Best practice in heat treatment of large dies made of hot work tool steels

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Tool steels are a widely used material for construction of tools designated for shaping and forming of metal, plastic and other elements in mass production. These elements include extruding dies, pressure casting dies, moulds, punches and various other elements for plastic shaping of other materials preheated to temperatures in the range of 250-700 °C (**Fig. 1**). Since shape stability constitutes the basic requirement any tool has to meet, the material it is made from is expected to withstand loads without any plastic strain while maintaining high abrasion resistance. Additionally, a tool should feature good hardness and strength as well as appropriate ductility and impact strength which condition crack resistance, and these qualities are to be obtained at high working temperatures (up to 700 °C).

The ultimate mechanical properties of a tool are determined by heat treatment which consists of a quenching process followed immediately by temperings. Austenitizing temperature is a compromise between the need to control the growth of primary austenite grains and the need to dissolve the alloy carbides. It also influences temperature resistance and impact strength. Depending on the tool size, the hardening process is aimed at obtaining a martensite structure (for smaller elements) or martensite with bainite (larger tools). That is followed by at least two runs of tempering at or above the temperature of secondary hardness effect in order to reduce the retained austenite, increase ductility and resistance to thermal fatigue. Sometimes other processes are introduced such as deep freezing after hardening, application of various coatings (CVD, PVD) or nitriding, the aim of which is to ensure additional hardening of the working surface and to improve resistance to abrasion and corrosion.

Properly performed heat treatment is decisive for mechanical and operational properties of tools as well as the economy of their use. Allowing any irregularities leads to faster wear, deformation or defect of the working elements; in extreme cases it may even lead to their damage (cracking) as early as during heat treatment, which causes notable financial loss. Needless to say, appropriate quality and condition of the initial material also matters. Difficulties ensuring quality of large-size tools (moulds and dies) have led to the creation of their processing standards. The most widely known and spread studies in that area were published by the American association NADCA (North American Die Casting Association) [1] and the leaders of automotive industry, among others such concerns as Ford [2], General Motors [3] and Toyota. These standards relate mainly to steel X37CrMoV5-1 and X40CrMoV5-1 (DIN, EN)

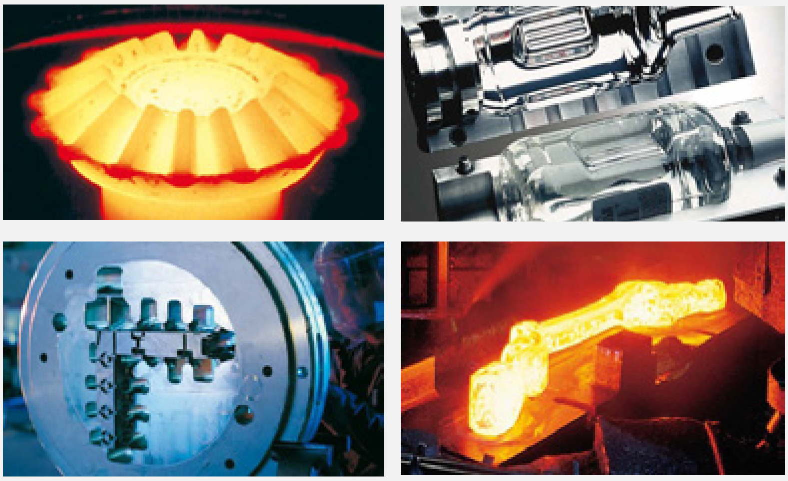


Fig. 1: Hot working tools

and modifications thereof: they refer to quality inspection of initial material, guidelines for conducting and controlling of the heat treatment process and researching its results. No such complex approach to tool manufacturing has been recorded in Europe, nevertheless standards of that kind are also developed on an industrial level, especially by automotive concerns and steel manufacturers. It is not a mystery that those standards are also based on NADCA guidelines.

NADCA GUIDELINES FOR HEAT TREATMENT

North American Die Casting Association got deeply involved in the issues of manufacturing hot work steel tools. As a result of that involvement, a guidebook was produced titled "Special Quality Die Steel & Heat Treatment Acceptance Criteria for Die Casting". The study focuses on the issues of initial material quality, vacuum heat treatment and welding methods. Before heat treatment, the parameters and quality of the steel have to be confirmed through:

- classifying steel grade with respect to the chemical composition of alloy additions and the contents of sulphur and phosphorus (grades from A to E),
- measurement of hardness after annealing (below 235 HB),
- analysis of the contents of microimpurities,
- checking whether there are no internal defects such as: cracks, presence of oxides, porosity, segregation etc. (ultrasound examination),
- defining grain size (above 7 acc. to ASTM E112),
- examination of microstructure (ferrite with evenly distributed spheroidal carbides).

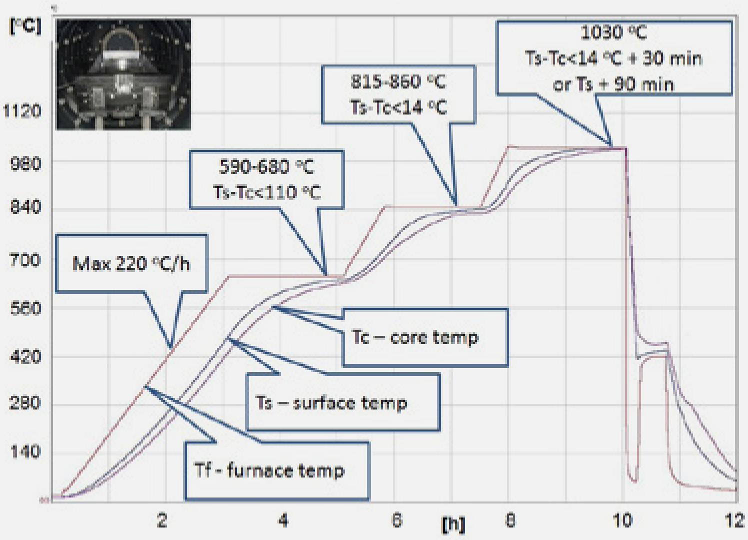


Fig. 2: Guidelines and progress of real austenitization and interrupted quench with monitoring of furnace temperature and of die surface/core temperatures (acc. to NADCA)

According to NADCA criteria, the heat treatment process should be performed in a vacuum furnace with a high pressure gas quench while monitoring and controlling the surface and core temperature of the processed piece (workload thermocouples have precisely preset locations).

Preheating to austenitizing temperature is done gradually not to allow excessive temperature difference. The first stop occurs at approx. 590-680 °C and continues until temperature difference between core and surface is below 110 °C (much less in practice). The next stop is preset at the temperature of 815-860 °C and continues until temperatures are compensated with a difference not bigger than 14 °C. Finally, the austenitizing temperature of 1,030 °C is reached at which the load is held for 30 minutes from temperature compensation point (with allowable temperature differences below 14 °C) or for maximum 90 minutes until 1,030 °C is obtained on the surface. These guidelines limit thermal deformations and excessive growth of austenite grain. **Fig. 2** presents a graph illustrating proper heating of a die according to those criteria.

Dies are hardened by quenching at maximum speed down to the temperature of 150 °C in the core. The average cooling rate for the surface from 1,030 °C down to 540 °C should be at least 28 °C/min. In the case of large dies (cross-sections above 300 mm) interrupted quenching (isothermal stop) at surface temperature of 400-450 °C is applied when the core temperature diverges by more than 110 °C. The interrupted quench is completed when one of the following conditions occurs:

- core temperature differs from surface temperature by less than 110 °C;
- surface temperature drops below 400 °C;
- 30 minutes passed from the start of the interrupted quench.

Interrupted quenching is presented in **Fig. 3**.

Ford and GM have similar requirements concerning interrupted quench with the only difference being that Ford shortens the time to maximum 15 minutes while GM to only 5 minutes and at the same time accelerates the quenching rate to 39 °C/min (28 °C/min for NADCA).

Quenching is continued until 150 °C is reached in the core (50 °C on the surface) and then it is immediately followed by tempering. The workpieces should not be cooled down below the temperature of 33 °C. The required cooling rate is significant due to the risk of excessive grain boundary release of carbides, which results in worse impact strength. Interrupted quenching limits the temperature difference between surface and core and thus reduces stress and deformations, protects the workpiece against cracking while at the same time preventing creation of pearlitic structure.

The first tempering is carried out at the minimum temperature of 565 °C by holding for the time which depends on tool cross-section (1h / 25 mm), though not less than for 2 h. This is followed by cooling down to ambient temperature and second tempering at the minimum temperature of 550 °C. Third tempering is not necessary and is applied only for final adjustment of hardness. Tempering reduces internal stress and ensure dimensional stability as well as proper structure and required hardness, usually within the range of 42-52 HRC.

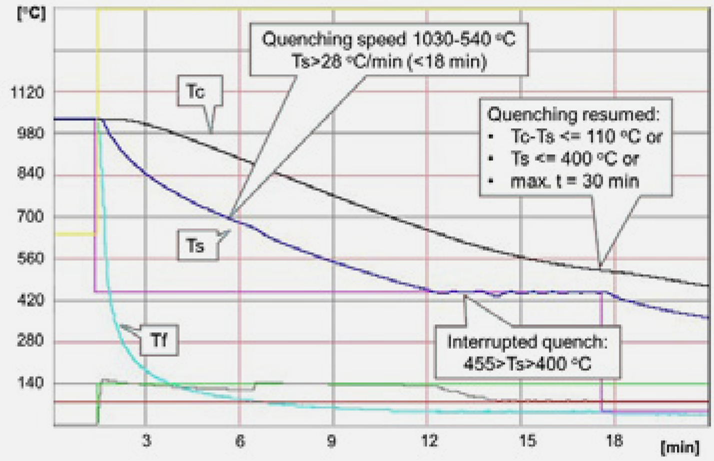


Fig. 3: Guidelines and progress of real interrupted quench with monitoring of furnace temperature and of die surface/core temperatures (acc. to NADCA)

VACUUM FURNACE FOR HEAT TREATMENT OF TOOLS

The requirements concerning heat treatment of moulds and dies, dictated by NADCA, Ford, GM and others, can be achieved in a single chamber vacuum furnace equipped with high pressure cooling system in inert gas (type HPGQ – high pressure gas quench) [4-8]. Seco/Warwick offers a type-series of furnaces named VECTOR which are especially dedicated to heat treatment of tools. These furnaces meet the most restrictive requirements in the branch and are delivered to customers worldwide (Europe, USA, Canada, Mexico, Brazil, China, India and even as far as Australia). Furnaces of various dimensions of working space are available, beginning from 400/400/600 through 600/600/900, 900/800/1,200, 1,200/1,200/1,800 [mm] and larger as well as other of optional size, featuring horizontal and vertical loading systems (**Fig. 4**). Those furnaces feature a compact design and due to lack of emission of contaminants and other noxious substances may be installed and operated in clean rooms and production facilities. They are equipped with a graphite heating chamber which provides for heating the workload to maximum temperature of 1,300 °C with temperature uniformity of +/- 5 °C and better. This is facilitated by circumferentially located heating elements which work by radiation in vacuum and inert gas (convection, system ConFlap), which ensures effective and uniform heating also at low temperatures (tempering). The furnace quenches in high pressure inert gas (15 bar) with closed-circuit circulation enforced by a blower. The cooling gas

Fig. 4: Horizontal vacuum furnaces VECTOR line (Seco/Warwick) size 900/800/1,200 mm, 15 bar.

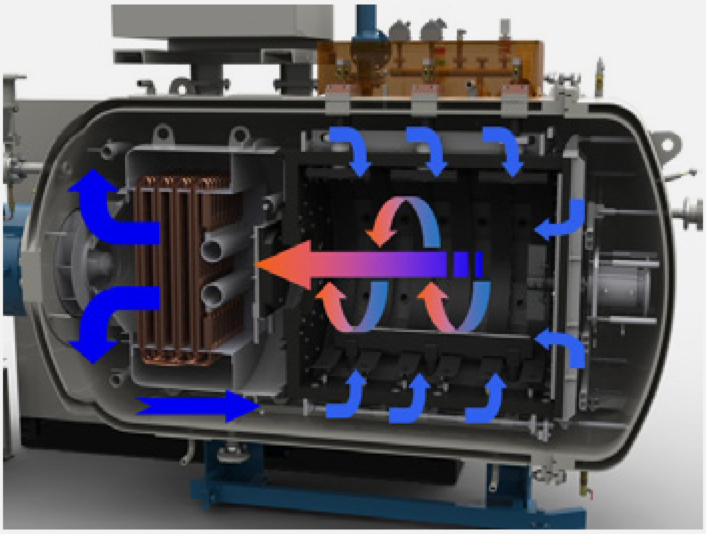


Fig. 5: Cooling gas circulation at quenching phase shown on cross-section of VECTOR furnace

is accelerated in circumferentially located nozzles to the velocity of 50-70 m/s and hence directly onto the workload where the heat is transferred and collected to an internal heat exchanger. The system ensures very high intensity of cooling in nitrogen comparable to cooling in free oil (heat transfer coefficient α up to 800 [W/m²K]) and uniformity throughout the entire working space as well as very good penetration potential in the densely packed load (**Fig. 5**). This cooling system enables interrupted quenching by controlling cooling intensity through blower rotation and gas pressure, depending on the surface temperature of a processed workpiece. In the case of tools of defined shape it is possible to programme an adequate sequence of directing the inflow of cooling gas – dynamic cooling. The choice includes gas inflow from all directions, from top and bottom, from both sides, 270 ° (4 options) and from the front (**Fig. 6**). The process may progress statically or change dynamically at optional sequence and time, thus allowing practically unlimited number of combinations. The above presented options permit adjusting the cooling system operation depending on the geometry of workpieces and configuration of the workload in order to improve cooling uniformity and reduce deformations of quenched details.

Cooling with circumferential 270 ° inflow, dynamically changed at appropriate time sequence, proved to be particularly effective. A significant acceleration of cooling rate was achieved as well as better equalisation of temperatures on workpiece surfaces.

The effectiveness of gas quench in VECTOR furnaces was proved on a reference steel block sized 400/400/400 mm (**Fig.7**) by obtaining surface cooling rates substantially exceeding the minimum requirements for both NADCA – 28 °C/min and GM – 39 °C/min. Depending on the size of furnace's working space the following cooling rates of the steel block surface were achieved quenched in nitrogen at 14 bar:

■ 1,200 x 1,200 x 1,800 mm	> 40 °C/min
■ 900 x 800 x 1,200 mm	> 55 °C/min
■ 600 x 600 x 900 mm	> 80 °C/min (over 200 °C/min for 24 bar He)

A vacuum furnace provides for the entire processing to be effected in a single piece of equipment without transferring the workload, in a single work cycle, by performing the sequence of: preheating for austenitization, interrupt-

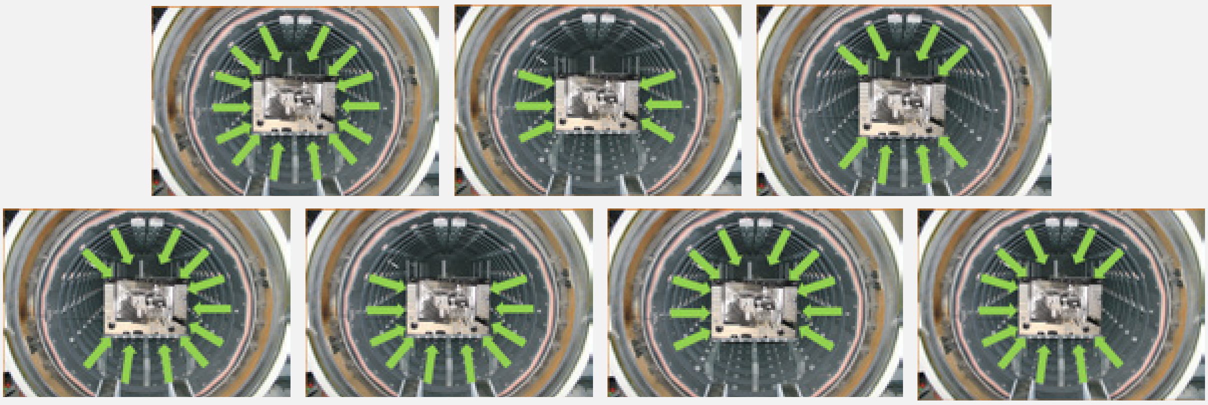


Fig. 6: Basic gas inflow options during quenching in VECTOR furnace. Top pictures: all around 360°, side-side, top-bottom. Bottom pictures: 4 options of 270°

ed quenching, mutiple tempering and also nitriding. The process may be monitored by workload thermocouples located at a critical place in the processed tool. Carrying out the treatment in vacuum and inert gases facilitates maintaining an ideal surface of the workpieces (**Fig. 8**).

TOOL STEEL QUENCH SIMULATOR

Defining interdependencies of structure, technological process and operating properties is of key importance for proper and optimum processes of tool manufacturing. Today the traditional trial-and-error method of optimalizing product properties and technological parameters is commonly replaced with simulation and prediction methods which permit having both the product and the technological process designed by computer. It is also in the area of thermal and thermo-chemical processing that we observe an increased interest in the applications for modelling and simulation of such phenomena. This pertains both to the progress of the process and to the final properties of the processed elements [9-15].

The G-Quench Pro software (**Fig. 9.**) which VECTOR furnaces are equipped with, is meant for simulation and control of gas quench of tool steels and reduces the need for test runs. The mathematical basis of quench process and the dependence of material hardness from cooling time were drawn up following the research performed at the Technical University of Lodz, Poland and Seco/Warwick as well as available literature. A direct result of simulation is determining the course of cooling curve in given conditions. Determination of cooling curve is done on the basis of the parameters of the material, the process and the physical workpiece such as quenching temperature, type and pressure of quench gas, dimensions of the workpiece and its shape, workload density in the cooling chamber. Combined with individual phase diagram for the material, the curve provides feedback on the phases through which the steel passes in the course of quenching. The ultimate effect of the simulation is defining the quench rate and expected final hardness of the material (at setup depth).

As mentioned earlier, the individual parameters of the quench equipment largely determine the actual progress of the process, thus causing the same parameters preset on two different machines to give different results. For this reason, at the installation phase the software is configured to suit a given physical piece of equipment. This way the individual characteristics of a given furnace is also taken into account when calculating the final properties of the product.

G-Quench Pro provides for monitoring of the quench process in real time (on-line monitoring). In this mode the software is connected to the furnace control system and draws on-line the cooling curve on a phase diagram on the basis of actual temperature measurements obtained from workload thermocouples. This option permits assessment of correctness of quench process while the latter is still in progress and allows appropriate amendments to be introduced.

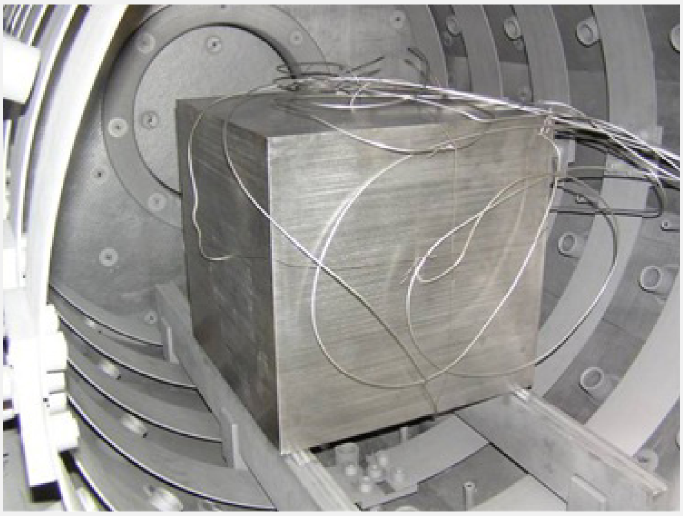


Fig. 7: Quench rate test acc. to NADCA on a reference steel block 400/400/400 mm

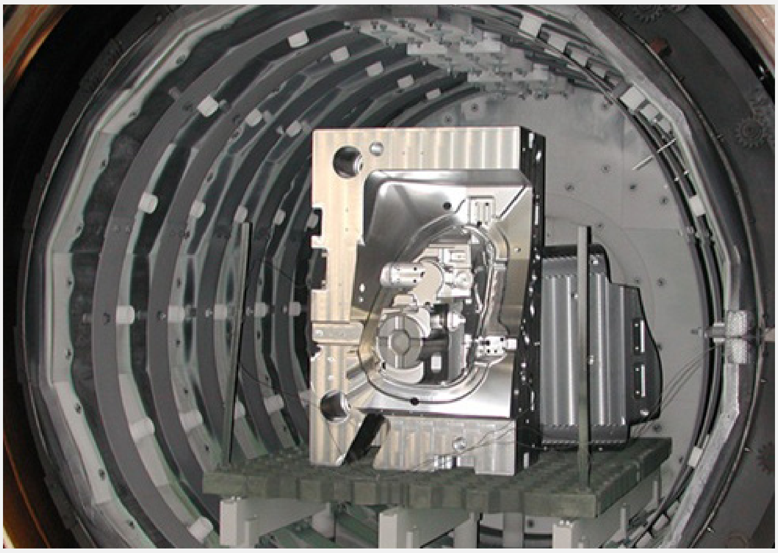
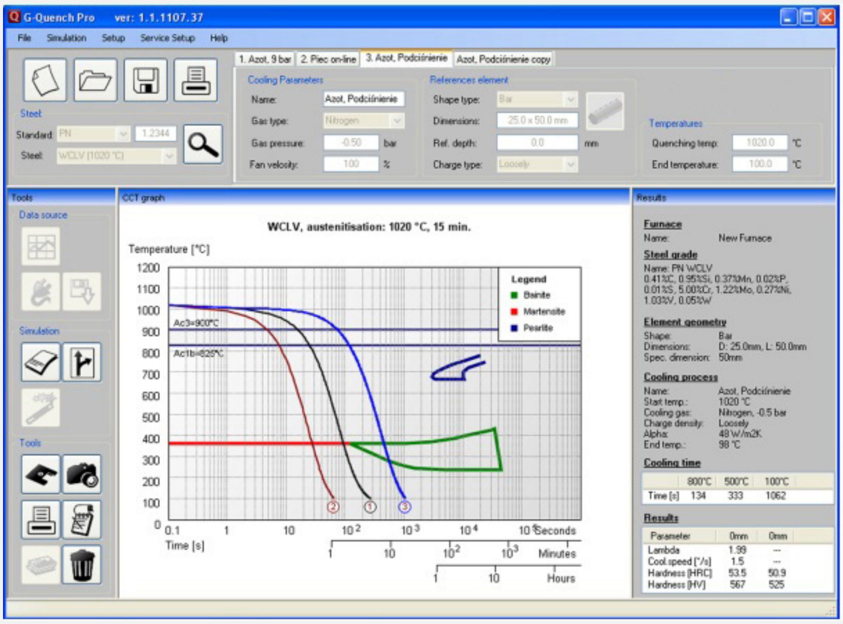


Fig. 8: A die in vacuum furnace chamber following complex heat treatment



Steel
Standard: PN 1.2344
Steel: WCLV (1020 °C)

Cooling Parameters
Name: Azot, Podciśnienie
Gas type: Nitrogen
Gas pressure: -0.50 bar
Fan velocity: 100 %

References element
Shape type: Bar
Dimensions: 25.0 x 50.0 mm
Ref. depth: 0.0 mm
Charge type: Loosely

Temperatures
Quenching temp: 1020.0 °C
End temperature: 100.0 °C

WCLV, austenitisation: 1020 °C, 15 min.

Furnace
Name: New Furnace

Steel grade
Name: PN WCLV
0.41%C, 0.95%Si, 0.37%Mn, 0.02%P, 0.01%S, 5.00%Cr, 1.22%Mo, 0.27%Ni, 1.03%V, 0.05%W

Element geometry
Shape: Bar
Dimensions: D: 25.0mm, L: 50.0mm
Spec. dimension: 50mm

Cooling process
Name: Azot, Podciśnienie
Start temp.: 1020 °C
Cooling gas: Nitrogen, -0.5 bar
Charge density: Loosely
Alpha: 48 W/m2K
End temp.: 98 °C

Cooling time

	800°C	500°C	100°C
Time [s]	134	333	1062

Results

Parameter	0mm	0mm
Lambda	1.99	---
Cool.speed [°/s]	1.5	---
Hardness [HRC]	53.5	50.9
Hardness [HV]	567	525

Fig. 9: Overall view of software for simulation and control of tool steel quenching process

CONCLUSION

Worked out by NADCA, the criteria and standards for production and exploitation of hot working steel are commonly applied or adopted in both American and European industry. The guidelines cover an entire spectrum of processes and process control referring to tool manufacturing, beginning from raw material, then heat treatment to application and repairs.

Heat treatment of hot working tools should be effected in vacuum furnaces with gas quench and isothermal stop. The treatment should be performed at appropriate heating and cooling speed and should be monitored with workload thermocouples to control temperature difference within the material.

Vacuum furnaces by Seco/Warwick series VECTOR, equipped with high pressure gas quench system (to 25 bar) with interrupted quench provide an ideal solution to meet NADCA, Ford, GM and other requirements concerning complex heat treatment of hot working tool steel. They also have potential to meet more restricted requirements in terms of cooling speed and uniformity in the future. The system of dynamic cooling enables programmed (sequential and temporal) defining of quench gas inflow direction, which positively influences cooling uniformity and reduces deformations. The G-Quench Pro quench simulator provides prediction of process results and optimum adjustment of cooling parameters to a given workpiece and the equipment, which ensures appropriate technological outcome.

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