium [2].

Effect of Increasing Bath Temperature

The temperature of the quenchant influences the rate of part cooling. Increasing the bath temperature from 21°C (70°F) to 120°C (250°F) produces a slightly faster rate of cooling in Stage 1 (because the viscosity of the oil decreases). In Stage 2 cooling also slightly increases, and in Stage 3 cooling actually decreases near the end of the quench (because the temperature differential between the bath and the steel is decreased).

Various characteristics of quenching oils allow for varying cooling rates as a function of not only their boiling point, but also their temperature. This has a direct bearing on properties such as viscosity, conductivity, and heat rejection (based on the log mean temperature differential, or LMTD) of the heat exchange system. Bubble size as well as the conductivity of the vapor barrier in all three stages of cooling is influenced by oil choice. For most quench oils, other than marquench oils, bath temperatures between 50°C (120°F) and 65°C (150°F) are normally where the optimum rates of cooling are obtained.

For most quench oils other than marquench oils, the optimum rates of cooling are normally obtained when the bath temperature is between 50°C (120°F) and 65°C (150°F). In this temperature range properly refined mineral oils are indefinitely stable and the effect of viscosity is drastically reduced. Various manufacturers usually have an optimum temperature range for their product. The instantaneous rate of rise of the entire quench bath is also important. This is normally design dependent averaging between –7°C (20°F) to 4°C (40°F) in most cases.

Part Two

The subject of oil quenching of fasteners continues in Part Two where we look at the effect of agitation, quench tank design and investigate common problems and their solutions. ■

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