# SIMULATION AND CONTROL OF TOOL STEEL QUENCHING PROCESS

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**ABSTRACT**

Tool steels are widely used materials for making elements of metals, polymers, ceramics and composites. Inflated consumer expectations of contemporary civilization entail the manufacture of better and better tools, accompanied by reduced energy consumption. The application of simulators and controls of technological processes enables the design of optimum processes without the need for time consuming and costly experimental research.

The present article is devoted to a tool for simulation and control of tool steel quenching in gases (helium, nitrogen, argon, hydrogen), both at negative as well as at high pressures. The simulator takes as its input the quenching parameters, the individual characteristics of the furnace and the material, dimensions and shape of the treated workpiece, yielding in effect a cooling curve and the forecast post-quench hardness. The monitoring program, which constitutes an integral part of the tool, works on-line with the industrial equipment, thus allowing continuous control of the quenching process with respect to the simulation in progress.

In the subsequent sections the article presents the operation of the simulator and the monitor, the field of practical applications thereof, and describes a practical application working with an industrial furnace. Particular attention is drawn to the verification stage of the mathematical model and the results of experimental processes of tool steel quenching.

## INTRODUCTION

The accelerated development of civilisation has given rise to boosted consumer expectations towards a number of industries, particularly concerning product quality and durability with simultaneously anticipated reduction of detrimental emissions and minimised energy consumption. This resulted in a series of changes in attitude towards manufacturing. Today, the traditional manner of arriving at optimum product and process parameters through trial and error method is commonly replaced with simulation and prediction methods which facilitate the design of both the product and its production process with a computer. In numerous cases the computer has entirely taken over the control of manufacturing while the increasing popularity of this solution is reflected in the expanding market for digital equipment (milling machines, lathes, machine tools, etc.)

Heat treatment and thermo-chemical treatment also indicate an interest in applications for modelling and simulation of such phenomena. This pertains both to the technological process itself (heat flow, diffusion, emission effects) as well as to the resulting properties of treated elements (material hardness, quenching deformations) (Dybowski 2005; Dobrzański et al. 1996; Dobrzański and Sitek 1999; Dobrzański and Trzaska 2004ab; Kwaśny et al. 2007; Liujie et al. 2006; Liujie et al. 2007; Kula et al. 2007; Kula et al. 2009; Wołowiec 2009).

The simulation programmes in general use take into account only the model parameters of a phenomenon, which yields results with certain errors. One way to increase calculation accuracy is to take into account the ambient parameters of the process environment, in this case the individual characteristics of the heat treating furnace. It would seem that the individual properties of a machine tie the application to that particular piece of equipment, nevertheless a proper parameterisation of the program allows the universality of the software to be maintained. Thus, it may be applied with various units of equipment.

The circumstances outlined above as well as the growing interest in heat treatment dedicated to individual parts of machines were the impetus to launch research into a new software for the simulation of quench processes. A detailed market analysis determined the need to have the software functionality expanded by introducing the function of monitoring the furnace process in real time, which permits the operator's intervention should any irregularities in the quenching process be detected. Until now such software has not been available in industry.

## TECHNICAL PRINCIPLES AND RANGE OF OPERATION

At the first stage of work on the new simulator, detailed technical principles and range of operation for the latter were determined.

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Generally, the cooling process may be effected in a number of ways. There are steel grades which harden in the air, so in that case no further action is required. However, in a vast majority of cases special equipment is needed to ensure adequate conditions for the proper removal of heat from the quenched element. In industrial applications, oil baths have enjoyed popularity for some years now as they provide efficient quenching, although other quench methods have also been considered due to the drawbacks of oil baths such as excessive harmful emissions, the need for a post-quench wash and the troublesome recycling of the used quench oil.

### Universal Vacuum Furnace

Today the universal vacuum furnaces (Fig.1) constitute the basic technological equipment of the most sophisticated commercial hardening plants as well corporate heat treatment centres in aviation, motor, tool and machine industries. In the last decade the technical potential of such furnaces has been expanded to include the technologies of high temperature, low pressure thermo-chemical treatment of construction elements, mainly vacuum carburizing and advanced modifications thereof, carried out sequentially in one unit of equipment, complete with high pressure gas quench (Olejnik 2002; Korecki 2005).

Figure 1: Universal Vacuum Furnace for High Pressure Gas Quench

These furnaces are considered to be extremely environmentally friendly. The consumption of process gases and emission of greenhouse gases in the universal vacuum furnaces are from several dozen to several hundred times lower when compared to traditional equipment. The replacement of oil quench with gas quench is definitely more environmentally friendly, not to mention the application of nitrogen or helium which are totally neutral to the environment. In this regard, the energy saving potential is merely an additional advantage.

Therefore, a perspective outlook at the heat treatment trends authorizes the thesis that a simulator should be engineered with a view to using modern, efficient and energy saving gas quench equipment, although at present such equipment is still second in popularity behind the traditional oil quench systems.

### Tool steels

A major impulse to create a new piece of equipment was the authors' current interest in the issue of effective quenching of a steel group known as tool steels.

Tools made of tool steels find application in cold and hot forming of all types of materials: metals, polymers, ceramics and composites. Furthermore, tool steel is the basic material for manufacturing tools, components of gauging instruments and top-reliability holders.

Properly hardened tool steels are characterised by high hardness, abrasion resistance, minor deformability and little susceptibility to overheating. Since the essential properties of those steels (abrasive wear resistance, strength, crack resistance, ductility) are largely dependent on the hardness they reach, it is that parameter that so often comes into focus. Therefore, properly handled quenching of tool steels is of utmost significance for the final hardness of the steel element and thus a decisive factor in its operational suitability.

## SIMULATIONS OF QUENCHING PROCESS

Determining the dependence between structure, technological process and functional properties is of key importance for properly optimised tool manufacturing processes. The selection of appropriate material and technological process ensures the best product durability at the lowest cost (Sitek 2010).

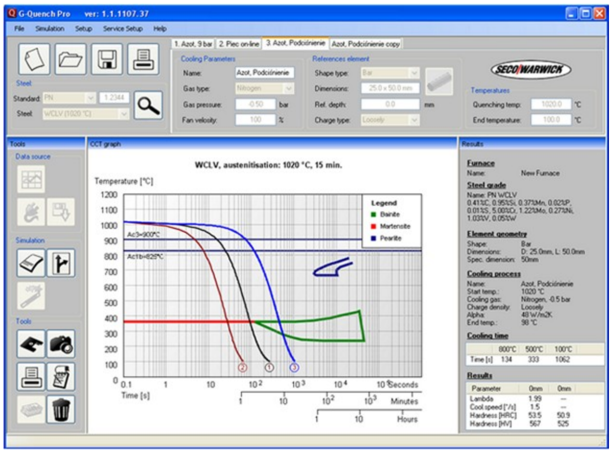


Figure 2: General view of the ***G-Quench Pro*** program

The ***G-Quench Pro*** program (*Gas Quenching Simulator*) (Fig. 2) is used to simulate and control the process of tool steel gas quench, also at high pressure, and it reduces the need for test runs. It was developed by the authors hereof for the use by the worldwide manufacturer of heat treatment equipment

Seco/Warwick S.A. The mathematical basis for quench process and dependence of material hardness on quench time were worked out on the grounds of the research carried out at the Polytechnic of Łódź and at Seco/Warwick S.A., supported with available literature (Atraszkiewicz 2005).

The simulation of a process follows the parameters defined by the user. A major stage is to define the material for which quench processes will be simulated. Pursuant to that input the program displays a phase diagram for a given steel. At the next stage cooling parameters are determined: the pressure and the type of quench gas, the fan rotation speed and the temperature at which quenching begins (Fig. 3). The result of a simulation is largely dependent on both the dimensions and the curvature of the quenched element. The packing density of the workload in the heating chamber also influences the quench rate, so this parameter is also taken into consideration.

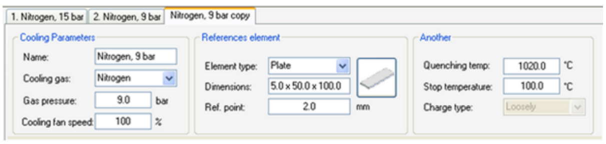


Figure 3: Quench Process Parameters Display

An immediate outcome of a simulation is the determination of the cooling curve for a particular material in given conditions. Combined with the phase diagram, the cooling curve provides information about the phases the material will go through in the course of treatment. The final effect of the simulation is defining the expected hardness of the processed material.

Individual parameters of a heat treating unit extensively determine the real course of treatment and cause the situation where the same parameters preset on two different units of equipment may result in differently hardened steels. For that reason, at the installation phase the ***G-Quench Pro*** program requires configuration of its settings in relation to the particular piece of equipment it is assigned to. In this way the individual characteristics of a furnace will be taken into account when calculating the outcome properties of a product.

To sum up, in the simulation mode the software provides a fully functional tool for the design and analysis of gas quench processes, which features adaptability to a given piece of equipment.

## QUENCH PROCESS CONTROL

Simultaneously to predictive functionality, the functions monitoring the course of real quench process were developed. In the monitoring mode, the software requires connection to the furnace by being mounted thereon or by a remote connection between the furnace computer and the computer on which the software is run. ***G-Quench Pro*** co-operates with the furnace software to receive an input indicating the current temperature in the furnace chamber or in the heat treated element. The user defines the location of the temperature readout.

In the subsequent moments a real process curve is superimposed on the cooling curve determined by the simulator. In this way a progressive verification of the quench process correctness is ensured.

It must be pointed out that the program features the possibility of simulation and control not only for hardening, but for every process of cooling in the general understanding of the term.

Apart from the functionality described above, the program features a number of standard functions such as logging and readout to file, making screen dumps or reports for printout, which, due to their self-evident nature, will not be detailed herein.

## EMPIRICAL VERIFICATION

Empirical verification of the simulator was carried out in two ways. At the first stage, the ***G-Quench Pro*** simulation results were compared to the results obtained from a commercial heat treating simulation program by Dr Sommer (Dr Sommer 2004). In the majority of cases the results from both simulators were compatible or indicated negligible differences. Fig. 4 and Fig. 5 present material hardness diagrams in cooling time function for quench at temperature range $800^0$ - $500^0$ C. The causes for divergence should be sought in the assumptions concerning properties of materials, as in the literature there also exist discrepancies in the descriptions of thermal dependence of density, heat conductivity and the specific heat of individual grades of tool steel.

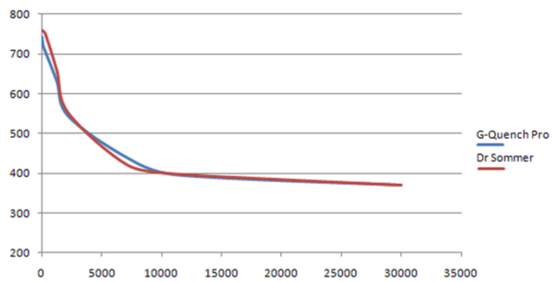


Figure 4: Hardness Diagram (HV) for WNLV (W500) Steel in Cooling Time Function (s)

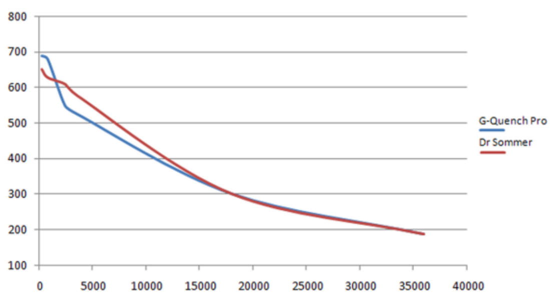


Figure 5: Hardness Diagram (HV) for H10 (W303) Steel in Cooling Time Function (s)

Simultaneously, experimental treatments were carried out on a real industrial furnace.

The research material consisted of samples of WCLV steel (1.2344) of cylindrical shape and dimensions from ϕ25x150 to ϕ200x500 mm (Fig. 6).

Figure 6: Furnace with Samples

The samples were quenched in a 25.0VPT-4035/36 furnace (manufactured by Seco/Warwick S.A.) in nitrogen at the pressure of 9 bar (0,9 MPa), then tested for the cooling curve and hardness of surface and core, and finally compared to the simulation results.

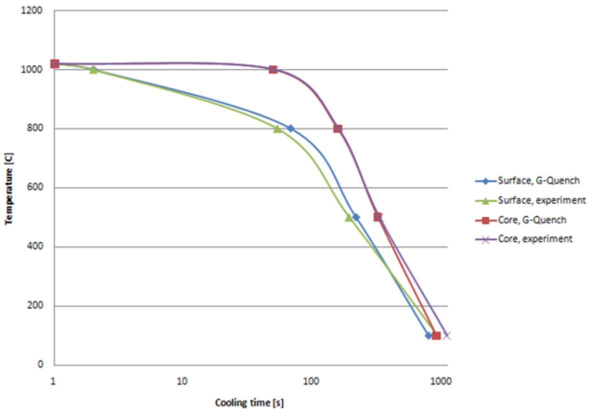


Figure 7: Cooling Comparison for WCLV steel

The real and the simulated cooling curves are presented in Fig. 7. Both curves are convergent and the difference does not exceed 5% of the cooling rate at the key temperature range 800-500°C. Comparative results of the hardness test are also highly satisfactory, reaching 54 HRC +/- 1 HRC.

## CONCLUSIONS

Tool steels constitute a basic material for forming all groups of materials and for the manufacture of tools. A properly designed and controlled quench process is of major significance for the final effect of heat treatment of an element and thus for its durability and service usability. Modern equipment and technologies of vacuum heat treatment provide for high-volume and effective heat treatment of tool steels, while simulators such as the ***G-Quench Pro*** enable engineering of new treatments with a simultaneous reduction in time-consuming experimental research.

Currently, the program is undergoing the complex verification process for compatibility of the simulation with real processes. Following this stage, a commercial implementation of the application is scheduled to be effected on equipment working in industrial conditions, as well as further development of the software.

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