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GAS QUENCHING WITH CONTROLLABLE HEAT EXTRACTION

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Abstract: - High pressure gas quenching became a modern way of quenching finally machined engineering components, having many advantages compared to quenching in liquid quenchants. The main shortcoming of this technology is the problem of achieving adequate hardness in the core of bigger workpieces, because of inadequate quenching intensity. Due to the possibility to change gas pressure and its flow velocity, combined with transient spraying of liquid nitrogen *during* the quenching process, the intensity of cooling can be instantly increased during selected time intervals. In this way *the heat extraction dynamics* can be automatically controlled, and a predetermined path of the heat transfer coefficient can be followed. Preliminary experiments show that using the *controllable heat extraction* (CHE) technology, the mentioned shortcoming can be eliminated. Theoretical background of the CHE technology is described, with particular attention to the depth of hardening, and to residual stresses. Possibilities and prerequisite conditions for application of the CHE technology in vacuum furnaces, and for automatic heat extraction control, are discussed.

Key-Words: - High pressure gas quenching; Heat transfer coefficient; Cooling curve; Hardness distribution; Automatic control

1 Introduction

High pressure gas quenching in vacuum furnaces, using circulated nitrogen of 5 to 10, and as far as 20 bar pressure, became already a standard practice. There are several known advantages of this technology (substantially reduced size change and distortion of workpieces; no need to wash the parts after quenching; ecological acceptability etc.) compared to quenching in oil or other liquid quenchants. Two other advantages of gas quenching which are usually forgotten are:

a) While quenching in liquid quenchants is a higly non-stationary heat transfer process (having very different heat transfer coefficients during vapour film, nucleate boiling and convection stages), making it difficult for mathematical modelling, gas quenching (when using constant parameters) is a Newtonian mode of cooling.

b) Cooling the workpieces in a gas takes much longer time than quenching them in a liquid quenchant; consequently quenching parameters (gas pressure, temperature and its circulation velocity) can be changed *during* the quenching process, while there is no possibility to change practically anything during quenching in liquid quenchants.

Besides all these advantages the existing high pressure gas quenching technology has an important shortcoming: it cannot in all cases provide enough high quenching intensity, which is necessary to obtain the required hardness in the core of workpieces having bigger cross-section size, especially when batches of great mass are quenched. This shortcoming is particularly evident when quenching workpieces made of low-alloyed structural steels (case-hardening steels; steels for hardening and tempering; and steels for roll-bearings), i.e. steels of low hardenability.

A real way to eliminate the explained short-coming, and to increase substantially the quenching intensity during corresponding period of the quenching process, is the application of the *Controllable Heat Extraction (CHE) technology.* It is a combination of the main stream of gaseous nitrogen (of adequate pressure and velocity) and a temporary spraying of liquid nitrogen, causing instantly very low ambient temperatures, so that big temperature differences between the surface of workpieces and the cooling medium cause high heat fluxes and high heat transfer coefficients respectively. CHE technology enables to follow a predetermined time-temperature path, i.e. to realize different quenching procedures (intensive quenching; delayed quenching; martempering, austempering).

The most important feature of the CHE technology is its ability to intentionally influence the depth of hardening, and the condition of residual stresses.

2 Theoretical background

2.1 How CHE technology can influence the depth of hardening

Every quenching process is actually a simultaneous development of two different processes, and the mutual interaction between them. The first one is *the heat extraction dynamics* and the second is *the structure transformation kinetics*, shown for each steel grade by the relevant Continuous Cooling-Transformation (CCT) diagram. The former process is a constantly changing relation between the heat flux within the workpiece and the heat transfer on its surface which can be described, in gas quenching applications, by the Newton's law of cooling:

$$q = \alpha\,(T_s - T_o) \qquad (1)$$

where:

q = *heat flux density* [W/m^2]
α = *heat transfer coefficient* [W/m^{2}K]
T_s = *surface temperature of the workpiece* [K]
T_o = *temperature of the surrounding gas* [K]

The later process doesn't start in all cross-section points simultaneously with the start of the quenching process. It starts actually *to different times for different points*, when the temperature in respective point decreases to the transformation start temperature A_1. Fig.1 shows a CCT diagram of the steel grade AISI 4140 with superimposed cooling curves for: surface (S), three quarter radius (3/4 R) and centre (C) of a cylindrical workpiece of 50 mm diameter. This means that cooling of any cross-section point from the austenitizing temperature to the A_1 temperature is irrelevant to the attained hardness at this point after quenching, because in this temperature region there is no structural transformation. For the steel grade AISI 4140, as can be seen from Fig.1, this temperature region amounts to: 850-720 = 130 °C. Time required to cool a specified point from the austenitizing temperature to A_1 temperature depends on the cross-section shape and size, on the distance of this point from the surface, and on cooling intensity of the cooling medium. The resulting hardness at each particular point depends on constituents of the structure transformed, which heavily depend on the harden ability of the steel concerned, i.e. on the incubation times at every isotherm. Because incubation times are counted only at temperatures below A_1, not the cooling rate from the austenitizing temperature to A_1, but *the cooling rate in the critical temperature range from A_1 to M_s* (martensite start temperature) is of paramount importance. According to equation (1) the heat flux density on the workpiece's surface depends on difference between its surface temperature and the temperature of surrounding gas. During cooling this difference becomes continuously smaller, resulting in smaller heat flux density on the workpiece's surface and smaller cooling rates in its core, just in time when the core passes the critical temperature range A_1 to M_s. If the cross-section size is big enough and actual cooling rate in the core is smaller than the *critical cooling rate* for the steel grade in question, no martensite can be formed, and no remarkable hardening of the core will be attained.

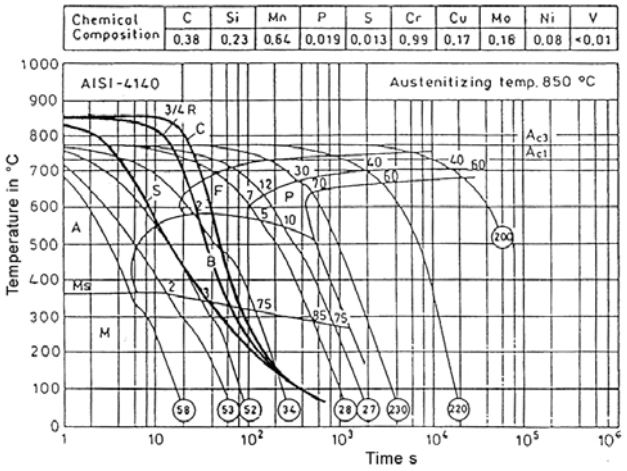

Fig.1. *Calculated cooling curves for surface (S), three quarter radius (3/4 R), and centre (C) of a 50 mm dia. bar superimposed on the CCT diagram of the steel grade AISI 4140*

By applying the CHE technology, according to equation (1) one can counteract this situation by increasing the heat transfer coefficient (α), by means of increasing the gas pressure and/or its velocity, and simultaneously substantially increasing the temperature difference (T_s-T_o) by spraying with liquid nitrogen. Both actions will result in great increase of the heat flux density. Increasing later, during the quenching process, the quenching intensity in described way, means actually to have a delayed quenching with *discontinuous change of cooling rate.* When discontinuous change of cooling rate is involved, as it is known from the work of Shimizu and Tamura [1], the pearlitic transformation behavior is different from that given by the CCT diagram, and is related to the incubation period consumed before changing the cooling rate.

The incubation period at any given isotherm is the time until the transformation starts (Z), while (X) is the incubation period consumed before the discontinuous change of the cooling rate has taken place. Fig.2 which is a schematic illustration of a discontinuous change of cooling rate shows that at time t_1 and temperature T_1 (point P) a discontinuous change of cooling rate occurred. Up to this moment the surface of the workpiece has consumed a portion (X) of the total incubation time (Z), but the centre has not, because at the moment t_1 the centre had a temperature above A_1. Further cooling below the point P has proceeded with substantially increased cooling rate changing the transformation start curve of the CCT diagram, as shown in Fig.2b. Because for the centre no incubation time has been consumed, the cooling curve for centre starts from temperature A_1 at zero time. In this way the cooling curve for centre, which doesn't intersect any pearlitic region results in higher hardness than the cooling curve for the surface, which has started from the point P and intersected a portion of pearlitic region. This is the theoretical explanation of the "inverse" hardness distribution (showing higher hardness in the core than at the surface), which Shimizu and Tamura have found by quenching specimens in oil [2], showing also how great is the capability of the CHE technology to increase the depth of hardening, provided the workpiece's cross-section size and steel hardenability are adequate.

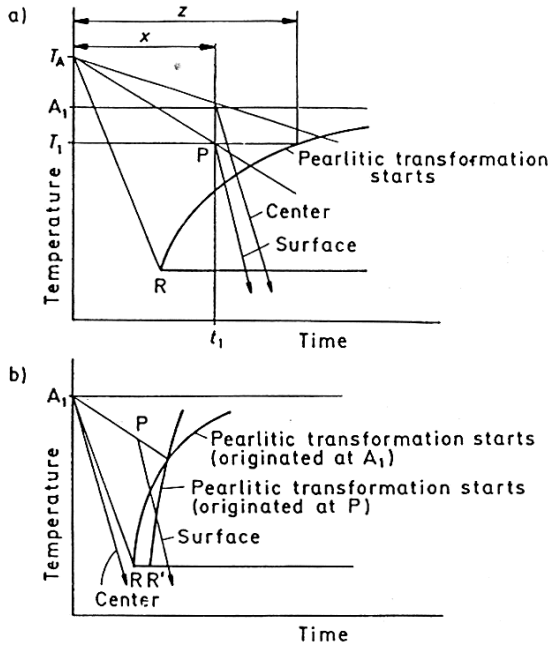

Fig.2. *Shematic illustration of discontinuous change of cooling rate causing 'inverse' hardness distribution after quenching, according to Shimizu and Tamura* [1]

2.2 How CHE technology can influence residual stresses

Generally speaking the CHE technology is not only described high pressure gas quenching method in vacuum furnaces, but every quenching process with exactly controlled heat extraction dynamics. For the purpose of analysing the development of surface residual stresses let us take the case of the Intensive Quenching method, developed by N.I. Kobasko [3]. This quenching method is used mostly for workpieces made of non-alloyed or low-alloyed steels, quenching them in pure water flowing with high velocity.

If a cylindrical workpiece is cooled *very rapidly and uniformly* martensite forms simultaneously over the entire surface, creating a strong hardened "shell".

Assume that the workpiece's surface layer consists of a set of "segments" joined together by "springs" to form an elastic ring. When austenitizing the workpiece, i.e. heating it above A_{c3}, there are no stresses between the "segments". This condition corresponds to Fig.3a (σ=0).

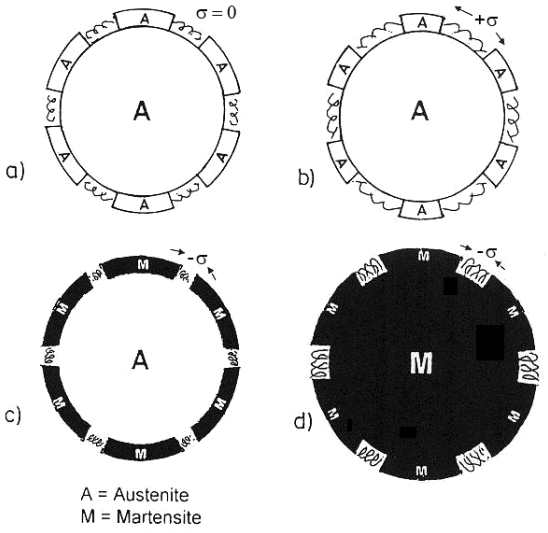

Fig.3. *Surface stress conditions during intensive quenching. Source: Brochure of the IQ Technologies Inc., Akron, OH*

When quenching starts, the surface layer cools rapidly resulting in the contraction of the "segments", while the "springs" expand simulating development of tensile stresses (+σ), as shown in Fig.3b. When the surface layer cools to the martensite start temperature M_s, the austenite phase in the surface "segments" transforms into martensite. Because the martensite specific volume is greater than the austenite one, the surface "segments" expand, causing the "springs" to contract, simulating

development of surface compressive stresses (-σ), as shown in Fig.3c. As the workpiece continues to cool, martensite starts forming in its core resulting in an increase in volume, or core "swelling" (Fig.3d). Due to the core expansion the distance between the surface layer "segments" increases, resulting in expansion of the "springs". Their expansion reflects the reduction of the compressive stresses in the surface layer. Fig.4 shows the development of surface stresses during Intensive Quenching. The main feature of the Intensive Quenching method is to interrupt rapid cooling of the workpiece at the moment when compressive stresses on the surface are at maximum. The martensite phase advance ceases resulting in no further core "swelling", and compressive stresses in the surface layer are maintained.

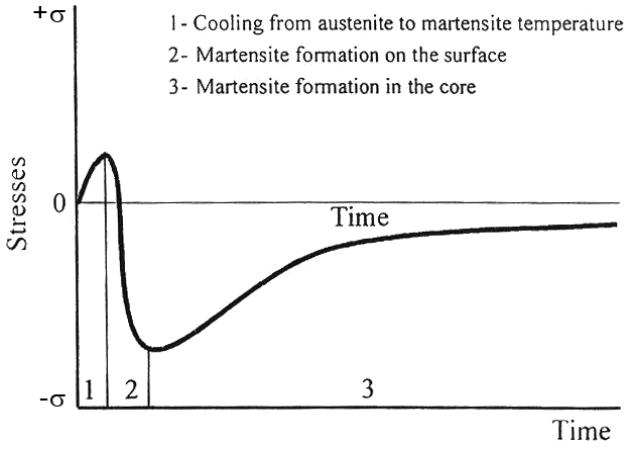

Fig.4. *Development of surface stresses vs. time when intensive quenching is applied*

3 Technical possibilities for the CHE technology in vacuum furnaces

Contemporary vacuum furnaces with a *cold* high pressure gas quenching chamber are generally suitable for the CHE technology, provided that an adequate nozzle-field system for spraying liquid nitrogen, and a relevant control system are built in. This is necessary to enable a broad range of quenching intensities, which can be instantly changed during the quenching cycle.

Simultaneous application of the circulated gas and dispersed liquid nitrogen enables to use three following heat transfer mechanisms: *a) convection by the circulated gas; b) radiation from the hot surface of the workpieces to the cold walls of the quenching chamber; c) vaporisation of the liquid nitrogen.* Dispersed liquid nitrogen is sprayed transiently, only during those periods, when high quenching intensity is needed. The advantage of liquid nitrogen evaporation is not only to take away the heat for its evaporation (which is about 11 times smaller than in case of evaporation of water), but the very low temperature of its vapour (-196 °C at atmospheric pressure), which is about 300 °C lower than in case of evaporated water. The huge temperature difference between the workpiece's surface and the nitrogen vapour produces instantly high heat flux values in the workpiece's surface region.

4 Automatic heat extraction control

The necessary control system consists of three main parts:

- An instrumented probe to measure its own temperature at the reference point;
- Control devices for every quenching parameter;
- Software-package with auxiliary files and relevant programs for calculation of the heat transfer coefficient α(T), and cooling curves respectively.

The instrumented probe (having dimensions of real workpieces) has to be of similar shape as the quenched workpieces (a cylindrical probe; a plate like probe; or a workpiece itself acting as a probe, in case of complicated shape).

Fig.5 shows the algorithm for automatic control of the quenching intensity i.e. of heat extraction during quenching a batch of workpieces. The required hardness at the specified cross-section location is the most important information of the input data.

The relevant Continuous Cooling – Transformation (CCT) diagram for the steel grade in question is taken from the file of CCT diagrams, and the cooling curve which assures attaining the required hardness at the chosen cross-section location, is drawn onto the diagram. Using temperature dependent physical properties of the steel in question, and the relevant software program (supposing adequate ambient temperature), the heat transfer coefficient as function of the surface temperature α(T), which satisfies the drawn cooling curve, is calculated. With this calculated function α(T) (for the workpiece having different cross-section size than the probe), *the target cooling curve* at the reference point of the instrumented probe, is calculated. The reference point on the middle length cross-section of the probe should be close enough to the probe surface, in order to assure that change of every cooling parameter is instantly sensed (without greater damping effect and time lag).

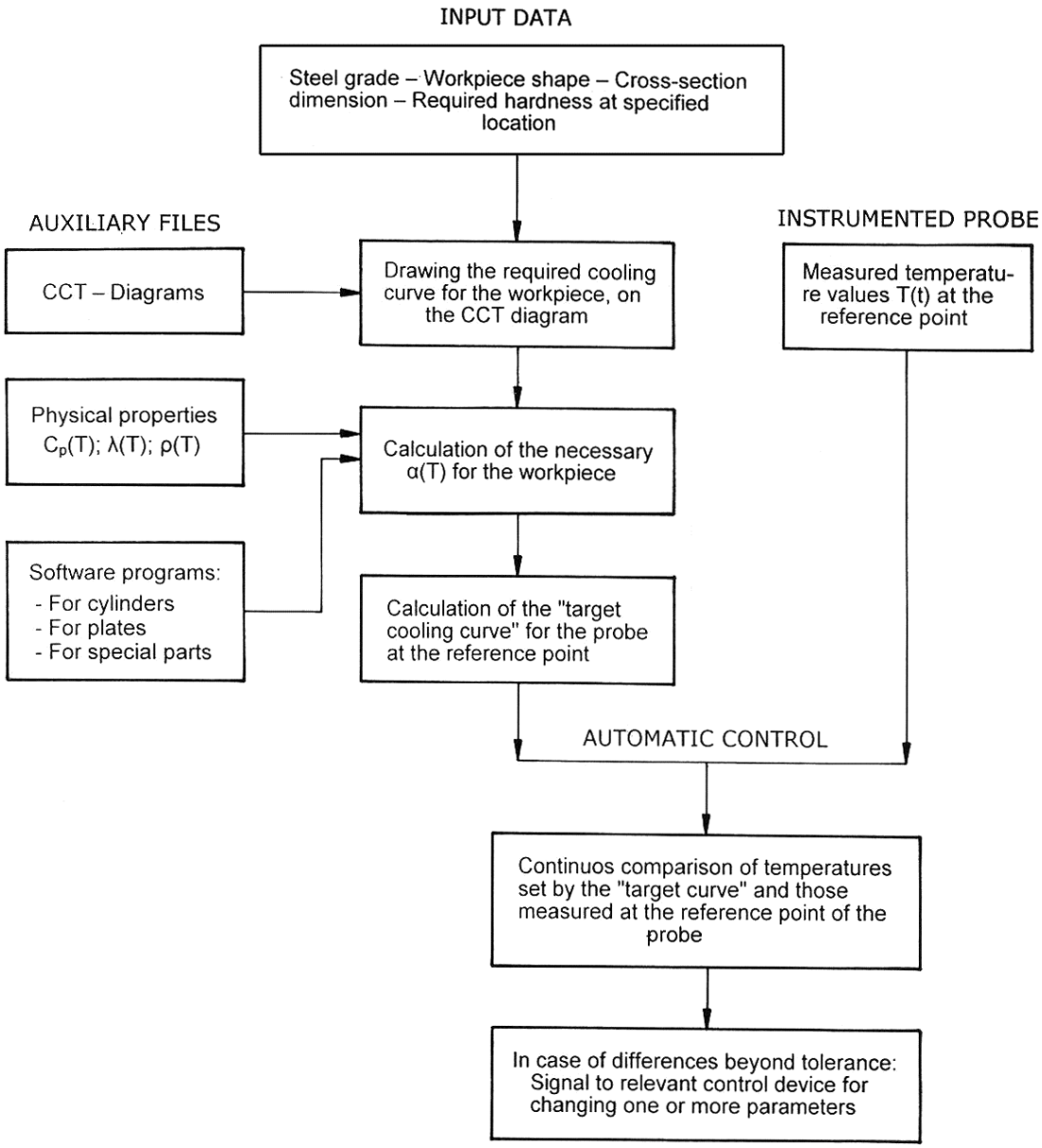

Fig.5. *Algorithm of automatic control of the heat exctraction during quenching of a batch of workpieces in vacuum furnace (Source: Liscic 2001.)*

In order to take into account the influence of the mass and loading arrangement of the batch, the probe should be put at a representative place within the batch (in standing or in laying position, as the workpieces are loaded), and heated and quenched together with the batch. Temperature at the reference point of the probe is measured during the whole quenching cycle, and compared with the calculated *target cooling curve.*

If during this comparison discrepances, beyond a certain tolerance arise, between the calculated *target cooling curve* and the measured cooling curve, a signal is automatically given to the device of the relevant cooling parameter, in order to increase or decrease the quenching intensity. The action of the relevant cooling parameter lasts only for the period until both cooling curves become equal.

5 Conclusion

Metals' quenching was a skill already in ancient civilizations, but through centuries it was a "black-box" operation. During the 20th century (and in many places even today) main consideration was given to the selection of the quenching medium itself, and to its specific quenching intensity (hardening power or severity).

Only after introduction of computer-assisted calculations, people started to look at the quenching process as a heat transfer problem, what every quenching process actually is. When calculating heat transfer coefficients it became clear that not only the cooling intensity of the quenching medium itself, but its temperature, its circulation velocity, the characteristics of the workpiece (its mass, shape, surface condition), loading arrangement and the mass of a batch, are factors having smaller or bigger influence on the heat transfer. Shortly after heat transfer calculations started it was noticed that not the awerage value of the heat transfer coefficient (α) of a quenching process is sufficient, but the heat transfer coefficient as a function of time α(t), or a function of workpiece's surface temperature α(T). Especially when quenching in evaporizable liquids, the value of the heat transfer coefficient changes through different stages even more than an order of magnitude. So it became evident that in real quenching operations not only the specific quenching intensity of the quenching medium (as it is measured in laboratory tests), but *the heat extraction dynamics*, is the main factor on which structural transformations and resulting hardness distribution on a workpiece's cross-section depends.

With introduction of high pressure gas quenching technology it became possible to intentionally influence *the heat extraction dynamics* by changing several parameters during the quenching process. Using simultaneously the stream of circulated gaseous nitrogen, with dispersed liquid nitrogen and an automatic control of several quenching parameters, enables to change the quenching process from a "black-box" operation to a controlled heat extraction process adapted specifically to the concrete batch of workpieces, which assures repeatable results of the hardness distribution, as well as of residual stresses and distortion respectively.

6 References

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[3] N.I. Kobasko: Basics of Intensive Quenching, *Advanced Materials & Processes 9/95*, p. 42W-42Y.