Vacuum Oil Quenching: Applications and Unique Properties

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Hardening of steel is a major operation in heat treatment. Originally performed in aqueous solution, the nature of the quenching media influences the final steel characteristics and thus allows for optimization of the hardness, the microstructure and also the deformation of the treated parts.

Fig. 6. Example of a flexible vacuum processing cell including oil-quenching furnace

Depending on the steel grades and desired results, for quenching the industry turned to either oil, salt bath or (in recent years) pressurized inert gas with the growing use of vacuum furnaces.

This paper will not detail the mechanisms of hardening. It will, however, describe the potential of oil quenching performed in a vacuum furnace in comparison to conventional oil quenching and high-pressure gas quenching of 20 bar.

Quench Oil Problems

Like in any hardening process, the purpose of oil quenching is to transform an austenitic phase into a martensitic structure by imposing a rapid cooling in order to achieve the desired hardness values.

Depending on the steel grades and cooling profiles, it is possible to achieve several different structures (Fig. 1). When the austenitized parts are plunged into the oil, several successive cooling phases exist (Fig. 2).

- Vapor phase: Oil in contact with the part will rise in temperature by conduction and thus will produce moderate cooling.
- Boiling phase: Because of the heat effect, the oil transforms into vapor phase. This will lead to fastest cooling due to the absorption of the latent heat of vaporization. This is the most decisive phase of the tempering/hardening operation but also the most difficult to control. The formation of a vapor sheath around the part can cause excessive insulation, thereby reducing cooling-speed efficiency.
- Convection phase: When the temperature becomes lower and thus insufficient, the vapor phase disappears. The convection of the oil can then finish the cooling to the equilibrium temperature.

The adequacy of these theoretical curves ensures the success of the operation. This vision is, of course, simplistic. Indeed, the cooling of the part is never uniform because of different section thicknesses of the part itself. These cooling heterogeneities – minor or important – will lead to martensitic transformations at different times during the quenching phase. The crossing of the Ms point at a different time can generate abrupt part expansion and cause distortions inherent in the quenching operation.

The increased cooling speed will lead to a higher temperature gradient in the part. It is thus recommended to adjust the speed to the optimum value.

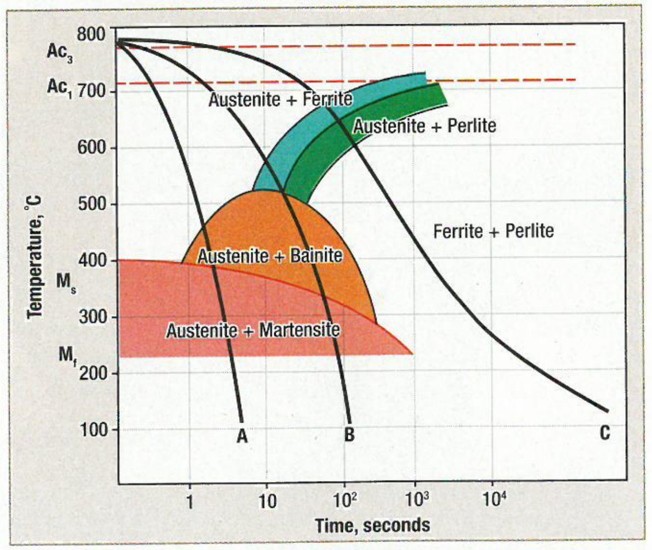

Fig. 1. Example of a CCT (continuous cooling transformation) diagram of low-alloy steel. Microstructure depends on cooling speed. Area A is predominantly a martensitic structure, typically the objective. B is a mixed structure martensitic/bainitic, which is targeted if a higher resilience (with resulting lower hardness) is desired. C has a structure quite similar to equilibrium with hardening not being achieved.

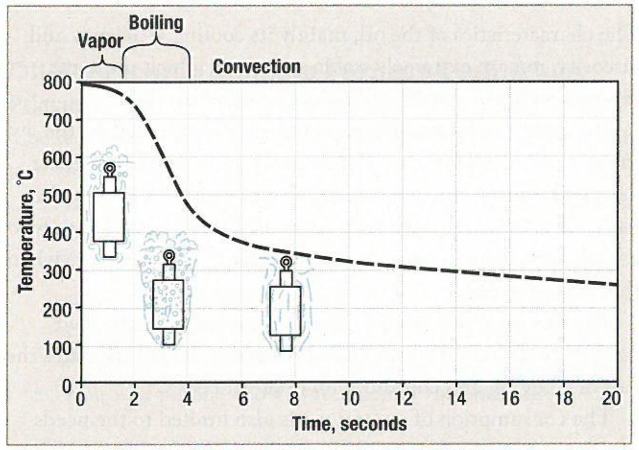

Fig. 2. Type of cooling-oil quenching profile. Various thermal-exchange phases influence cooling speed.

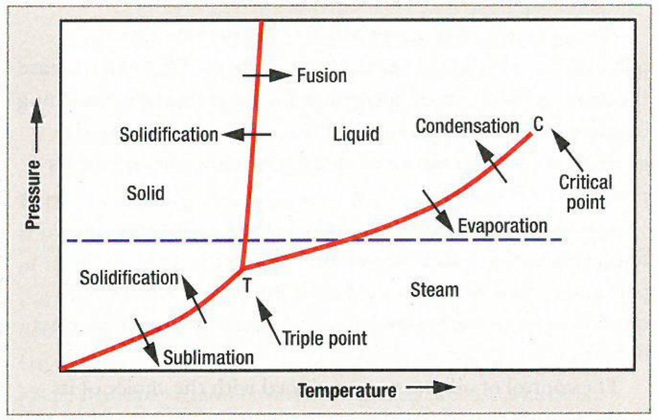

Fig. 3. Example of phase diagrams for a pure substance. Equivalent diagrams are not available for quenching oils, which nevertheless follow the same trends.

Proper adjustment of quenching parameters allows mechanical characteristics to be achieved, distortions to be reduced and acceptable geometric criteria to be obtained. If the gas quenching method reduces distortion by slowing the cooling speed, it is not efficient for low-alloy steel and massive parts because core hardness is difficult to achieve.

Advantages of Vacuum Oil Quenching

Vacuum heat treatment has become more common over the last 20 years. However, it is generally associated with pressurized inert cooling gas. Vacuum oil quenching remains marginal, but it presents interesting advantages for the industry.

Advantages During Heating

The heating takes place in a vacuum furnace, which allows surface protection by the total absence of oxidation or decarburization. The easy management of partial gas pressure further expands the possibilities. Partial pressure of inert gas (nitrogen, argon) limits alloying-element sublimation. Also, partial pressure of active gas allows the possibility of carburizing or carbonitriding at low pressure and higher temperature, which reduces cycle time.

Cooling Control

As the transfer of the charge is taking place under vacuum or inert-gas protection after we vacuum purge the furnace, the part surface is always protected until it is completely immersed into the oil. Surface protection is very similar whether quenching in oil or gas.

The major advantage compared to conventional atmospheric oil-quenching solutions is the precise control of cooling parameters. With a vacuum furnace, it is possible to modify the standard quenching parameters – temperature and agitation – and to also modify the pressure above the quenching tank.

Modifying the pressure above the tank will induce a difference in pressure inside the oil bath, which changes the oil-cooling efficiency curve defined at atmospheric pressure. Indeed, the boiling zone is the phase during which the cooling speed is the highest. The change in oil pressure will modify its vaporization due to the heat of the load (Fig. 3).

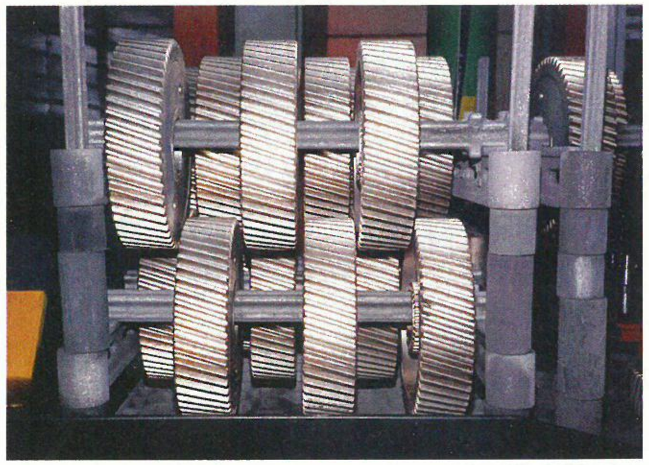

Fig. 4. Example of a dense load of gears

Fig. 5. Example of a mixed load of gears of various mass

The reduction of pressure will activate the vaporization phenomena, which initiates the boiling phase. This will increase the cooling efficiency of quenching fluid and improve hardening capacity versus atmospheric condition. However, the massive generation of steam can cause sheath phenomenon and incurs potential deformation.

The increase of pressure in the oil inhibits the vapor formation and retards evaporation. The sheath sticks to the part and cools down more uniformly but less drastically. Oil quenching in vacuum is therefore more uniform and incurs less distortion.

The control of oil pressure combined with the choice of its initial cooling specification, its temperature and its mode of agitation gives the user additional leverage to optimize the conditions for hardening, and it increases his capabilities to find the right compromise between speed and homogeneity and, therefore, between hardness and deformation.

Compared to a high-pressure gas quenching (HPGQ) treatment usually used in vacuum or low-pressure furnaces, the high cooling efficiency of oil offers a warranty and a safety margin, especially with large-section parts or parts from low-hardenability steel. For these applications, the vacuum is no longer an obstacle thanks to the quenching oil.

Experience shows that the accurate control of quenching conditions, including the oil-pressure adjustment, can result in deformation similar or better than can be achieved in gas quenching with much higher charge densities (Fig. 4) and mixed charges with fixtures and baskets (Fig. 5).

Low Costs of Maintenance and Consumables

The total absence of oxygen during quenching not only protects the parts but also the oil from oxidation. The hardening operation does not generate combustion of the oil as is the case in conventional oil hardening, even under controlled atmosphere.

As a result, oil aging is only limited to thermal cycling. The characteristics of the oil, mainly its cooling efficiency and viscosity, remain extremely stable over time, which improves reproducibility of results and reduces needed controls.

Oil vapor produced during quenching is condensed on the inner walls of the furnace, mainly in a water-cooled condenser designed for this purpose. Thus, the oil returns directly to the bath. Renewal is required only occasionally and partially, only to complement consumption due to the retention by the parts when they are unloaded.

The few impurities in the oil are generated from the load only, so continuous filtering is not necessary. This eliminates the risk of clogging and consumption of oil filters.

The consumption of neutral gas is also limited to the needs of filling the quenching tank at a pressure close to atmospheric. Compared with the best solutions for high-pressure gas quenching and equivalent load, this consumption is reduced by a factor of 10-15. The use of expensive gases or mixtures is no longer necessary to ensure the quenching quality.

Ease of Industrial and Environmental Integration

Vacuum furnaces have proven their integration ease into industrial units. This is even more evident in the case of a vacuum oil-quenching furnace. For example:

- The use of cold walls and the lack of flames or burners ensures complete safety for operators.
- The containment of vapors in a sealed enclosure and the extraction of the heat-treatment residuals from vacuum pumps protect the workshop from heat-treatment exhaust. This allows integration into a flexible cell (Fig. 6-intro) or even the tool shop.
- The low inertia of the heating chamber, designed on the same principle as the gas-cooled vacuum furnace, allows furnace shutdown when it is not used. Significant energy savings can be made during nonworking days without affecting the productivity of the equipment during the restart.

Fig. 7. Oil vacuum furnace type P164TH

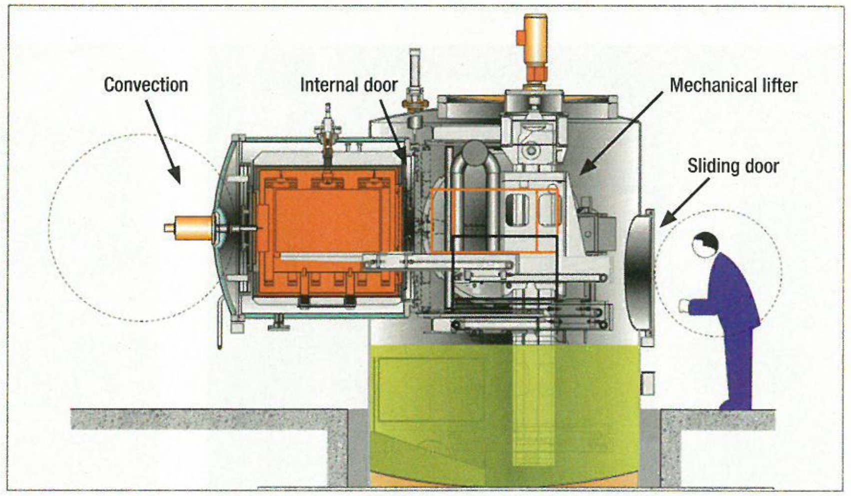

Fig. 8. Functioning principle of P16_TH series

Oil-Quenching Vacuum Furnace Technology

Principle

The technology of vacuum oil quenching is very close to vacuum gas-cooled furnaces.

- All or part of the external enclosure is cooled by double-wall water circulation.
- Building materials and insulation of the heating chamber are mainly derived from graphite. A convection turbine may be available to improve the circulation at low temperature <750°C.
- Groups of pumps allow evacuation of the enclosure.

Oil quenching adds subassembly to complete the equipment. A specific example can be seen in Figures 7 and 8. The subassembly includes:

- An oil tank, equipped with propellers, heating elements and cooling exchanger
- A load-handling system allows automatic and fast transfers between the area of loading/unloading, the heating chamber and the quenching tank.

Elements for Furnace-Type Selection

The range of oil-quenching vacuum furnaces has expanded in recent years. Many solutions are now available, and the user must do a precise analysis to select the most adequate equipment to serve production. The following factors must be analyzed.

- Volume and gross load: These are the first elements to be defined. They are based on unit size and shape of the most cumbersome parts and production volume. Depending on the furnace technology (one- or two-chamber), the cycle time can vary, which impacts the size of the furnace.
- Vacuum level required: If a primary vacuum level is usually sufficient for hardening low-alloy steels, some more exotic applications may require a higher vacuum. The two-chamber furnaces allow the addition of a diffusion pump.
- Flexibility of cooling: Oil quenching can be complemented with accelerated cooling by forced convection of inert gas. This allows performing the carburizing and annealing operations, for example. Oil/gas quenching can be equipped with a high-pressure cooling chamber and thus expand the range of steels, which increases the equipment versatility.
- Need for load thermocouple(s): Some applications (e.g., aerospace industry) may require the use of these pyrometers. The complexity of the systems implemented and the short life of oil-cooled thermocouples limit their use to a minimum.
- Transfer time: Alloys with low hardenability require quick transfer time. If the 20-40 seconds of transfer time can be achieved in almost all modern ovens, a need for transfer time of less than 15-20 seconds limits the number of equipment options in the market.
- Possibility of civil engineering: Some installations require a pit to be installed, and some do not. In some cases (e.g., flexible cells), solutions such as "mezzanine" can replace the pit configurations, provided that the height of the building is compatible.

Range of Vacuum Furnaces with Tempering Oil

If you are in search of a vacuum furnace with quench oil, a range of products exist. Each of these products has its advantages and limitations. These include horizontal furnaces with single or double chambers for oil and gas quenching. Some designs handle larger volumes, and some are better for a shop with smaller loads. Multiple-chamber vertical furnaces are also available. These are good for distortion control on long parts but typically require a pit and a larger initial investment. Identify your specific requirements before purchasing your vacuum furnace.

Conclusion

Vacuum oil quenching is a less-familiar process. Combining the benefits of vacuum safety with the quality of treatment, however, provides an industrial solution that is efficient, clean and competitive.

These advantages face a number of wrong assumptions, including:

- The pieces soaked in oil are distorted. An adequate adjustment and a precise control of the hardening conditions can often do better in terms of deformation than HPGQ.
- The pieces soaked in oil should be cleaned. It is true that cleaning after quenching is necessary to remove the oil. However, the oil film on the surface preserves the part to the point that it is impossible to make the visual difference between a part soaked with oil or gas. In addition, generally, a washing solution is already required before heat treatment. The additional step of cleaning often does not require more equipment or significant additional costs.
- Vacuum oil-quenching furnaces are expensive. Like any piece of equipment, the competitiveness of a furnace must be an assessment of its investment cost and operation. Providing benefits including reduced cost of consumables, this solution may be more competitive in the medium term. In addition, the cost of single-chamber oil vacuum furnaces is particularly attractive, even compared to traditional furnaces.

The option of vacuum oil quenching must be carefully analyzed by any company planning to invest in equipment for heat treatment of low-alloy steels. It must be compared with conventional oil-quenching solutions and the HPGQ alternative, integrating operating costs and enhancing the potential productivity gains offered by this technology. IH

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