Heat Treating Equipment Selection

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For heat treatment of tool and alloy steels, the end-user has a wide range of basic types of heat treating equipment to choose from. This article reviews them and details the criteria that must be considered in selecting equipment for a specific application. In making this choice, the most important criterion must be the quality of the tool or part after processing.

Optimum Performance

Part or tool performance is related to the overall microstructure of the piece and is normally measured in terms of hardness, toughness (Izod, Charpy, etc.) and fatigue performance. Other secondary properties, such as wear resistance and resistance to thermal checking, are also important, and all of these criteria can be related to the microstructure of the treated piece.

Surface Finish and Sub-Surface Properties

Where the workpiece will not undergo further machining or polishing of critical working surfaces after heat treatment, e.g., as on certain plastic mold tools, its surface quality is equal in importance with its microstructure. In most other cases, however, surface quality generally ranks second. However, sub-surface effects, such as those caused by electrical discharge machining or by carburization and decarburization, are also important and cannot be ignored.

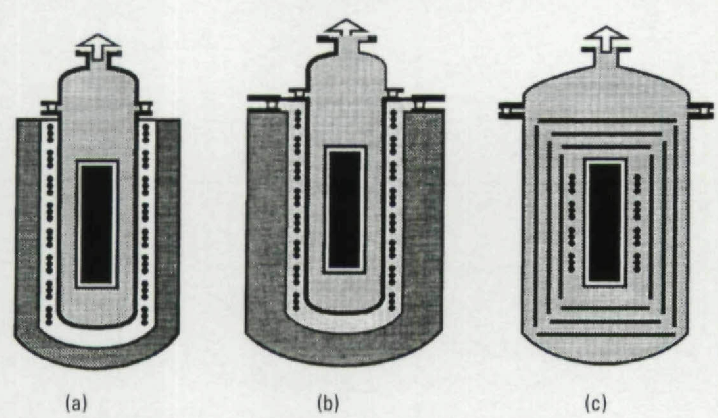

Fig. 1 — Typical electrical resistance batch-type vacuum furnaces. (a) Hot-wall, externally heated type. (b) Hot-wall, double-chamber, externally heated type. (c) Cold-wall vacuum furnace.

Shape and Size Distortion

Distortion is less a problem to the end-user than to the tool or part maker, who must take preventive action to ensure that the final dimensions will be achieved, or alternatively, to provide for sufficient machining allowance after heat treatment so that the required tolerances can be met. As a result, this is an area where conflicts can arise between the toolmaker and the end user, because sometimes each has different criteria (e.g., the former requires minimum distortion, while the latter requires maximum performance).

Equipment Selection

The metallurgical criteria must be satisfied when considering which technique or equipment is to be used for the heat treatment cycle. In assessing equipment the following factors are generally compared:

- Temperature range and uniformity
- Heating and cooling rate
- Atmosphere integrity

These factors rank highest because they most directly affect the major criteria of quality control and reproducibility. If the equipment meets these requirements, then the other considerations to be weighed are

- Environmental considerations
- Capital and operating costs
- Ease of operation and maintenance.

The basic heat treatment equipment types and techniques from which this selection can be made are reviewed below.

Vacuum Furnaces

Vacuum furnaces vary from batch type (Fig. 1) to semi-continuous (Fig. 2). They can be either of cold-wall or hot-wall design.

Temperature Range and Uniformity. The temperature range of vacuum furnaces is generally 700–1400°C (1290–2550°F). Below 700°C, convection heating is more effective, and vacuum-purged, hot-wall furnaces are generally preferred for tempering. Temperature uniformity in an empty furnace that has reached equilibrium is typically 5°C (9°F), although this can vary to a much greater degree when loads are in the hot zone, because this almost always means some workpieces are shielded from direct radiation, particularly at low temperatures. This problem has prompted manufacturers of the more recently designed vacuum furnaces to add forced convective heating in nitrogen or another inert atmosphere, up to temperatures of 700°C, before switching to vacuum processing at higher temperatures.

Heating and Cooling Rate. Without forced convection, the heating rate of vacuum furnaces at low temperatures is very slow compared with that of other types of furnaces. At higher temperatures it increases because of the radiation effect. Because of shadowing, heating uniformity is only average compared with other furnace types. Vacuum furnace quench cooling methods are numerous, but they can be classified into three main types.

Sub-Atmosphere Pressure Quenching. Initially most vacuum furnaces were built with this option, which, after vacuum treating, backfills the heating chamber with an inert gas to slightly below atmospheric pressure. The gas is recirculated at varying flow rates through an internal or external heat exchanger until the charge cools down (Fig. 3).

Positive Pressure Quenching. The fast cooling rates required for certain grades of steels led to development of positive pressure quenching for vacuum furnaces. Quenching pressures up to 20 bar (290 psi), but normally 3 to 6 bar (44 to 87 psi) above atmospheric pressure, can yield the cooling rate improvements shown in Fig. 4, over sub-atmospheric cooling. (Atmospheric pressure is 750.1 torr or 1 bar and is acknowledged as absolute atmosphere, so that in practice a vacuum or negative pressure is any pressure below 750.1 torr (1 mm Hg), and any pressure above 1 bar is considered to be a positive pressure. Therefore what is commonly known in the trade as a 2-bar pressure quench furnace has a positive pressure in the chamber of 1 bar, and a 6-bar furnace has a positive pressure of 5 bar. This causes confusion in some literature, and this factor should be taken into consideration whenever conversions for bar to psi are encountered.)

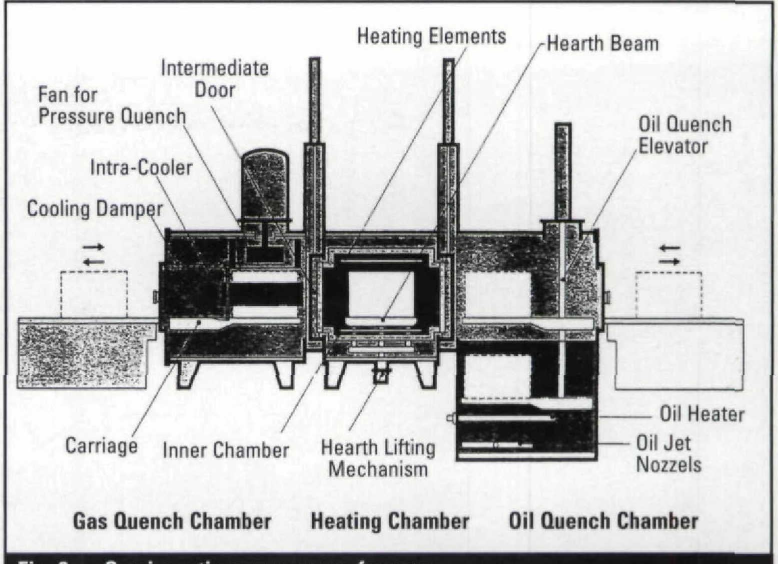

Fig. 2 — Semi-continuous vacuum furnace.

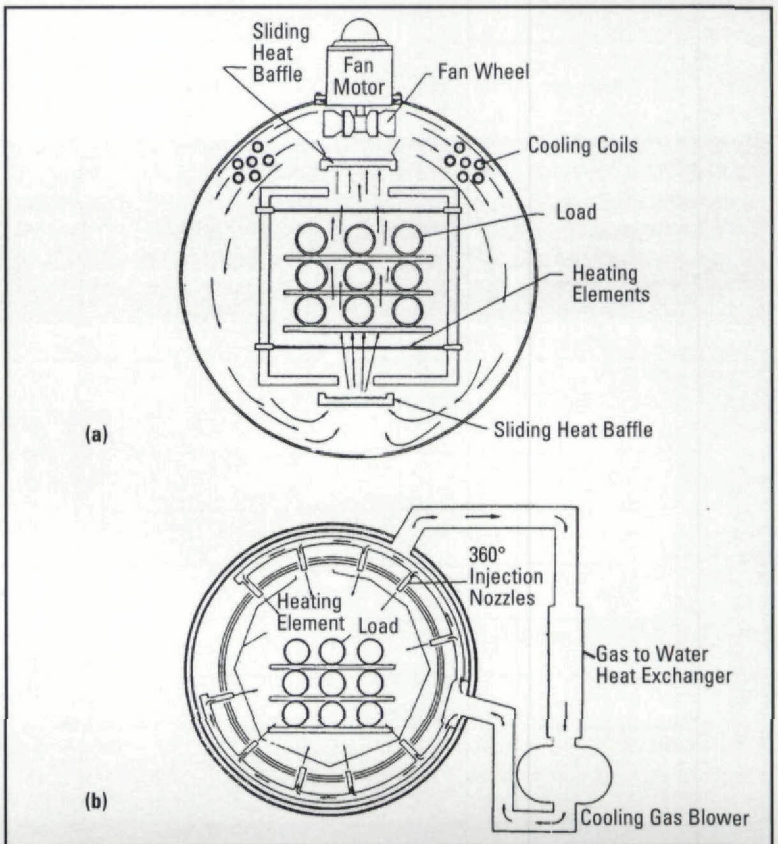

Fig. 3 — Representative cooling systems in vacuum furnaces. (a) Internal heat exchange and enclosed fan cooling. (b) External cooling.

Liquid Quenching. Some vacuum furnaces have also been integrated with oil quenching

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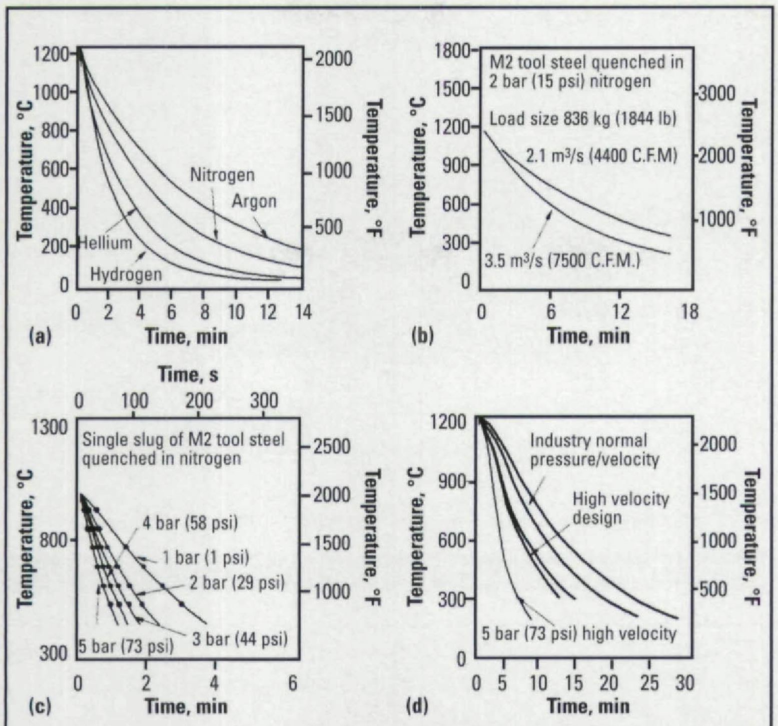

Fig. 4 — Representative improvements in cooling rates by the use of positive pressure quenching. (a) Effects of gas properties on the cooling of 25 mm (1 in.) diameter steel slugs. (b) Effect of gas velocity on cooling of 25 mm (1 in.) diameter steel slugs. (c) Effects of gas pressure on cooling of 25 mm (1 in.) diameter steel slugs. (d) Range of cooling characteristics in industrial furnaces.

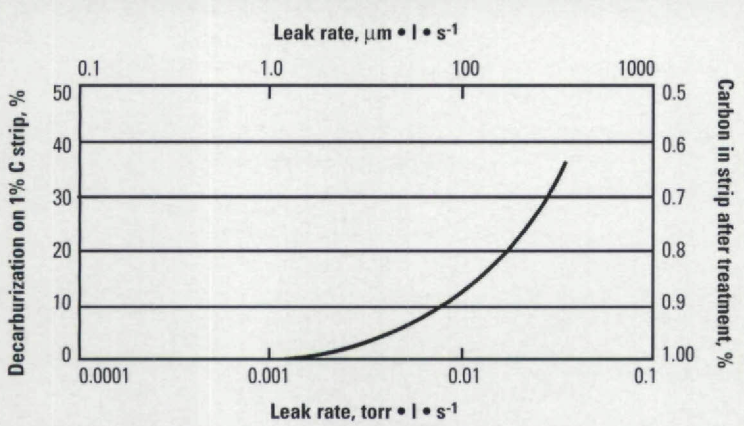

Fig. 5 — Relationship between leak rate in a vacuum furnace and decarburization of a 1% C steel strip 0.15 mm (0.006 in.) thick. Treatment time: 2: hours at 1050°C (1920°F).

facilities to permit oil and gas quenching to be performed in the same furnace.

Atmosphere Integrity. The "atmosphere" of a vacuum furnace, which guarantees neutrality to the surface of the part, is really a vacuum and as such is subject to leakage. For this type of furnace, the greatest variable in atmosphere integrity is its leak rate, which controls the effectiveness of the vacuum. Fig. 5 shows the effect of leak rate on decarburization of a 1% plain carbon steel. However, it is also important to remember that the vapor pressure of various alloying elements (e.g., manganese and chromium) can affect their behavior in a vacuum. Care must be taken to match the vacuum level used to the alloy steel being heated to avoid alloying element losses. Fig. 6 shows chromium loss related to vacuum level for type D3 steel.

Salt Baths

A metallurgical salt bath is a container of metal or ceramic filled with molten salts, such as nitrites, nitrates, carbonates, cyanides, chlorides or caustics, in which metal components can be heat treated by heating and cooling them. Salt bath furnaces may be externally heated by gas or oil or by electrical-resistance elements or by passing alternating current through them from immersed electrodes, generating heat resistively within the salt itself. This heat is quickly distributed by a downward stirring action imparted by the electrodes. Molten salt baths heat the workpiece by conduction, quickly and uniformly. When a cold workpiece is plunged into a salt and its temperature approaches that of the bath, a thin insulating film of solid salt forms between the molten bath and the metal. As work is withdrawn from the bath, a thin film of liquid salt protects it from oxidation as it is transferred to the quench.

Temperature Range and Uniformity. In general, salt baths have a temperature range from just above solidus up to 1300°C (2370°F). Unfortunately the various salts used for heat treatment have varying operating ranges, and this can cause some problems with drag-over and contamination. In addition, it means that several furnaces are needed to cover the full range of processes. The temperature uniformity of salt baths is better than ±5°C (±9°F), and uniformity of heating, because the salt acts as a liquid, is excellent.

Heating and Cooling Rate. The salt bath is one of the fastest methods of heating available, second only to a molten lead bath in terms of general heat treatment, although of course much slower than induction. The cooling rates of various combinations of salts can vary from almost as fast as those of oil to relatively slow, depending on the conditions chosen. Uniformity of heating and cooling are good because of the fluid nature of the bath, and stirring the salt makes for excellent uniformity. In most aspects salt baths are ideal for heat treatment, but the environmental and corrosion problems they give rise to are the reason why they are now being replaced by other types of furnaces.

Atmosphere Integrity. In the case of salt baths, it is the salt composition and its equilibrium with the steel being heated that replaces a totally neutral atmosphere. (In practice, provided careful quality control is performed, parts or tools heated in salt experience neutrality on their surfaces although, as detailed later, some surface roughening is observed.) Careful control of the salt composition is crucial to what might be referred to as the "atmosphere integrity" of this type of furnace.

Fluidized Beds

Temperature Uniformity and Range. Because, like the salt bath, the fluidized bed acts as a liquid, temperature uniformity can be typically ±3°C (±5.4°F), and each part is uniformly heated. The range of the fluidized beds is currently up to 1250°C (2282°F), and this can be achieved in one furnace, although two or more units are usually employed.

Heating and Cooling Rate. The heating rate of the fluidized bed is slightly slower than those of salt and lead, but faster than those of vacuum, atmosphere and forced convection furnaces. With the use of special gases, cooling rates approaching those of oil quenching can be achieved. Fluidized beds behave in a similar manner to molten salt to all intents and purposes.

Atmosphere Integrity. In the fluidized bed, the integrity of the atmosphere, like all retort type atmosphere furnaces, is dependent on the purity of the fluidizing gas used. Use of high-purity gases such as nitrogen and argon, combined with the metal retort and the fact that a positive pressure is prevalent in the bed itself, assures integrity equivalent to that of vacuum furnaces and the very best of the atmosphere furnaces. The quality of the gas must be monitored because contaminated gas can lead to surface decarburization.

Controlled Atmosphere Furnaces

In controlled atmosphere furnaces, there are again many variations, but they can be categorized into ceramic-lined and metal-lined furnaces. Representative types are shown in Figs. 7 and 8.

Temperature Range and Uniformity. The temperature uniformity of controlled atmosphere furnaces is similar to that of radiation type

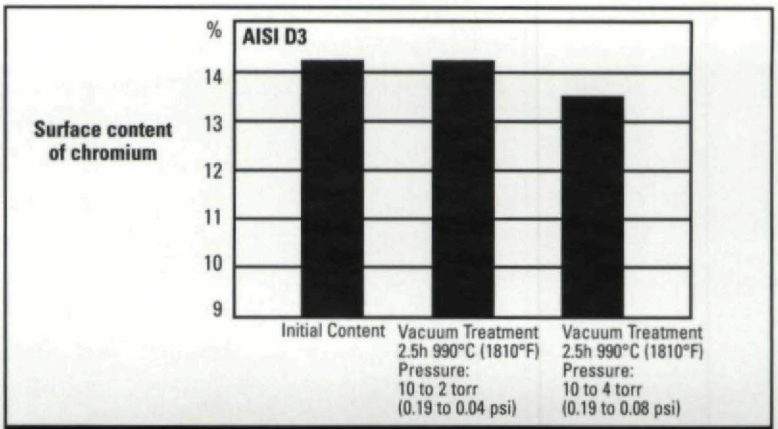

Fig. 6 — Relationship between loss of chromium from a D3 type tool steel and vacuum level.

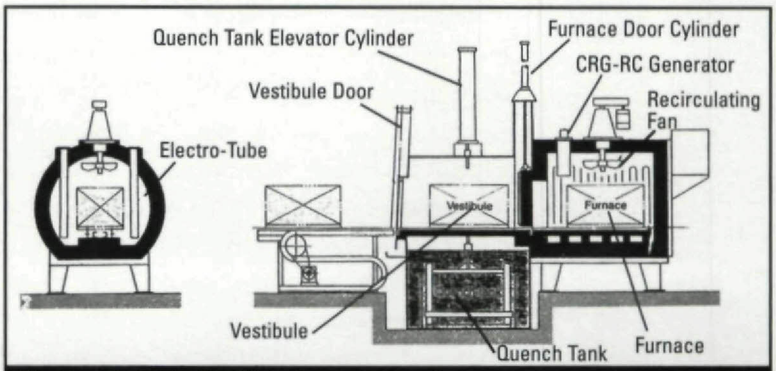

Fig. 7 — Ceramic-lined batch atmosphere furnace.

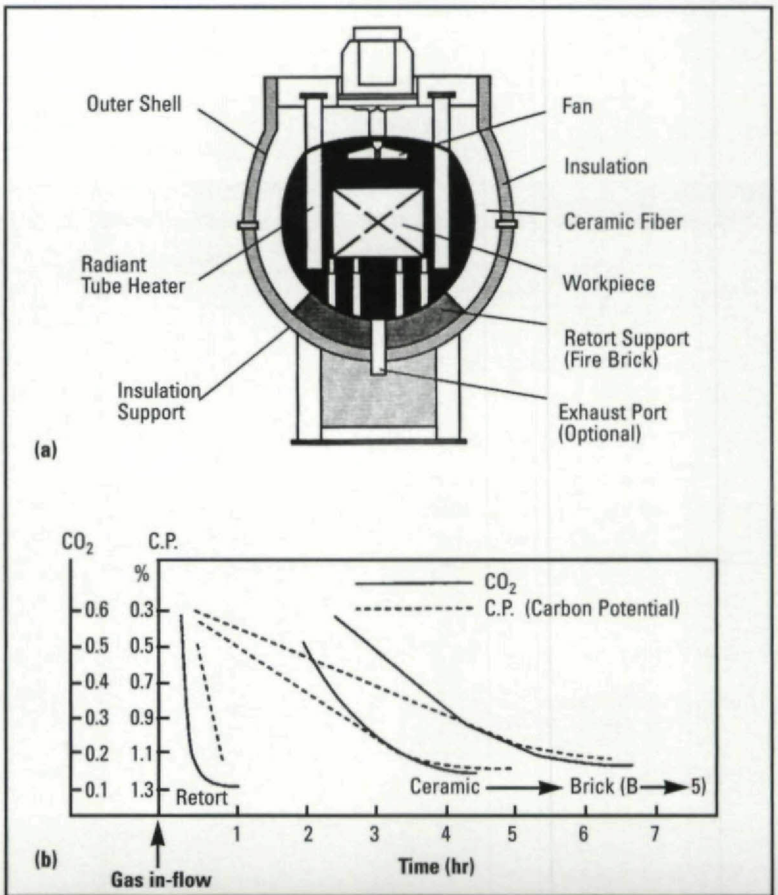

Fig. 8 — (a) Metal-lined batch atmosphere furnace. (b) Relative rate of conditioning between ceramic-lined and metal-lined batch atmosphere furnaces.

furnaces, such as vacuum furnaces above and below 700°C (1290°F). As with forced air circulation furnaces, variations do occur across a load. It has been shown that the circulation of the protective gas has little effect on temperature uniformity above 700°C (1290°F) because of the density of the hot gas and relatively low gas velocities. The temperature range can be up to 1250°C (2280°F), depending on the type of furnace, but normally controlled atmosphere furnaces are limited to about 1100°C (2010°F).

Heating and Cooling Rate. The cooling rate options are similar to the options discussed for vacuum furnaces.

Atmosphere Integrity. The atmosphere integrity depends on the type of furnace lining. While ceramic furnaces can be used after suitable conditioning, the metallic type is preferred. (Fig. 8 shows the relative rate of conditioning between the two types of furnaces.) When the metal retort type is used, high atmosphere integrity can be guaranteed subject to the purity levels of the gases being used. The control of the level of oxygen or mixtures of gas, such as nitrogen/methanol, needs to be monitored by oxygen probes or an equivalent system.

Pack Hardening

Pack hardening is very rarely used because of its lack of control and poor efficiency. It is worth noting that in certain circumstances the parts to be treated can be wrapped in stainless steel foil and then pack hardened. This improves the surface of the part being processed, but does not guarantee surface integrity.

Ranking of Equipment Types

A rating of each type of equipment discussed is given in Table 1. The basis of the rating system is detailed below.

Temperature Range and Uniformity. On the basis that 1200°C (2190°F) is generally the maximum temperature used for heat treatment of most tools and alloy steels, all plants with the exception of the pack process receive the maximum points in this category.

The temperature uniformity within a part and throughout a load are important factors. In general all furnaces subject to suitable equalization of temperature in an empty furnace can exhibit better than ±5°C (±9°F) and in the case of salt baths and fluidized beds, ±3°C (±5.4°F). However, the temperature variation is significant in loaded vacuum and controlled atmosphere furnaces and reflects the problems mentioned in the previous section. Therefore the rating for uniformity of temperature is reduced for these two alternatives.

Heat Transfer Rate and Uniformity of Heating. An important aspect of heat treatment is the uniform heating of all parts in a load during a heat treatment cycle. Liquid-like media are far

Table 1 — Rating of Equipment Based on Quality Factors

Factor	Possible Points	Vacuum Furnaces < 1 Bar (14.5 psi)	Vacuum Furnaces +5 Bar (73 psi)	Vacuum Furnaces Option (Multi)	Fluidized Bed	Atmosphere Furnace Ceramic	Atmosphere Furnace Metal	Salt Bath	Pack Hardening
Temperature Uniformity Empty	10	8	8	8	10	8	8	10	5
Temperature Uniformity Loaded	10	7	7	7	10	8	8	10	5
Heating Rate	10	6	6	6	9	8	8	10	5
Uniformity of Heating	10	8	8	8	10	9	9	10	6
Surface Finish	10	10	10	10	8	8	8	7	5
Surface Structure	10	10	10	10	10	8	10	9	7
Temperature Range 1200°C (2190°F)	10	10	10	10	10	7	10	10	8
Cooling Structure	10	5	8	10	10	8	8	9	5
Cooling Distortion	10	10	8	10	9	9	9	9	10
Quality Control of Variables	10	9	9	10	10	8	9	7	7
Rating %	**100**	**83**	**84**	**89**	**96**	**73**	**83**	**91**	**63**

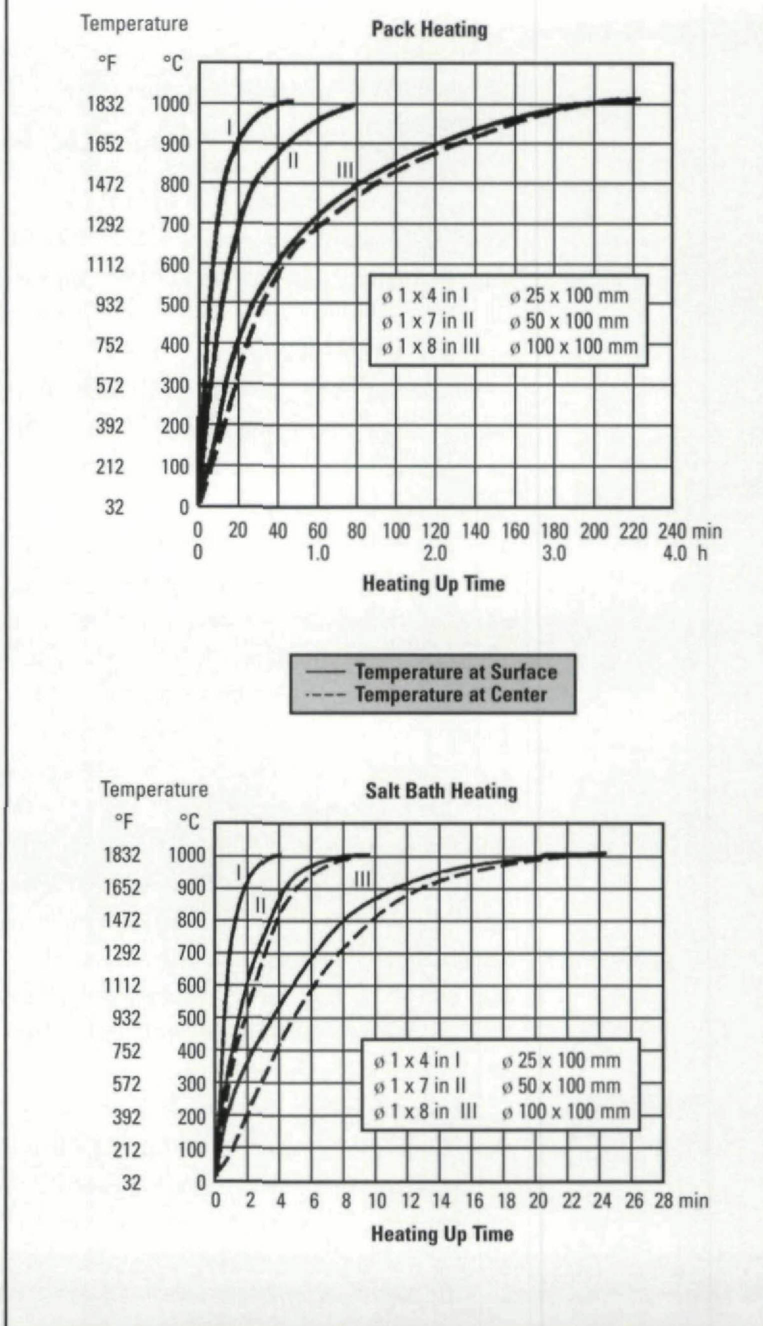

Fig. 9 — Comparison of heating rates, salt bath heating vs. pack hardening.

more uniform, achieving similar heating performance throughout a load, than those processes relying on radiation and/or convective heating unless, of course, only one part is being treated. Liquid salt baths give excellent results. Correct loading of the parts and correct processing have been shown in a number of papers to produce uniform results.

Similar results can also be shown with fluidized bed furnaces. For uniform quality of heat treatment, all parts should have exactly the same time at holding temperature, but in practice, because of radiation and part shielding in the center of loads, a wide tolerance is placed on the holding time with vacuum furnaces. Alternatively, techniques such as forced convective heating, stepped heating or holding at a lower hardening temperature for a longer time have been adopted to overcome this problem, and, subject to careful control, reported results have been satisfactory. However, these steps introduce a time and economic penalty by comparison with salt and fluidized bed furnaces and therefore are rated lower in Table 1. Atmosphere furnaces have similar problems in practice, although the use of a high-temperature fan circulating the protective gas is an improvement.

Distortion Control During Heating. The control of distortion during heating is achieved differently in different processes. In general, to minimize distortion it is important to equalize the temperature throughout the part before it undergoes phase changes. In the case of liquid-like media, step heating at various temperatures is used to equalize the temperature between the center and surface of the part. In radiation furnaces where the temperature difference between the center and surface of the part is less, some preheating steps are still necessary. For example, Fig. 9 shows the differences between the center and surface of sections 25 to 100 mm (1 to 4 in.) diameter, when heated to 1000°C (1830°F) in cast iron chips and a salt bath furnace. If the procedures above are adopted, then experience shows that control of distortion during cooling is more important than during heating.

Distortion Control During Cooling. It is in the cooling phase of heat treatment that most shape and size distortion occurs. For example, for optimum structure in H13, M2 and high-speed steels, the fastest cooling rate possible is required to avoid formation of proeutectoid carbides, pearlite and bainite. This causes significant size distortion during quenching, and while tempering reduces it somewhat, for optimum quality this distortion must be accepted by the user. A compromise process called marquenching, which balances good microstructure against low distortion, requires quenching as quickly as possible to just above the martensite start temperature and equalizing the section temperature before further cooling. For this use, salt baths and fluidized beds with fluid-like media prove best.

In vacuum furnace pressure quenching, the use of step quenching, as originally proposed by this author in 1972, is theoretically possible and in some cases practiced, but some inherent problems must be overcome. The gas used for the quench is generally at approximately 50–70°C (120–160°F), to achieve maximum cooling rate, and this can cause thin sections of the workpiece to transform to martensite long before the rest of it has reached 500°C (930°F). If an attempt is made to avoid this by decreasing the cooling rate, an unsatisfactory microstructure results.

In addition, many heating and cooling tests confirm that forced convection causes variable cooling rates over the surface of parts being treated, because of a large difference in the relative rate of heat transfer between vertical and horizontal flow, as well as temperature differentials in the gas being circulated. Quenching in salt baths and fluidized bed furnaces is much more satisfactory than in vacuum and controlled-atmosphere furnaces. Another factor to be considered is the relative cost of pressure quenching, which requires 52–75 kW (70–100 hp) fans vs. 1.5 kW (2 hp) for fluidized beds, compared with salt bath or fluidized bed cooling. The use of fluidized beds and salt baths in conjunction with vacuum, i.e., heating in a vacuum and quenching in a fluidized bed, is an obvious way to overcome the problems associated with pressure quenching.

Atmosphere Integrity. The effects of atmosphere integrity are most evident in the surface microstructure and finish of the workpiece. It is important to understand the variables that can affect the surface in any of the above processes. For example, the surface finish after heat treating in a vacuum furnace may be bright, but the surface may have been decarburized, or certain of the alloying elements may have been removed from it. In a vacuum furnace, the absence of an atmosphere is what preserves surface quality. The two critical parameters are the leak rate of the furnace and the vacuum level at which it is operated. It is generally recognized that a well-maintained vacuum furnace has excellent atmosphere integrity. Such furnaces are used for critical applications in the aerospace industry. In using a vacuum furnace, it is important to check its leak rate at regular intervals. In critical work, it should be monitored by means of a residual gas analyzer, because every time a vacuum lock or door opens or closes, the possibility of a leak increases. It should also be understood that most vacuum furnaces have pumps that are sufficiently oversized to maintain a reasonably good vacuum despite the presence of a significant leak. Thus a vacuum gage reading at the proper level does not necessarily mean atmosphere integrity is perfect.

For controlled atmosphere furnaces or fluidized beds, the effect of trace gases on the surface of metals has been thoroughly discussed in the literature and will not be covered in detail. The major gases of concern are oxygen, carbon dioxide, carbon monoxide and water vapor, as well as traces of hydrocarbon gases. Where high-purity gases such as nitrogen or argon are

Table 2 — Recommended Grit Sizes for Polishing After Heat Treatment

	Grit Size				
Steel Grade	Vacuum	Cast Iron Chips	Salt Bath	Fluidized Bed	Protective Gas
O1	≤600	≥180	≥180	≤400	≥400
P20	≤600	≥180	≥180	≤400	≥400
H13	≤600	≥180	≥180	≤400	≥400
D2	600	≥180	60	400	≥220
M2	≤600	≥180	≥180	≤400	≥400
Stainless Steel	≤600	≥180	≥180	≤400	≥400

used to protect the surface of the part, trace gases can be critical to satisfactory results. For instance, nitrogen must contain less than 10 ppm of oxygen, the same specification required for the nitrogen used for quenching in a vacuum furnace. It is not enough to check the gas as delivered. The gas must also be checked and monitored in the furnace chamber itself, because piping leaks and backward diffusion of unwanted gases into the chamber can contaminate it in use. In some controlled atmosphere or fluidized bed processes, endothermic gas is used as the carrier gas, with additions of hydrocarbon gases to produce the correct carbon potential. Monitoring the ratio of the gases is performed by oxygen probe, carbon dioxide, dew point or a similar system. With proper control of the atmosphere and correct quenching, the surface of the workpieces can be free of decarburization or carburization. As discussed below, the degree of surface roughening caused by heat treating in controlled atmosphere furnaces or fluidized beds is only marginally less than that which occurs in a vacuum. In addition, metallurgical and chemical analysis shows the sub-surface structure to be unaffected when all process variables are correctly controlled.

In a salt bath, atmosphere integrity is a matter of controlling the salt chemistry. In practice, decarburization in barium chloride salts must be monitored closely, e.g., by examination of periodic test coupons of the steel undergoing heat treatment.

Finally, the importance of cleaning the work load before processing is important, because surface contamination can affect critical reactions during processing. In this respect, vacuum cleans the surface more effectively than the other techniques, because it tends to remove any contaminants present during initial pumpdown. In tests performed to establish the relative effects of various atmospheres on surface chemistry and surface finish, samples of typical tool steels were processed for up to 1 hour at hardening temperature, followed by immediate quenching to avoid any possibility of surface contamination. The samples were tested for surface roughness before and after hardening and then chemically analyzed to determine their base carbon level 10µm (394 µin.) below the surface. Fig. 10 shows the results of these tests on a D2 tool steel. The vacuum furnace produced a bright finish and required a minimum of polishing after heat treatment. However, the controlled atmosphere and fluidized bed furnaces also produced bright finishes with only a slight amount of surface roughness. In this respect, salt bath and pack carburizing yield clearly inferior results. Based on these factors, recommended grit sizes for polishing after heat treatment are given in Table 2. Apart from pack carburizing, all results of chemical analysis were satisfactory, with no carburization or decarburization detected. ○

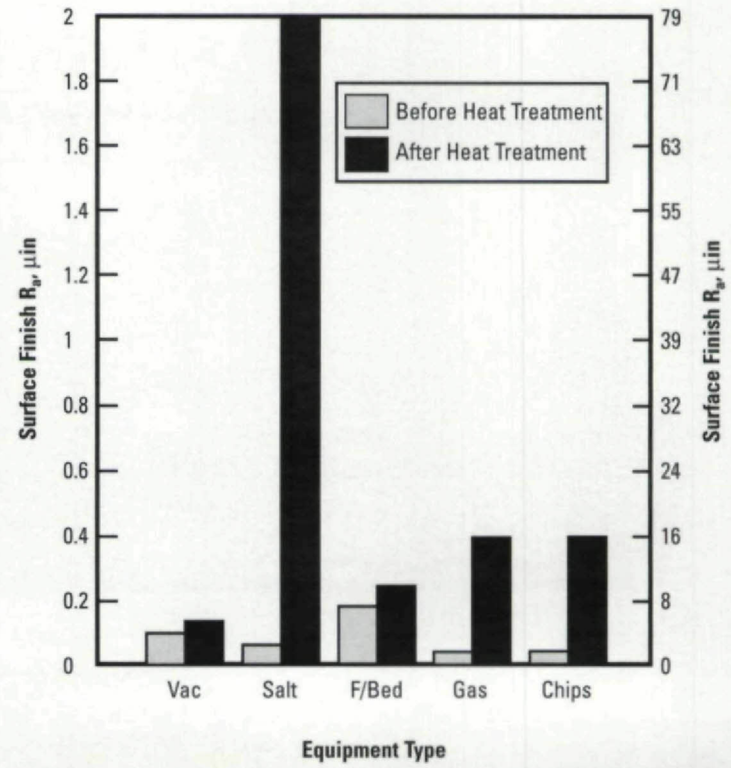

Fig. 10 — Comparison of surface finish before and after heat treatment.

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