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Devices for modern vacuum heat treatment

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ABSTRACT

Purpose: A review regarding the devices for vacuum heat treatment is presented.

Design/methodology/approach: Devices for modern heat treatment has been reviewed. The devices has been classified regarding the heat treatment (quenching, carburizing, nitriding, tempering and annealing). The possible application, materials and parts for heat treatment as well as parameters of the devices has been analysed.

Findings: There is a wide range of modern vacuum heat treatment devices. All currently used heat and thermo-chemical treatments may be proceed in vacuum equipment. It is also in many cases preferable to use vacuum- because of economic reasons, better metallurgical results or environmental friendliness. Also software simulators which facilitates the planning of heat treatment are available with the equipment.

Practical implications: Because of the industry expectations regarding efficiency, quality, economy and safety, vacuum equipment becoming the subject of wider and wider attention. In particular, aerospace and automotive industries pay a lot of attention to these aspects. The basic task of vacuum devices is fast, effective, environmentally friendly production of high quality machine parts.

Originality/value: The synthetic presentation of modern devices for vacuum heat treatment was presented, in particular furnaces for quenching, carburizing, nitriding, tempering and annealing. The products characteristic and applications has been presented. Also equipment for some advanced vacuum applications has been presented. Modern software which complements the devices in terms of designing heat treatment processes has been described.

Keywords: Heat treatment, Vacuum heat treatment, Furnace, Carburizing, Quenching, Low pressure carburizing, Nitriding, Advanced vacuum applications

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MATERIALS MANUFACTURING AND PROCESSING

1. Introduction

Depending on the effect which is desirable for a given parts and material, the proper heat treatment must be applied. Usually the aim is to harden the part which is too soft or to soften the part which is too hard. Heat treatment can be aimed at improving mechanical properties, hardening the surface layer and increasing abrasion resistant or improving an impact strength and toughness. Regardless the effect to be obtained, the treatment will be performed in a specially selected heat treatment device.

Furnaces for heat treatment may be classified in many ways. There is a furnace classification by heat source, fuel, use, atmosphere, technology, industry, materials which can be treated or operating mode: batch or continuous [1,2]. Typical batch furnaces are: pit, bell, vertical or horizontal retort, box or chamber, multi-chamber. Typical continuous furnaces are: conveyor belt, rotary hearth, ring hearth or pushers. Generally, in chamber or pusher furnaces, the mass-production medium-sized parts are treated. In pit-type furnaces large size parts are treated. In conveyor belt furnaces, small mass production parts are treated [3].

Because of the growing market requirements, heat treatment devices are constantly modified and improved. New products are entering the market and trying to meet growing expectations, which are primarily:

- shortening the duration of heat treatment processes,
- reduction of process costs (consumption of gases, energy etc.),
- high-tech technological processes control,
- meeting high technological requirements,
- repeatability and precision of the results,
- longer lifespan of furnace elements,
- environmental friendliness.

When we look at heat treatment market by equipment, atmospheric furnaces take 64% and vacuum furnaces 18% (the remaining market share is occupied by induction – 15% and others – 3%) [4]. On the other hand, vacuum heat treatment market is a growing one and according to the forecasts, it will grow around 6% by 2020. That is influenced mainly because of increasing demand for automobile industry (in Asia, Africa), the growth of steel and copper industries and the need for hardening dissimilar materials [5].

The main heat treatment markets divided by the type of processes are: hardening (21%), annealing (including stress relief and normalizing: 17%), tempering (9%) carburizing (8%) and brazing (7%), nitriding (3%) [4]. For these processes the most equipment is supplied and those will be presented in this paper.

2. Modern devices

One of the most modern are vacuum furnaces which continuously increase their share of the market. They can carry out all heat treatment and metallurgical processes, including: hardening, tempering, annealing, normalizing, case hardening (carburizing, carbonitriding, nitriding, nitrocarburizing), sintering, brazing, solution treating, metal injection moulding, degassing and some special processes like hydrizing and dehydrizing [6]. Vacuum furnaces are generally classified because of: the mode of loading (vertical, horizontal), workload size, operating pressure, maximum temperature, cooling medium (oil, gas) and working mode (batch or continuous) [6].

In general, the main parts of vacuum furnaces are: vessel, hot zone, pumping system and cooling system. They are usually the cold-wall designs (this solution has been dominating since 1960s), so the vessel is cooled with water and keep the temperature near the ambient during high temperature processes [6]. Hot chamber is completely sealed against the outside atmosphere. The heating elements are usually made from graphite but there all also all-metal constructions. The choice depends on the operating temperature and other required parameters. There is no oxygen in high-temperature vacuum furnaces which prevents the load from oxidation and decarburization. It cannot be present in high temperature also because of the graphite elements – which would burn with presence of oxygen. The pumping system usually consists of two pumps. The standard solution (Root's and rotary vane pumps) allows to reduce furnace pressure below 10^{-3} mbar. If lower pressure is necessary, diffusion pump or other must be implemented [3]. To choose the correct pumping system, it is necessary to take under consideration factors like volume of the vessel and its surface, outgassing of the workload and the required time for the gas evacuation to the final pressure [6].

2.1. Furnaces for quenching

Quenching equipment is one of the most popular group of vacuum heat treatment devices. Partly because of that, it will be the most detailed and widely described section. Besides quenching, also a number of other operations can be carried out in those devices (for example carburizing, carbonitriding, annealing, tempering).

When choosing the right device for hardening, a number of requirements must be reconciled. Not only the size and type of production is important but also the geometry and material of the parts and the requirements after heat treatment. Frequently contradictory requirements such as minimizing deformation and high hardness have to be brought together. In high volume production, heat treatment lines are most often used. In small and medium volume production batch furnaces are used. When hardening the parts from steel with lower hardenability, the parts must be quenched in oil, but with higher hardenability gas may be a good choice.

Quenching may be carried out in both, atmospheric and vacuum devices. Atmospheric devices are usually sealed quench chamber or continuous furnaces. Among the modern vacuum devices for quenching double- or triple chamber furnaces with oil or gas quenching or single chamber furnaces with gas quenching are used.

Multi chamber furnaces consist of series of chambers which are separated with internal doors. The process parameters in each chamber are different. The load is moved from chamber to chamber thanks to internal transport system. In triple chamber furnace the loading and unloading are performed from the opposite sites. The most common size of working space is 900 x 900 x 1200 mm with the load gross mass of 1200 kg. In double chamber furnace loading and unloading is performed through the same side (Fig. 1). The most common sizes of working zone are 600 x 600 x 900 mm and 900 x 900 x 1200 mm [3]. Maximum temperature in heating chamber is 1250°C and the vacuum level in a range of 10^{-2} mbar.

Fig. 1. The example of double chamber vacuum furnace

In triple chamber furnaces, there are two heating chambers and one quenching chamber. The load may be preheated in the first chamber, then heated to the austenization temperature and soaked in the second chamber, then transported to the last quenching chamber to be quenched in oil or in gas. In the first option there is a quench tank with oil. The charge is lowered into the oil bath thanks to vertical transfer mechanism. There is also an option to cool the charge down in the neutral gas over the oil bath (up to 1.5 bar). When there is a cold wall quenching chamber, the load is transported to be quenched in gas [3,7]. The effect of using multi chamber furnaces is shortening the process time – few batches are together in the furnace at the same time (one batch in each chamber). The working cycle of those, depends on the longest cycle in one of the chambers. There are also furnaces with two or three hot chambers attached to one cooling chamber, where load does not go through all the chambers but is heated in one chamber and transported to the quenching chamber. Depending on the design, either a heating chamber or a cooling chamber are movable.

Another group of vacuum quenching devices are single chamber furnaces with high pressure gas quenching. They are primarily intended for hardening higher alloyed steels (tool and stainless steels, HSLA) but as always it depends on the exact requirements, material and cross-section of the parts – also lower alloyed steels may be treated in them. Single chamber furnaces enable to conduct entire heat treatment cycle (hardening with several tempering processes) in one device, without reloading the batch or additional inter-operative operations (like cleaning). Furnaces are available with various sizes of working space and maximum load weight (the most typical are sizes 400/400/600 mm, 600/600/900 mm, 900/900/1200 mm) [8-10]. Furnaces having smaller or larger charge capacity are generally designed for a specific technical purpose. In single-chamber furnaces horizontal charge loading is the most popular, but vertical loading is also in use (Fig. 2) [11].

Fig. 2. The example of single chamber front loaded vacuum furnace

Single chamber vacuum furnaces have graphite heating elements located all around the chamber. They allow to heat the charge up to a maximum of 1350°C with a uniformity of ±5°C or better. Standard operating vacuum level is in a range 10^{-2} mbar, but also high vacuum and ultra-high vacuum are possible. [12] Quenching is realized in neutral gas (usually nitrogen, but also helium and argon are used) under the pressure of up to 25 bar. The pressure is selected depending on the requirements, chemical composition of steel and maximum cross-section of the treated parts. Parts from tool steel can usually be quenched in nitrogen up to 10 bar overpressure. The cooling gas is injected onto the load uniformly through graphite nozzles.

They are located symmetrically in hot zone cylindrical wall. Hot gases are lead out from the hot zone through a gas outlet window in the rear wall and transported on the water cooled heat exchanger. During the cooling process, it is possible to adjust the process intensity – by changing the cooling pressure and the speed of the blower. These devices enable also to conduct isothermal hardening and precise control of temperature on the surface and in the core of the parts [8-10,13].

To reduce the need for running number of trials, modern software for predicting the cooling speed and results of quenching has been developed. Tool steel's heat treatment simulation software is available with the single chamber vacuum furnaces. The effect of the simulation is cooling curve and expected hardness of the material. The simulator takes into consideration all important factors: parameters of the material, size and shape of the part, quenching temperature, type and pressure of the quenching gas and workload density in the furnace chamber. The software provides also online monitoring of the quenching process – it draws cooling curve on the phase diagram based on actual temperature measurements. This option allows to adjust the quench process while it is still in progress [12,14].

In all devices described above, vacuum is a protective atmosphere. There is no problem with internal grain oxidation or decarburization. The surface of the parts is bright and shiny silver and there is no need for cleaning the parts after hardening when quenching in gas. There are also no flames and no CO_2 or other gases with harmful constituents for the environment [15]. There is no additional equipment necessary like atmosphere generators. The hardening process if effective and the reduction of time may be obtained.

2.2. Furnaces for carburizing

Carburizing is one of the most popular thermo-chemical treatment in the industry. It is carried out usually in temperatures between 900-950°C. The main steels for carburizing are low-carbon with or without alloying elements (chromium, manganese, nickel, molybdenum). The most common steels for carburizing are 16MnCr5, 20MnCr5, 20CrMo4, 18CrNiMo7-6. The effect of the process is high hardness on the surface of the part and ductile core with good impact strength. To provide these properties, carburizing is used in technological processes of gears, pinions, camshafts, pistons and spherical bolts, rings and rollers of large-dimension rolling bearings.

The process which always follows carburizing is quenching (and then low tempering). Because of that, the devices for carburizing also enable to quench the parts. Usually carburizing and quenching are conducted in one device and tempering is conducted in another device. Process may be carried out in batch or continuous furnaces.

Atmospheric batch furnaces with endo generators are the most widely used for carburizing. Nevertheless, vacuum carburizing is becoming more and more popular and can successfully replace traditional technology. It was invented in late 60s, however it has begun to be used in industry worldwide around two decades ago. Within the last 10-15 years, rapid growth and acceptance of vacuum carburizing is observed in the industry. In comparison to the traditional technology it provides faster, more uniform and precise results [7,16]. Vacuum carburizing may be carried out in single and multi-chamber furnaces, which were described in the previous section of this paper. However, it is worth to note a few features related to the carburizing process itself.

Vacuum carburizing process consists of precise carburizing mixture proportioning in a given quantity and period of time. The sequence of boost/diffusion is programmable via software simulator (Fig. 3). During the boost stages, the hydrocarbon gas or gas mixture are introduced into the chamber. The gas dosage is performed by precise mass flow controllers. Hydrogen and other process by-products are removed by vacuum pumps [17]. After vacuum carburizing there is no internal grain oxidation and the process may be proceed in higher temperatures then in atmospheric carburizing.

The software simulators allows to design process parameters and forecast real results. Steel grade, parts shape and geometry, surface carbon concentration, furnace size, surface area, process parameters – all of this factors are taken into consideration when calculating proper case depth. The result is not only carbon or hardness profile but also the amount of carburizing gases needed for the process. Simulated sequence of boost/diffusion can be transferred to furnace control system and incorporated into process recipe. [18]

Low pressure carburizing can be performed in both: single and multi-chamber furnace. If hardenability of the material allows to harden the parts in gas, single chamber furnace with high pressure gas quenching may be applied. For high-volume production, triple chamber furnace with gas or oil quenching is a reasonable choice (Fig. 4). The charge goes through three chambers: it is loaded into the first chamber (where is heated-up to 750°C in inert gas), then is reloaded to the second chamber (where after reaching the final temperature, vacuum carburizing proceeds) and finally is moved to the oil chamber (where it is quenched in oil).

Fig. 3. Overall view of software for low pressure carburizing simulation process

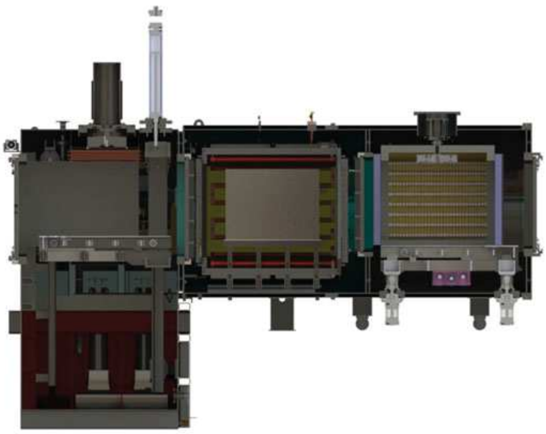

Fig. 4. Triple chamber vacuum furnace with oil quenching

Thanks to this design, three batches may be in the furnace at the same time. Because of that, triple chamber furnaces can reach even double throughput in comparison to double chamber furnaces. The working cycle of the device is determined by the LPC chamber (it is usually the longest cycle) [7].

Modern industry requires more repeatable and precise results as well as integration into the production line. Figure 5 shows revolutionary vacuum device dedicated for case hardening with low pressure carburizing and high pressure gas quenching using single-piece flow method. In traditional and modern case hardening devices, the parts are processed on fixtures in batches. Because of that, each part in the batch is affected by different process parameters.

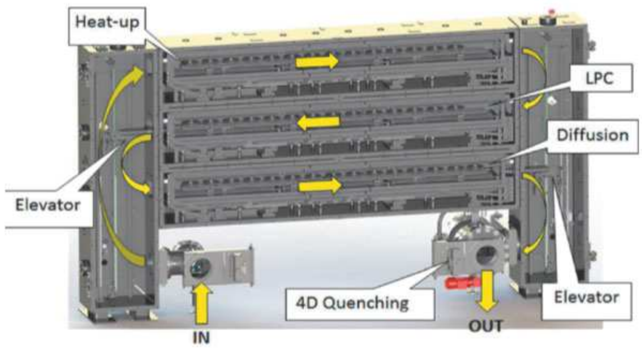

Fig. 5. Vacuum device for single-piece flow case hardening

The parts in the middle of the batch reach the process temperature later than those on the outside layers of the batch. The same with the carburizing temperature or cooling. All of that causes non uniform results within the batch. A solution may be the system for single-piece flow case hardening, which treats every part the same way and provides it the same process parameters. It consists of three horizontal chambers: first one for heating up the parts, second one for carburizing and the third one for diffusion and cooling before quenching. After lowering of the temperature the parts are transported to a specially designed quenching chamber. Each part follows the same sequence and is treated in the same way. Thanks to single-piece flow, there is a great improvement in precision and repeatability of the results. By using specially designed quenching chamber (4D Quenching) the distortion level is lower and more stable. The true single-piece flow case hardening system is a unique global solution and it meets the productivity demands of high-volume gear manufacturers [7,19].

2.3. Furnaces for nitriding

The purpose of nitriding is to produce hard and abrasion resistant surface layer while proper mechanical properties of the core are maintained. The process temperature is usually between 500 and 550°C. The parts for nitriding are previously quenched and high tempered and the tempering should be performed in temperature higher than nitriding. The process is performed for parts from non-alloyed and alloyed steels as well as from tool steels. It is very common for elements of engines and pumps manufactured in the aircraft, shipbuilding and automotive industry, like crankshafts, cylinder liners, gears, rollers, pistons, rings and piston pins [20].

Nitriding is most often realized in atmospheric or ionic furnaces. Furnaces for atmospheric nitriding are batch furnaces: pit, bell, box, tip-up [3]. The typical nitriding process consist of following stages: heating-up and oxidation, nitrogen purging, heating up to nitriding temperature, nitriding and cooling the load. The furnaces design allows not only to nitride the parts but also to conduct other processes like oxidation, nitrocarburizing, tempering and annealing.

For plasma nitriding and atmospheric nitriding with a vacuum purge low-temperature vacuum furnaces are used [3]. The plasma nitriding process use the plasma discharge of reaction gases to heat the parts surface and to supply nitrogen ions. It was developed in 1932 but did not found industrial acceptance until 1970s [21]. Today plasma furnaces are cold-wall or hot-wall constructions. They can be horizontal (single or multi chamber) or vertical (bottom loaders, bell). The working temperature is up to 600-700°C and the vacuum level is 10^{-2} mbar. The main differences from the conventional vacuum furnaces are: high-voltage generator (with continuous-current output or pulsed-current output), the plasma current feed-through, gas dosage and distribution system. Other elements (like chamber and pumping system) are basically the same [6,22,23].

Nitriding process can also be conducted in single chamber vacuum furnaces with high pressure gas quenching- especially in case of thin layers. This kind of process is called low pressure nitriding. It is mainly carried out on tools for cold and hot forming, injection moulds, cutting tools [24,25]. It is therefore dedicated mostly to the tool steels. The treatment is carried out in the cycle: quenching, tempering (single or double), nitriding – all in one furnace. Standard single chamber vacuum furnace allows for fulfillment of all those parameters due to its versatility.

The vacuum nitriding process involves introducing ammonia to the chamber in temperatures which are used for this process. It allows to obtain uniform and thin nitride layer during few hours long nitriding. Thanks to vacuum there is no need for chemical surface activation before nitriding [26]. The layers are less brittle than those produced with atmospheric nitriding, in both: compound layer and diffusion layer [24,27]. Without a question, the limitation of number of devices to just one is a great advantage which may be used in many applications.

2.4. Furnaces for tempering and annealing

Tempering and annealing are the most common low temperature vacuum processes. They are usually run in temperatures between 180 and 750°C and may be conducted in single chamber vacuum furnaces or in retort furnaces with vacuum purge [28].

Retort tempering furnaces with vacuum purge are usually horizontally loaded with vacuum level 10^{-1} or 10^{-2} mbar (Fig. 6). External forced cooling system with cooling air flowing over the retort is a standard solution but to shorten the process time, also an internal forced cooling system may be applied. The furnaces are usually produced with working zone areas 600 x 600 x 900 mm, 900 x 900 x 1200 mm or 1000 x 1000 x 1500 mm. The operating temperature range is 150-750°C, which covers most of the processes [29]. Single chamber vacuum furnaces may also be used to these kind of processes. They offer vacuum level up to 10^{-3} mbar and convection heating (in inert gas). The load may be cooled to room temperature in gas over-pressure [28].

Fig. 6. Retort tempering vacuum purged furnace

The choice of vacuum tempering or annealing is mainly influenced by high quality of parts' surface. The cleanliness of the surface and bright finish can be relatively easy to obtain. It is typically used for copper and copper alloys, stainless steel, carbon and low alloyed steels and tool steels. For stainless and tool steels, vacuum furnaces are used not only because of the high quality of the surface, but also because of the gas quenching, which is proper for these kind of materials [4].

Fig. 7. High vacuum furnace with working zone 1200 x 1200 x 1800 mm

In some applications, high vacuum furnaces may be the best solution (Fig. 7). In case of heat treatment of titanium alloys, superalloys, some stainless steels or other sensitive materials it is necessary to obtain higher then standard vacuum level. It is also necessary in brazing processes and in many advanced vacuum technologies. High vacuum furnaces offer vacuum in a range 10^{-4} to 10^{-7} mbar. Pumping system is based on mechanical pump (10^{-2} mbar) and oil diffusion pump (10^{-4}-10^{-6} mbar) or turbomolecular / cryogenic pumps (below 10^{-7} mbar). They are available with vertical or horizontal loading configurations with different sizes and load weight [30].

2.5. Furnaces for other vacuum technologies

Besides the most common processes, vacuum technology is present also in many other applications. For example vacuum deposition- chemical (CVD) or physical (PVD) vapor deposition or plasma-assisted coatings. Aluminium ion vapor deposition is a type of PVD process for applying aluminium coatings to various substrate. It is applied mostly for corrosion protection and better surface quality on ferrous alloy parts [6]. It is used in aerospace for pins, bolts, hydraulic and fuel components, landing gear components, engine components, turbines, fasteners. Depending on the size of the parts two types of IVD aluminium coaters are available: the rack type coater for large parts and barrel coater for large volume of small parts [31]. The process itself requires pumping down to the pressure level $9x10^{-5}$ mbar, filling the chamber with argon gas, the temperature around 500°C and the usage of high-voltage system [6].

Another advanced vacuum application is diffusion bonding. It is usually a solid-state joining process, involving atoms diffusion between surfaces in close contact. The joining parts are heated while held together under a force. There is no additional material needed to create a joining. The process is generally run in vacuum furnaces (10^{-4} to 10^{-6} mbar) or in hydrogen partial-pressure atmosphere (because of the surface oxidation). The equipment – hot-press furnace systems – may operate at temperatures in a range 400-1230°C and up to 30 tons of force. There are also systems with higher maximum temperature and higher forces [6].

Vacuum furnaces are also used for single crystal heat treatment, zirconium and stainless steel annealing for nuclear industry, aluminium brazing, powder production, sintering, in additive manufacturing, induction melting and arc remelting– to name just a few more. Vacuum isothermal forging uses super-plastic deformation which resulting with quite small stresses in the material and nearly unchanged grain size [17].

3. Comparison and conclusions

Modern heat treatment equipment is constantly modified and improved to meet growing market expectations. Vacuum devices occupy an increasing market share and can successfully realize almost all of the most frequently performed heat treatment processes. Depending on the type of production, treated parts and their material, the right device can be choose. Among the hardening equipment, there are multi and single chamber furnaces. Double and triple chamber furnaces enable to carburize and harden the parts in oil or gas. Triple chamber furnaces allow to conduct semi continuous production and processing many batches in the same time. In the first chamber the batch is preheated, in the second chamber is carburized and soak and in the third chamber the parts are quenched. Each batch is in different chamber in the same time.

Single chamber devices are dedicated mostly to the high alloyed steels, but it depends on the parts size and requirements. They enable to perform the entire heat treatment cycle in one device without unloading the batch. Single chamber furnaces are all-purpose devices and allow to conduct not only high pressure gas quenching and low pressure carburizing but also low pressure nitriding, tempering, annealing, normalizing etc. Thanks to quenching in gas, the distortions of the parts are smaller and there is no need for washing the load between operations. Thanks to eliminations of oil, the costs of heat treatment are reduced and technology is environmentally friendly.

Low pressure carburizing process can be realized in both: multi and single chamber furnaces. Low pressure carburizing process consists of boost/diffusion stages and is programmable in specially design software. For high volume production of gears and bearings also single piece flow devices are available. In that case, every part is treated the same way in the same process parameters. That leads to an extreme repeatability and precision of the results in terms of carburizing layer and distortions.

Not only for thermo-chemical treatment but also for quenching, special simulation software is available. They allow to predict the treatment results with high accuracy without running trials. Software takes into account number of important factors like furnace parameters, process temperature, material grade and geometry, requirements, and forecast the process results. That allows to reduce the time and number of trials as well as save the material.

Thanks to vacuum and the presence of inert gases, the workpieces are protected against decarburization and oxidation during heat treatment. In low temperature vacuum processes of tool and stainless steel it is often important to achieve clean and bright surface after the processes. Sufficient vacuum level for most processes is 10^{-2} mbar, but also higher vacuum is in use when necessary.

All of the described furnaces cover the most popular heat and thermo-chemical heat treatment processes. All of them may be and have been successfully realized in modern vacuum furnaces. It is also in many cases preferable to use vacuum- because of economic reasons, better metallurgical results or environmental friendliness As it seems at the end, there is a vacuum furnace solution for any part and application.

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