Heat treatment of tool steels in vacuum furnaces with gas quench

Part 2. Review of industrial applications

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Introduction

Correctness of heat treatment is the key element deciding on operational usefulness of tool steel elements. The first part of this article (PPiK III/IV 2012) presented process requirements which provide proper structure of the material while this paper continues to present practical applications of vacuum furnaces equipped with high pressure gas quench systems, designed for extensive heat treatment of tool steels in selected branches of industry.

Royal Canadian Mint [1]

An interesting example of using tools on a mass scale is coin manufacturing at mints. The dies and punches applied for coinage of circulating or occasional coins or all kinds of medals and distinctions require high strength concerning compression, abrasion, fatigue and impact which occur in the course of a multitude of work cycles they go through (Fig. 1.). These properties are obtained thanks to appropriate design of the tool's working surface and its grip as well as appropriate steel grades and heat treatment.

Royal Canadian Mint, one of the most renowned mints in the world (Fig. 2.), for nearly 10 years has been using vacuum furnaces equipped with high pressure gas quench systems for toughening of their tools (Fig. 3.). Basic steel grades used for tools are the low alloy cold working tool steels, conventionally assigned for oil quench O1 (1.2510), O1M i O2 (1.2842, NMV). Until now quenching mint tools in oil has failed to bring best results due to deformations, surface contamination after heat treatment and the resulting problems

Fig. 1. Coining die

Fig. 2. Royal Canadian Mint building in Ottawa

concerning removal of the oxidated and decarburized layer from the chased surface of the tools. In order to break free of such inconveniences, a technology has been developed for quenching those steels in gas – in nitrogen at the pressure of 10-15 bar. A circumferential gas inflow system has been applied, which seems to work perfectly for workloads of densely packed details of cohesive dimensions, and which permits to achieve the required hardness and quenching uniformity.

Fig. 3. Vacuum furnace for toughening of dies and punches, SECO/WARWICK type 15.0VPT-4025/24HV

At the same time higher-alloy steels are used such as D2 (1.2379), A2 (1.2363), high speed steels M2 (1.3341, SW7M), M4 and other ones with a higher content of Cr, Ni and Mo, which are decidedly easier to quench in gas. The entire process of toughening is held in a single chamber furnace within a single cycle (i.e. without moving the load between pieces of equipment) and consists of preheating to austenitization, quenching in nitrogen at high pressure and tempering. The effects of such heat treatment are tools of proper hardness and mechanical properties and, what is equally important, of ideal (shining) surfaces free from decarburization and oxidation which may finally be shaped or coated (PVD, galvanic coats) to increase the durability of tools (Rys.4.).

Fig. 4. Mint dies in a basket after heat treatment

During thermal processing the surface of tools is exposed to decarburization or oxidation which result in decreased hardness that disqualifies their quality. This occurs due to particles of oxygen and water vapour which, once absorbed from air or workload contaminants, condense inside the furnace and then are emitted during the treatment and attack the surface of workpieces at high temperatures. Therefore, before starting to preheat to austenitization, the loaded furnace must be evacuated to a high vacuum of 10^{-4}–10^{-5} mbar, which successfully removes any oxygen-derivative contaminants and protects the surface of workpieces. On the other hand, high vacuum is not recommended at austenitizing temperatures as this facilitates sublimation of alloy additions from steel surface (Mn, Cr, Co, etc.). Lowered concentration of alloy additions reduces hardenability of steel and may be the cause of disadvantageous decrease of surface hardness. Therefore, at higher temperatures vacuum is maintained at the range of 10^{-1}-10^{0} mbar.

Taking into consideration the above mentioned process requirements, the optimum installation seems to be a vacuum furnace equipped with: a high capacity 15 bar nitrogen quench system, a high vacuum pumping system based on a diffusion pump and a partial pressure system to control vacuum level through proportioning of nitrogen.

Aesculap Chifa Sp. z o.o. [2]

Tool steels find numerous applications in the foodstuff and medical industries. Tools used there must posses appropriate mechanical properties and chemical resistance, including resistance to corrosion. For that purpose, stainless martensitic steels are used.

Domestic company Aesculap Chifa Sp. z o.o. of Nowy Tomyśl (Wielkopolskie Province) is not only a nationwide tycoon in the area of production of surgical tools, but also a leader of the B. Braun group and a worldwide exporter of their products. The company offers a range of over 6000 designs of surgical tools for applications in general surgery, microsurgery, gynecology, ostheosurgery, dental surgery and orthodontics. They have their in-house HT plant which not provides completely for the heat treating needs of the manufacturing department and, furthermore, supports the in-house tool room and provides external services. The HT plant operates three shifts, 5 days a week and employs a personnel of a dozen or so. Their chief equipment are single chamber vacuum furnaces with: a high vacuum system, a high pressure nitrogen quench system and convection heating indispensable in tempering.

Main steels used in manufacturing of surgical tools are: 2H14 i 4H14. Heat treatment consists in quenching and tempering in at single cycle in a vacuum furnace. Quenching is effected from a temperature below 1000^{o}C for 2H14 and above that value for 4H14, while tempering is done at the temperatures of 240^{o}C and 300^{o}C to obtain a hardness of approx. 45 and 50 HRC, respectively. A few key elements are decisive for the quality of the treatment. An ideal surface of tools is ensured by a high level of vacuum at the heating phase (10^{-4}-10^{-5} mbar) and purity of cooling nitrogen (99,999%). Particularly important is to obtain high purity of tempering atmosphere as stainless steel is more susceptible to oxidation at lower temperatures. For this reason tempering is carried out right after quenching, in the same furnace, without opening the charging door and in the same, pure atmosphere. Holding the process of tempering in another piece of equipment and thus exposing the workpieces to air entails a high risk of surface oxidation.

Fig. 5. Packing of surgical tools in a workload

An equally important process parameters are heating uniformity and temperature uniformity within the working area (+/- 5^{o}C) which are crucial for the accuracy of austenitizing temperature for the entire workload and each workpiece alone and which facilitate short holding times. It is not only the furnace properties that influence the above parameters but largely the experience in arranging individual elements of the workload (Fig. 5.). A failure to meet the temperature condition may result in a failure to reach the austenitizing temperature or overheating, which will adversely influence quench outcomes and steel microstructure (grain growth, release of carbides). Quench parameters are equally critical for the process. High pressure gas quench must be uniform and intensive. Although such steels feature good hardenability and martensitic structure is easily obtained for smaller cross-sections, intensive cooling down to 6 bar is applied in order to avoid the release of carbides which lower the resistance to corrosion. On the other hand, too intense cooling is not advantageous as it entails increased deformation of the tools. Surgical tools are slender details of elongated axis, particularly susceptible to deformations caused by uneven cooling. Directed cooling is preferred for this type of workpieces as it enables arranging them in such a way that the stream of cooling gas will pass parallel to the longitudinal axis of the details. A furnace featuring such a top-to-bottom directed gas flow has recently been delivered to the company (Fig .6.).

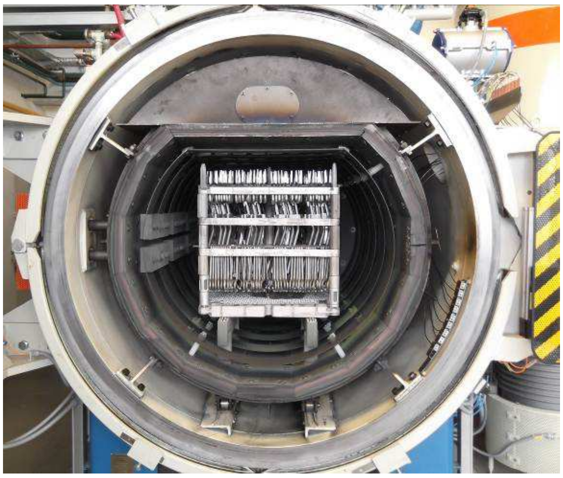

Fig. 6. A workload of surgical tools in the chamber of SECO/WARWICK 6.0VPT-4035/36HV with cooling direction top-bottom

Therefore, cooling in the hardening treatment necessitates a compromise between its intensity and uniformity, and requires a knowledge of the furnace, the workpieces and experience in arranging the latter within the workload.

Furthermore, certain more complicated and comprehensive treatments are carried out. These are realized within a single cycle, in a single vacuum furnace, without transferring the workload between pieces of equipment. This pertains to the tools with blades made of carbides. In such a case three technological steps are joined together: soldering of carbides, quenching and tempering.

Soldering is done with copper or nickel based soldering pastes at temperatures higher than the austenitizing temperature. Afterwards, the temperature is lowered until the solder sets and then workpieces are quenched and tempered. Soldering phase brings further impediments and compromises to the process since such terms are required as high purity, temperature accuracy, short time of soaking and setting the solder. On the other hand, cooling in the hardening phase may not be to intense as the carbides may break. Despite the above difficulties it is possible to preset process parameters and to arrange the workload in the furnace in a way that will ensure proper technological results.

All these treatments are successfully performed in single chamber vacuum furnaces equipped with high pressure gas quench systems.

Kuźnia Polska S.A. [Polish Forging Plant Ltd] [3]

A classic example of application of metal forming and shaping tools is the forging industry where the national captain is Kuźnia Polska S.A., a company of 200-year tradition, located in Skoczów in Śląsk Cieszyński. The business scope of the Forging Plant is manufacturing of high quality steel die forgings hot-forged at the temperature above 1000^{o}C, designated chiefly for automotive industry, but also for mining, railway engineering and machine industry. 80 % of production volume is exported. The products meet the most demanding criteria set by European and American automotive industry. The company is self-sufficient not only in the production of forging dies including machining and heat treatment, but also in the area of making their own tools used in the process of the production of forgings. These tools are used to forge, trim, pierce and straighten the forging dies and include, among others: inserts for press forging, cutting plates (finishing tools, trimming plates to remove burrs), cropping punches, piercing inserts, piercing punches, straighteners for hot and cold straightening of forging dies, hardened plates for forging devices (Fig.7). They are made of typical tool steels such as: WCL, WCLV, WNLV, SW7M, and to obtain the requested mechanical properties they go through the process of thermal toughening which consists of quenching and tempering.

Fig. 7. Examples of hot forging die inserts made of WCL steel

The process of toughening of the hot working tool steels (WCL, WCLV) applies all the guidelines provided by NADCA (North American Die Casting Association) which were discussed in Part I of the present article. The following are important: heating speed, number of heating stops, soaking time, cooling speed and temperature control in the material as well tempering parameters including the number of tempering cycles. Appropriate handling of the entire treatment is crucial for obtaining proper tool durability usually measured by cycles (from 3 000 to 20 000) which is achieved by high strength, impact resistance, hardness, abrasion resistance at high temperatures, and thermal fatigue.

Thermal toughening is performed in a vacuum furnace equipped with high pressure gas quench (nitrogen) system facilitating sophisticated cooling methods (isothermal cooling) which reduce structural and thermal stresses and thus reduce deformations and eliminate the risk of tool cracking. The facility of convection heating enables tempering to be held right after quenching and to provide effective and uniform heating of workload at lower temperatures (reduction of thermal deformations). Using a vacuum furnace allowed a thorough automation of heat treatment and avoiding such problems as tool surface decarburization and oxidation (Fig. 8).

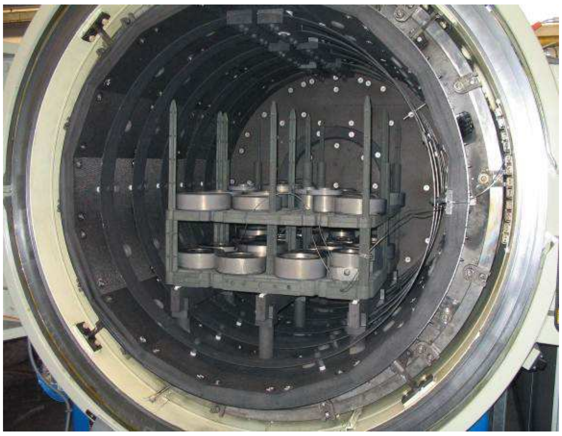

Fig. 8. Forging dies in the chamber of vacuum furnace SECO/WARWICK type 10.0VPT-4050/48IQ

Currently work is being focused on optimization of the quench processes with isothermal stop and the application of vacuum nitriding in order to provide additional surface hardening. Vacuum nitriding may be added as the final stage of heat treatment which is carried out in a single vacuum furnace, within a single process cycle consisting of quenching, tempering and nitriding of tools. Initial results of the application of vacuum nitriding are very promising, indeed.

Tool Factory FANAR S.A. [4]

Tool Factory FANAR S.A. is the largest Polish manufacturer of tool s for threads (Fig. 9.). They boast 40-year long experi

Fig. 9. Tool factory FANAR S.A.

ence in their trade and a list of reputable receivers of their products, both domestic and foreign. They manufacture an extensive range of thread tools including: taps, milling cutters, tool grips and auxiliary tools (Fig. 10.). The basic material for

Fig. 10. An assortment of high speed steel tools

thread tools is high speed tool steel type SW7M (SK5M, SK8M) which is heat treated to obtain appropriate mechanical properties. Heat treatment consists in quenching from the temperature of 1150-1200^{o}C (using gradual heating with stops at 850^{o}C and 1050^{o}C) followed by two or three runs of tempering at 550-560^{o}C to obtain the hardness of 62-65 HRC. Traditionally the process had been performed in salt bath furnaces until ten years ago when the salt bath furnaces were replaced with a single chamber vacuum furnace with convection heating and high pressure gas quench (Fig. 11.). Since that moment the treatment has been carried out automatically in a single vacuum furnace, within a single process cycle, which guarantees full control of the treatment and repeatability of results, ideal quality of treated surfaces while at the same time work safety and comfort are increased and environmental care is maintained. Positive economic effect was also significant as the treatment carried out in a vacuum furnace uses 50% less electrical energy, the per piece manufacturing costs are 30% lower and manufacturing efficiency is 50% higher compared to salt bath technology.

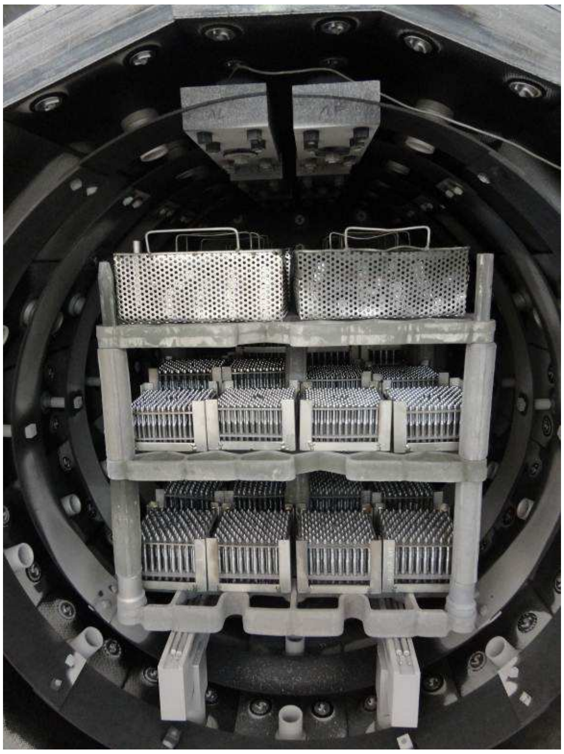

Fig. 11. A workload of threading tools in the chamber of SECO/WARWICK 10.0VPT-4035/36

Due to their flexible and slender shape and the necessity to maintain alignment, the quenched tools are greatly susceptible to all sorts of unevenness of heating and cooling, which results in excessive deformations. In order to keep this unwanted effect to a minimum, it is essential not only to control the progress of treatment but also, and above all, to arrange the workloads properly and to provide appropriate workload fixtures. Placing delicate workpieces close to the heating elements and cooling nozzles is avoided while vertical positioning, packeting and segregation are encouraged. Best effects come from hanging the workpieces although this solution is rarely practiced due to the noxiousness of operator's work. Above all, workpiece fixtures has to be as stabile as possible, straight and transparent both to the radiation of heat and to the flow of quench gas (Fig. 12.).

Fig. 12. Tooling, packeting and segregation of workpieces

Despite so many underlying conditions, the process of heat treating tools and SW7M steel elements has been mastered and successfully applied in vacuum furnaces with gas quench in numerous other companies in the trade, such as FENES S.A. or WUZETEM.

Table 1 presents the overall potential of vacuum furnaces with gas quench in the area of hardening tools made of most commonly used tool materials.

Materiał DIN [SAE]	GOST	Przekrój [mm] 80	100	120	140	160	180	200	uwagi	HRC
1.2721										59
1.2767										56
1.2510 [O1]										64
1.2550 [S1]										60
1.2842 [O2]										63
1.2363 [A2]										63
1.2080 [D3]	Ch12									64
1.2436										65
1.2379 [D2]										63
1.2713 [L6]	5ChNM									56
1.2714										57
1.2343/1.2344[H11/H13]	4Ch5MFS /4ChMF1S								wg zasad NADCA > 500mm	54
1.2365 [H10]	3Ch3M3F									50
1.2083 [420]										56
1.2316										50
1.3343 [M2]	R6M5									66

Table. 1. Overall potential of vacuum furnaces with gas quench in the area of tool hardening

The above presented four examples of applications of vacuum furnaces with high pressure gas quench fail to cover the entire aspect of such applications. Also common are applications for manufacturing of forming tools for light metals, plastics, metal powders, ceramics as well as tools for extrusion and pressing, e.g. those used in foodstuff industry, animal feed industry, and the like.

The significance of vacuum furnaces in heat treatment has been increasing continuously and the area of tool steels has been of key importance for a few decades. This is due especially to the neutrality of vacuum as a protective atmosphere and the ideal surface quality obtained in the course of heat treatment. Furthermore, there is a total separation of the furnace working area from the environment, which permits precise and effective heat treatment processes to be carried out in various atmospheres. Additionally, continuous advancement in the area of effective high pressure gas quench, now approaching the speed of oil quench, makes vacuum furnaces a sophisticated, economical and environmentally friendly alternative to the majority of atmospheric heat treatment technologies and oil quench.

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