Heat treatment of tool steels in vacuum furnaces with gas quench

Part 1. Process requirements and simulations

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In a few words

Tool steels constitute the basic material for forming of all groups of materials and for tool manufacturing. A properly designed and controlled cooling process is of major significance for the final effect of heat treatment and therefore it is underlying for the durability and service suitability of the treated element.

Contemporary heat treating equipment and technologies facilitate massive and effective heat treatment of tool steels, while process simulators such as G-Quench Pro® enable designing of new treatment methods with simultaneous reduction of the time consuming testing procedures.

Introduction

Tool steels are a widely used material for making metal, polymer, ceramic and composite tools which may be formed by machining or plastic forming. Since the crucial requirement for a tool is its shape stability, the material it is made from is expected to withhold loading without plastic strain and to be highly resistant to abrasion.

Tool steels are classified according to applications. Dies, punches, stamping dies, pressing rolls and other tools designed for cold processing are made of cold working alloy steel such as NCLV, NC10, NC11LV, NZ3 (although in practice both the material and the tools get slightly heating when working, say as a result of friction or deforming work). The large-size extrusion dies, pressure casting moulds, mandrels, punches and other elements for plastic working of other materials heated up to higher temperatures (within the range of 250-700°C) are made of hot working alloy steels (such as WCL, WCLV, WNLV, etc.). This group of materials is expected to show high degree of hardness, abrasion resistance, impact strength and good hardening capacity. The third group comprises high speed steels (e.g. SW7M, SW18, SK5M) applied chiefly to machine metals at high speeds (cutters, drills, milling cutters).

Generally speaking, all properly quenched tool steels are characterized by high hardness, abrasion resistance, small deformability and small susceptibility to overheating. Since the basic qualities of those steel grades (abrasion resistance, strength, crack resistance, ductility) are greatly dependent on the hardness achieved, it is that parameter that attracts a lot of attention. Properly run quench process is of major significance for the target hardness of steel elements and thus determines their functional suitability.

Heat treatment of tool steels

Heat treatment of tool steels consists of a hardening process followed immediately by a tempering process, which ensures an appropriate structure of the material. It must be mentioned at this point that properly selected chemical composition has a major influence on the properties of those materials. However, this is beyond the scope of the present paper. Tool steels require precision treatment, usually individualized for each grade of steel. Detailed guidelines are to be found in branch literature and manufacturers' material specifications while new concepts and trends in heat treatment are discussed in specialist magazines and at HT branch events [1-4]. Nevertheless, certain similarities can be found within application groups of those steels.

Quenching the cold working tool steels needs to ensure fine-grained steel resistant to abrasion and wear. Such properties are achieved by conducting the process in such a way that some of the carbides remain undissolved in the austenite. Therefore, in practice those steels are quenched down in oil from temperatures of up to 960^{o}C.

The hot working steels are quenched in oil or gas from temperatures of up to 1120^{o}C and then tempered at temperatures up to 600^{o}C. The austenitizing temperature is a compromise between the necessity to limit the growth of primary austenite grains and the need to dissolve the alloy carbides. Depending on the tool size, quenching process is aimed at obtaining a martensite structure (for smaller elements) or martensite with bainite (for larger tools). This is followed by twice tempering at temperature or above the point of secondary hardness in order to reduce the retained austenite and to increase ductility and resistance to thermal fatigue. Sometimes supplementary processes are introduced, such as applying various coatings (CVD, PVD) or nitriding, which additionally increase the hardness of the working surfaces of the treated tools as well as improve their resistance to abrasion and corrosion.

The high speed steels are quenched in oil or gas under pressure, down from temperatures of up to 1250^{o}C and then tempered within 500-600^{o}C.

A properly performed heat treatment is decisive for the mechanical and functional properties of tools and the economy of their application. Allowing any irregularities leads to quicker wear, deformation or defect to functional elements or, in extreme cases, to their damage (cracking) as early as in the course of heat treatment, which causes notable financial losses. Needless to say, proper quality and condition of the initial material is also significant.

Difficulties in ensuring quality to large-size tools (moulds and dies) have led to the creation of processing standards. The most familiar are the works published by NADCA (North American Die Casting Association) [5] and those published by the leaders in automotive industry, among others the concerns of Ford [6] and General Motors [7]. These standards apply mainly to the steel grade H13 (WCLV) and its modifications: they relate to quality control for initial material, guidelines for conducting and controlling HT processes and researching the results.

Guidelines for HT of hot working tool steels acc. to NADCA

According to NADCA guidelines, HT process should be performed in a vacuum furnace with high pressure gas quench while the surface and core temperatures of a processed workpiece is monitored and controlled (precise locations for workload thermocouples are predetermined).

Heating up to austenitizing temperature is effected gradually in order not to allow any significant temperature difference. The first heating stop is at the temperature of approx. 650^{o}C and continues until the temperature difference between the core and surface is below 110^{o}C (practically much below that). The next stop is preset at 850^{o}C and continues until the temperatures equalize, with the difference not exceeding 14^{o}C. Finally, the austenitizing temperature of 1030^{o}C is reached at which soaking follows for 30 minutes until the temperatures equalize (with permissible temperature difference below 14^{o}C) or for maximum 90 minutes from reaching 1030^{o}C at the surface. These guidelines limit thermal deformations and excessive growth of austenite grain.

Dies are hardened by being quenched at maximum speed down to the temperature of 150°C in the core. The average surface quench ratio down to 540°C should be at least 28°C/min. In the event of large-size dies (of cross-sections above 300 mm), isothermal cooling is applied at surface temperature of 400-450°C when the core temperature diverges by more than 100°C. Isothermal stop is finished when one of the following conditions occurs:

- core temperature differs from surface temperature by more than 100°C
- surface temperature drops below 400°C
- 30 minutes have elapsed from the onset of the isothermal stop.

Quenching is continued until 50°C is obtained in the core, following which tempering

starts immediately. Workloads should not be cooled down below the temperature of 33°C. The required cooling rate is essential due to the risk of emission of carbides at grain limits, which results in an impaired impact strength. Isothermal cooling restricts the temperature difference of the surface and the core and thus decreases stresses and deformations, protects the piece against cracking and prevents creation of a pearlitic structure.

The first tempering is performed at the temperature of minimum 565°C by holding for the time depending on the cross-section of the tool (1h / 25 mm), but not shorter than for 2 hours. This is followed by cooling down to ambient temperature and second tempering at the temperature not lower than 550°C. Third tempering is not necessary and is applied only for final correction of hardness. The tempering processes reduce the internal stresses, ensure dimensional stability and proper structure as well as the required hardness, usually within the range of 42-52 HRC.

Fig. 1. Horizontal vacuum furnace model 15.0 VPT (SECO/WARWICK)

Vacuum furnace with gas quench

The requirements set by NADCA concerning heat treatment of moulds and dies are made feasible in a single chamber vacuum furnace equipped with inert high pressure gas quench system (type HPGQ) [8-13]. National company SECO/WARWICK has developed a type-series of 15.0 VPT furnaces dedicated specially to heat treatment of tools. These furnaces meet the toughest requirements set by the tool branch and are delivered to customers all over the world (European countries, the USA, Mexico, Brazil, China, India, and even Australia). Furnaces of various volume of working area are available starting from 400/400/600 through 600/600/900, 900/800/1200, 1200/1200/1800 mm and larger, featuring horizontal or vertical loading system (Fig. 1).

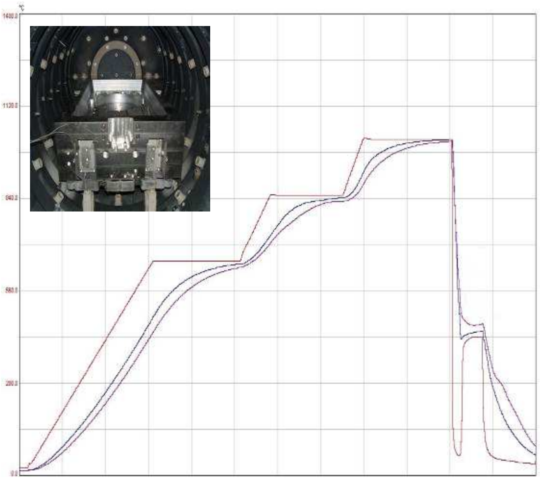

Fig.2. Austenitizing and quenching with isothermal stop and with monitoring of furnace temperature and temperature of die surface and core

The furnaces feature a compact design and as they do not emit pollutants or other noxious agents, they may be installed and operated in clean working spaces. They are equipped with a graphite heating chamber which permits heating the workload up to the temperature of 1300^{o}C with uniformity of +/- 5^{o}C or better. This is achieved due to the circumferentially placed heating elements providing radiation heating in vacuum and inert gas (convection, ConFlap system), which ensures effective and uniform heating also at low temperatures. The furnace quenches in inert gas at high pressure (15 atm) forced in a close circuit by a blower. Cooling gas is forced through the circumferentially placed nozzles directly onto the workload wherefrom the heat is collected and passed to the internal heat exchanger. The cooling system provides for isothermal quenching by controlling cooling intensity with the blower's capacity and gas pressure (Fig. 2). Effectiveness of gas cooling in 15.0 VPT furnaces was validated through tests on a reference steel block 400/400/400 mm (Fig.3.) when speeds from 40 to 80^{o}C/min were achieved (cf. required by NADCA – 28^{o}C/min and GM – 39^{o}C/min).

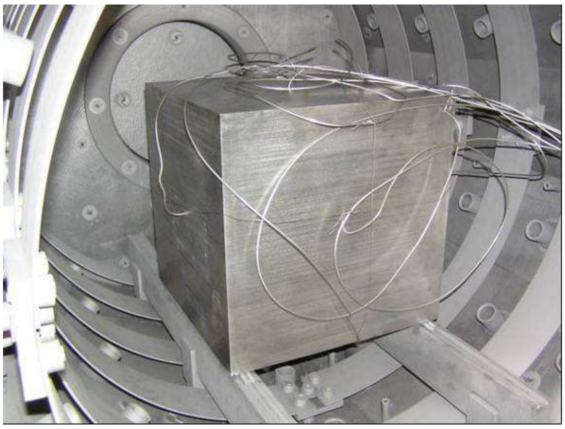

Fig.3. Test of quench speed acc. to NADCA on a reference steel block of 400/400/400 mm

A vacuum furnace enables carrying out the entire treatment in a single unit, without workload transfer, and in a single working cycle which contains the following subsequent stages: heating for austenitizing, isothermal quenching, repeated tempering and also nitriding. The process may be monitored through workload thermocouples located in an optional place of the die. Ideally clean surface of the workpieces is the effect of the treatment run in vacuum and in inert gases (Fig. 4).

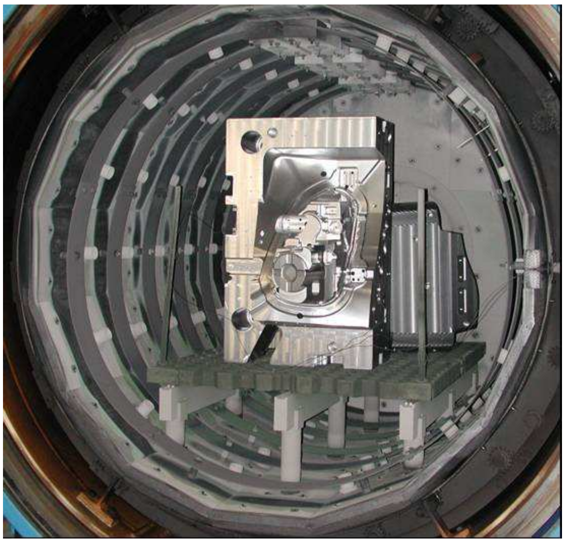

Fig.4. A die in the vacuum furnace chamber following complex heat treatment

Tool steel quench simulator

Determination of the interdependencies between the structure, technological process and functional properties is of key importance for correct and optimal tool manufacturing. It is so because selection of an appropriate material combined with an appropriate technology ensures the best product durability at the lowest cost.

Accelerated advancement of civilization has initiated increased consumer expectations towards a number of industries, concerning product quality and durability with simultaneously expected reduction in hazardous emissions and minimized energy consumption. This in turn has brought about a number of changes in the approach to manufacturing.

Nowadays, the traditional method of reaching optimum product properties and technological parameters by trial and error is commonly replaced with simulation and prediction methods which allow the product and its technology to be computer-designed. In numerous cases computer has taken over the control of manufacturing while the growing popularity of this solution is visible in the expanding market of digital equipment. Heat treatment has also witnessed an interest in applications for process modeling and simulation. This concerns the technological process itself as well as the final properties of heat treated elements [14-19].

The general use simulation software consider only the standard parameters of a given phenomenon, which leads to the final results being burdened with an error. A method to increase the precision of calculations is to take into account the parameters of the environment in which a process is effected, in this instance the individual characteristics of a quenching furnace as it is the case with the G-Quench Pro simulator. It may seem that the individual properties of a machine would tie the application to a given piece of equipment and thus render it useless for others. However, appropriate parametrization of the settings permits to retain the versatility of the software, thereby it may be used on various units of equipment. Despite the above, this solution is rarely found in industrial practice.

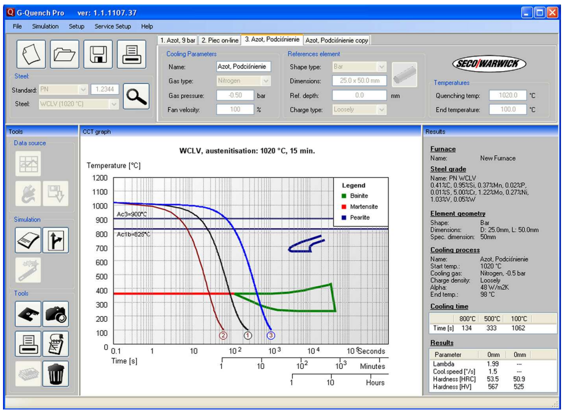

Fig. 5. Overall view of a software for simulation and control of tool steel quenching process

The G-Quench Pro software (Fig.5) is applied to simulate and control tool steel quenching in gas, thus reducing the need for test runs. The mathematical principles of the quench process and the dependence of material hardness from quench time have been developed on the basis of the research carried out at the University of Technology in Łódź, Poland and SECO/WARWICK company, with due consideration of available literature.

A direct result of such simulation is determination of a cooling curve for a given material under given conditions. The cooling curve is determined basing on the parameters of the material, the process and the workpiece such as quench temperature, pressure and type of cooling gas, dimensions and curvature of the workpiece and density of workpieces in the quench chamber. Combined with an individual phase diagram for the material, the curve provides information on the phases through which the steel goes during treatment. The ultimate effect of simulation is determination of quench speed and predicted final hardness of the material.

As it was mentioned earlier, individual parameters of a quench unit largely determine the actual process and, as a result, the same parameters preset on two different units may render differently hardened steel. Therefore, at the installation stage the software is configured for a particular physical piece of equipment assigned thereto. In this way the individual characteristics of a furnace is also taken into consideration when defining final properties of the product.

Quench process control

Monitoring of quench process is an essential element of the manufacturing cycle. Although process control is a cyclic procedure and occurs at every stage of production (design, process, testing final product), here it is exceptionally important as this is the last stage which offers a possibility of intervention and change to quench parameters. Testing the final product merely gives a possibility to acknowledge a faulty treatment afterwards. On the other hand, monitoring of the quench process in real time provides for immediate intervention of the operator should any irregularities in the progress of the treatment be found.

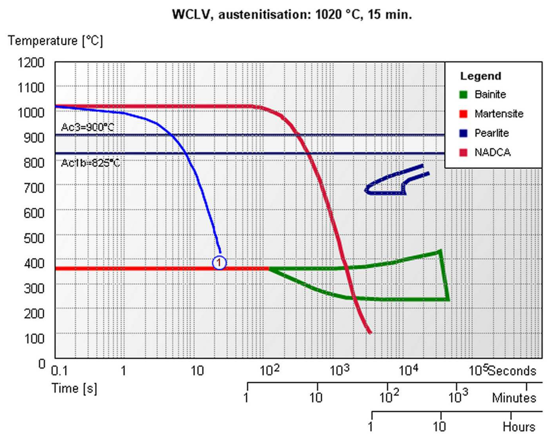

Fig. 6. Monitoring of proper progress of quench process in real time with the G-Quench Pro software

In the monitor mode the software requires a remote or direct connection to the quench unit. Co-operating with the furnace computer it downloads feedback on the current temperature in the chamber or in the quenched workpiece and then plots the readouts onto the phase diagram. Real time process curve is plotted upon the cooling curve determined by the simulator (Fig. 6). This way the quench process undergoes current verification.

Summary

Tool steels are basic material for forming all types of materials and for tool manufacturing. A properly designed and controlled cooling process is of major significance for the final effect of heat treatment and therefore it is underlying for the durability and service suitability of the treated element. Contemporary heat treating equipment and technologies facilitate massive and effective heat treatment of tool steels, while quench process simulators facilitate highly accurate prediction of process results with simultaneous reduction of the time consuming testing procedures.

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