Computer process planning of induction hardening

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SUMMARY

Phases in setting up the induction hardening procedure have been discussed. For the exact definition of working parameters, computer simulation is recommended. For the axially symmetric work-pieces a special simulation program has been developed. Performance of the simulation program has been tested for the case of induction hardening of steel cylindrical work-piece. The measured values of surface hardness and hardening depths have been compared with the specified values, indicating good corespondence between the simulated and obtained values.

1. INTRODUCTION

Thin surface layer (0,25 to 2,5 mm) on certain location of a workpiece made of steel or cast iron is hardened by the induction hardening process. The hardened layer is characterized by improved wear resistance and contact resistance, while in the same time, properties of core are not changed. Formation of the hardened layer must not cause significant changes in shape and dimensions of the workpiece [1, 2]. Quality conduct of the induction hardening procedure should result in required pattern of hardened layer, specified surface hardness and hardening depth. All required properties of the hardened layer will be achieved only if the specific details of the process have been taken into the consideration even in the design stage of the workpiece and correct conduct of process has been provided. Process planning includes also design and fabrication of the induction coil of the best-suited shape and dimensions, and selection of exact process parameters. This calls for the mathematical modeling and computer simulation of physical phenomena in the workpiece.

Applying commercially available software and proprietary developed program packages preparation of the induction hardening process may be set up with acceptable accuracy, requiring only a very small trial batch (usually containing only several pieces).

2. SETUP OF THE INDUCTION HARDENING PROCEDURE

Process planning of the induction hardening includes following steps:

- ❑ analysis of material and workpiece suitability for the induction hardening process,
- ❑ selection of the hardening method (single shoot, rotation, scanning, rotation with scanning)
- ❑ design and fabrication of induction coil/inductor (with or without magnetic flux concentrator) and quenching ring,
- ❑ selection of the induction heating power supply (power rating, operating frequency,…)
- ❑ positioning of induction coil and quenching ring relatively to the workpiece,
- ❑ specifying of the process parameters:
  - ▪ selection of the temperature and time of austenitization (or/and scan speed)
  - ▪ selection of the quenchant and parameters of quenching

- definition of control and measured values and specification of acceptable tolerances (austenization temperature, coil current and voltage).

The mentioned features of process planning do not affect the results of the induction hardening in a unique way, and beside the knowledge and experience, significant time is required, resulting in the increased cost of the process itself. Until recently, mentioned steps meant application of time-consuming “trial and error” method, including series of hardening trials and metallographic testing. Modern process planning of the induction hardening in now is directed to significantly shorter and less expensive computer simulations, where most important physical phenomena in material are mathematically modeled (transfer of electromagnetic energy from inductor toward the workpiece, heating and cooling, microstructural processes in material, internal stresses and changes of dimensions) [2, 3]. Mathematical models for the listed processes are different, ranging from simple experience-based expressions for a single process to complex systems of equations for multiple processes that can be solved only through application of numeric methods and computer simulation.

2.1. Suitability of material and workpiece for the induction hardening

Careful consideration of materials selection, prior microstructure and geometric features of workpiece can reduce costs and time for process planning and production processing. Basic recommendations for correct design of workpieces intended for heat treatment, including induction hardening, have been known for years. In automotive industry, one of the biggest users of induction hardening, DFI concept (design for induction) has been emphasized in the recent years. It is an imperative that engineering staff in charge for development of the heat treatment has influence upon the part design and selection of materials and its original microstructure in early stage of component design process [4]. In order to set the requirements for the induction hardening unambiguously, data on the required workpiece properties (hardness, strength, depth of hardening, surface hardness, etc…) need to be clearly entered directly into the component drawing [5]. The requirement data refer always to final stage as given in example in Fig. 1.

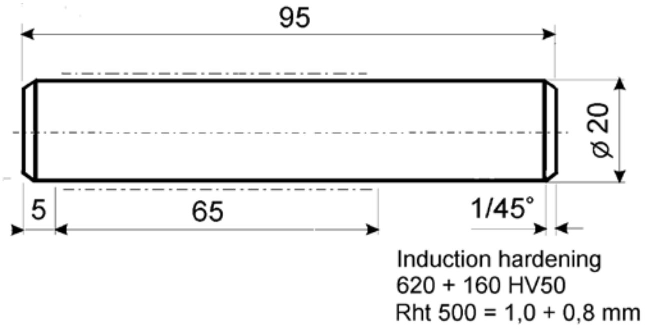

Figure **1.** Proper setting of induction hardening requirements

2.2. Design and fabrication of inductor coil and spraying ring

Properly designed induction coil must be able to produce hardened zone of required depth and shape, specified surface hardness at lowest possible energy losses, long service life, robustness to the allowable dimension deviations and positioning, low costs of fabrication, etc. Therefore, design of the induction coil is made in several steps, depending on whether it is design of a new coil, redesign of an existing inductor or development of a new one for a high-tech processes [6].

In design of a simple inductor (simple shape, without magnetic flux concentrator), mathematical modeling of transfer of electromagnetic energy and heating, aimed to check distribution of eddy currents and potential locations of workpiece overheating will be sufficient. In the case of HF induction hardening (f > 50 kHz), skin effect, effects of closely placed leads, effect of lead curvature, etc. should be taken into consideration. [1, 2, 6]. For design complex inductors, it is recommended to take into calculation, in addition to the mentioned effects, also mathematical modeling of microstructural transformations and residual stressing in the workpiece.

Basic modes of quenching at induction hardening include quenching in quench ring and immersion quenching in quench tank. Shape of the ring follows contour of the workpiece surface to be cooled. Ring is made as independent piece or integrated into the inductor. Design of the spaying ring must provide required cooling rate to ensure hardening of surface layer into specified depth, applying appropriate cooling agent and parameters (pressure, flow rate, temperature, concentration of polymer solution).

2.3 Selection of induction heating power supply

Modern induction heating power supplies are designed with power semiconductor units (thyristors, SCR), bipolar IGBT transistors (IGBT- Insulated Gate Bipolar Transistor) and MOS FET high voltage transistors intended for specified range of operating frequencies and power (Fig. 2.). Depending on their characteristics, they are applied for particular cases. Medium and high frequency power sources are more suitable for smaller depth of hardening. On the other hand, medium and low frequency power sources are more appropriate for deeper hardening, annealing and preheating [2].

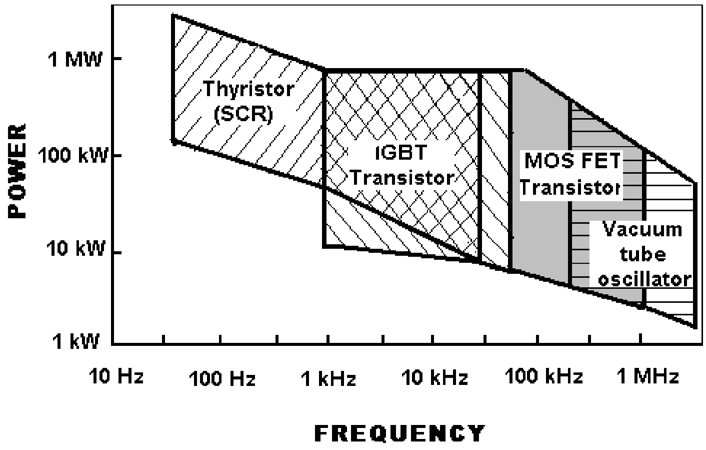

Figure **2**. Operating frequencies and power of modern induction heating power supplies [2].

Application of SCR thyristor power sources is limited to low frequency (<10 kHz) induction hardening processes for induction hardening depths exceeding 3 mm and for full hardening of smaller diameter workpieces. In design of induction hardening cells, there is a trend to replace the SCR power sources with IGBT sources.

IGBT power sources are characterized by better efficiency (approximately 85%) when compared with SCR units (approximately 75%) and wider operating frequency range (1-100 kHz). They can provide hardening depth of 2,5 mm.

Power sources outfitted with high voltage MOS FET transistors are less frequently used in design of induction hardening cells because their sensitivity to voltage drops in mains supply and higher price per kW of output power when compared with other power sources.

Induction power sources with vacuum tube oscillators are characterized by lower power efficiency (50-65%) than IGBT power sources, and need high operating voltage (>10 kV), but are most reliable in operation. High operating frequencies (> 0,5 MHz) are suitable for application where low depth induction hardening is required (less than 1,5 mm) and for workpieces containing sharp edges and thin walls. In such cases application of semiconductor induction power sources is precluded.

2.4. Setup of the operating parameters of the process

For the exact setup of operating parameters of the process and prediction of microhardness distribution in the hardened layer (eventually including the distribution of the internal stresses), all electromagnetic, thermodynamic and microstructural processes within the workpiece must be related by a certain algorithm (Fig. 3).

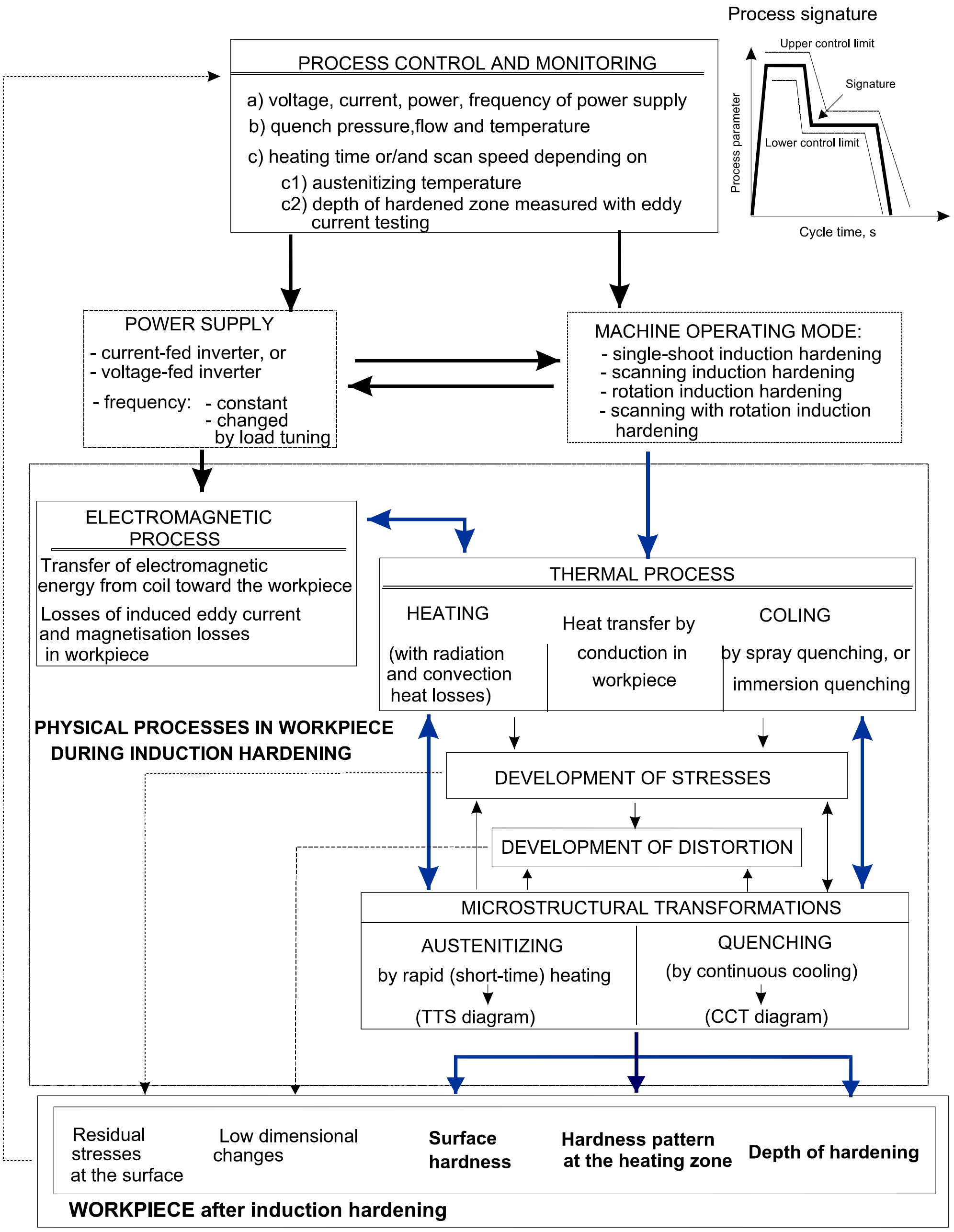

Figure **3**. Basic processes in the induction working cell and changes effected on the workpiece.

Depending on the complexity of the problem, size of batch, available time and allowed costs or process planning, one of the three levels of mathematical modeling is applied. Within the first level, approximate one-dimension mathematical model of electromagnetic processes is applied (using analytical or numeric equations), eventually including model of heat conduction within the work-piece. At the two-dimension level, electromagnetic, thermodynamic and microstructural processes in long or axially symmetric work-pieces are considered. Computer simulation of the three-dimensional mathematical model for all mentioned physical processes is applied for complex parts and high-tech procedures [3].

For less complex shapes of workpieces analytical expressions and/or numerical methods are used (method of finite differentials and method of control volumes). For more complex shapes of work-pieces, in 2D or 2d mathematical models methods of finite elements and/or method of boundary elements /2/ are applied [2].

For the simulation of cooling, heat transfer coefficient (α_G, W/m^{2}K) must be known. When iron materials are cooled, coefficient is most effectively related to the type of cooling medium (pure water, water solution of polymers), surface temperature, type of material to be cooled and impingement density (m_0, kg/m^{2}s), but some other conditions related to design of spraying ring and selection of operating parameters should not be overseen [7].

Design of specialized simulation programs requires full knowledge of mathematical modeling of induction hardening process, theory of physical processes that occur and engineering numerical methods. Therefore, rather simplified simulation programs are made most often (for “daily use”). They are produced by specialized companies and research institutions, frequently in cooperation with industrial users. Since application of such programs calls only for basic knowledge of the process, technologists responsible for heat treatment can successfully use them in everyday practice [3].

2.5. Measuring and control system of a induction hardening cell

Systems for control of the induction hardening process (with microprocessor or PLC controls) are based on the concept of the parameters signature in real time. Parameters are recorded by the monitoring devices. For a great majority of induction hardening applications, four signatures are sufficient to define the process (load power, scan speed, rotation speed and quench pressure of quench flow [2]. In majority of induction hardening cells, only scan speed (i.e. heating time) and load power is controlled (Fig. 4). Other possible control variables are kept at constant level. Most frequently measured values are operating power of inductor (i.e. current, voltage and power efficiency of inductor) and surface temperature of work-piece.

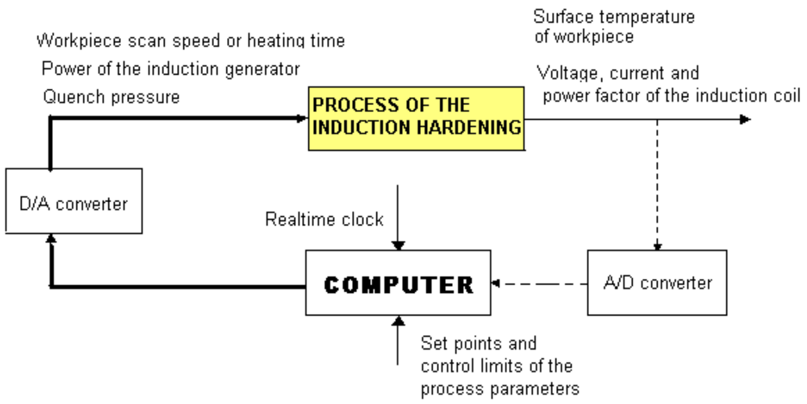

Figure **4**. Simplified diagram of control system for monitoring the induction hardening process.

At measurement of the operating power delivered by inductor, it should be taken into consideration that phase angle (cos φ) between vectors of voltage (U) and current (I) is changed, rather than their absolute magnitudes (i.e. effective values). Operating power of the inductor is:

$$P = U\, I\, cos\varphi \tag{1}$$

This means that exact measuring of all three values is required (U, I, cos φ). Measurement of current and voltage calls for application of measuring transformers with ferrite core and two channel digital oscilloscope able to record simultaneously time changes of current and voltage as well as the phase shift. Effective values of I and U are then calculated from the recorded curves $i=i(t)$ and $u=u(t)$.

Surface temperature of the workpiece is usually measured with optic or infrared pyrometers or heat radiation detectors. When selecting pyrometer or detector, it should be taken into consideration that spot of small diameter (<2mm) and fast response (<1s) is measured in semi-transparent environment (evaporation of oil and water from the surface), on a part that is rotating and/or is moved, surface of which has changeable emissivity coefficient. Optic pyrometers with accuracy of ± 2% will be sufficient for process control, but if more precise measurements are required (0,5-1,0%), infrared pyrometers are recommended [1]. Modern pyrometers provide digital reading of measured temperature, correction of surface emissivity, auto-focusing and linking to the process controlling and monitoring system.

3. OWN RESULTS

The marked surface of a cylinder (Fig.1), made of 42CrMo steel grade should be hardened to depth of 1+0.8 mm. The cylinders were hardened applying scanning with rotation method. Workpieces were heated using vacuum tube power supply (frequency 410 kHz, power rating 50 kW). Since the austenitizing temperature depends significantly on the heating rate, these two conditions for originating normalized structure of 42CrM4 steel grade have been selected from the references [8]. For the specified heating rate of 100-300 K/s, required austenitizing temperature is 850 ^{o}C. This steel grade also must be cooled at lover cooling rate to avoid occurrence of surface cracking. Therefore, quenching is made applying 17% water solution of PAG at impingement density of 8,77 kg/m^{2}min. Spraying ring was located 5 mm below the inductor.

Simulation of the hardening process has been made applying proprietary computer program developed for axially symmetric parts. The boundary elements method was used for modeling transfer of electromagnetic energy. Simulation of heat conducting into the workpiece, iterative monitoring of austenite rate formed on fast heating and analytic model for prediction of microhardness distribution was made applying finite elements method. Through the number of dialog frames, the user specifies geometry of part, its position within the inductor and spraying ring, main starting parameters and accuracy criteria.

Simulation has been made applying several different scan speeds within range 4 and 10 mm/s, supposing operating power of source within range 15 and 45 kW. Target was to establish the combination of parameters that will produce required depth of hardening and surface hardness. Simulation yielded two sets of possible operating parameters:

a) power rating 30 kW at scan speed 4 mm/s,
b) power rating 45 kW at scan speed 10 mm/s

With each set of listed parameters (a and b), trial hardening was made, each series containing 3 specimens. Specified power rating of source was verified by measurements of current and voltage on the anode of vacuum tube and recording the time changes of current and voltage in inductor (Fig. 5). The listed parameters (power, scan speed, quench intensity were kept at the constant level during the induction hardening process.

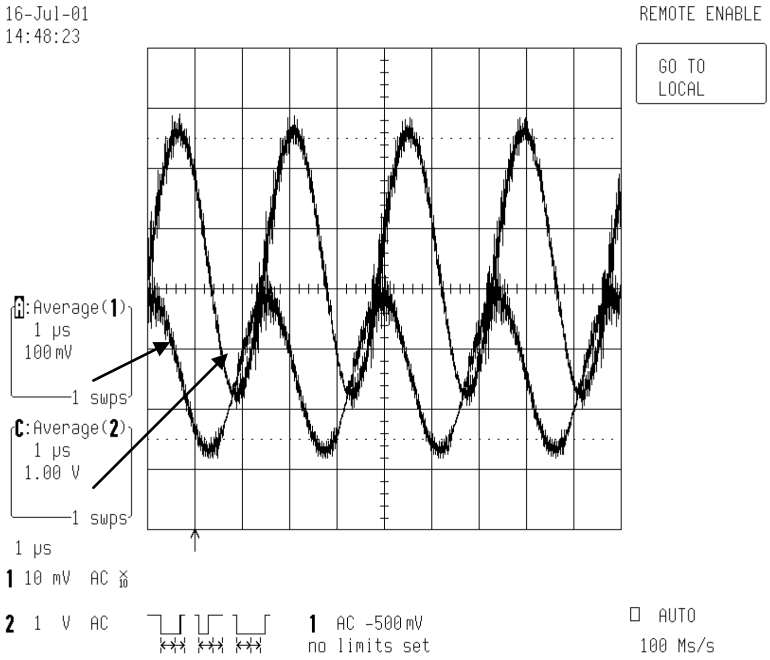

Figure **5.** Time changes of coil voltage (curve **1**, measurement transformer ratio 1:100) and coil current (curve **2**, measurement transformer ratio 1:1000) at induction hardening process for given power rating of 45 kW (measured DC values at the vacuum tube anode: voltage - 9,5 kV, current - 4,4 A).

Rockwell C method for testing of surface hardness has been used for all induction hardened cylinders. Measured values were 57 +2 HRC (equivalent to 640 –675 HV according DIN 50190). Distribution of hardness across the depth of hardened layer was tested on the metallographically prepared cross-sections of cylinders applying Vickers method with 9,81 N load (HV 1), Fig. 6.

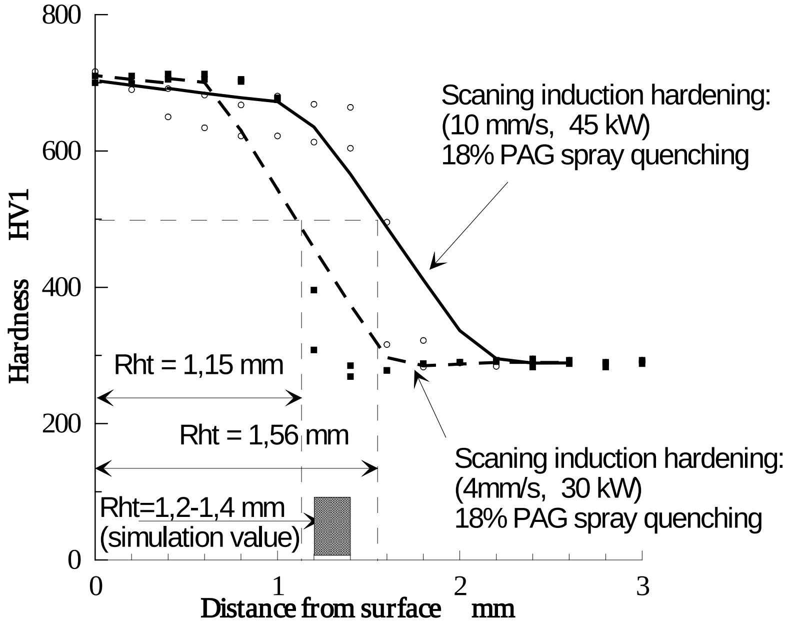

Figure **6**. Distribution of hardness in the transversal cross-section of induction hardened cylinders (diameter 20 mm) made of 42CrMo4 steel grade applying different parameters (f = 410 kHz)

From Fig. 6 it may be noted that both sets of parameters results in similar distribution of hardness. In both cases, hardness of approximately 690 HV1 was achieved at the surface. Micrographic investigation has revealed martensitic microstructure in the edge layers. Though the applied sets of parameters produced different hardening depths, both values meet the required specification.

4. CONCLUSION

Quality preparation of induction hardening process is a necessary condition for realization of specified properties of hardened part. It includes detailed analysis of specified requirements, design and manufacturing of inductor and spraying ring and setup of all necessary parameters of process. Because of complex phenomena within the workpiece during the induction hardening process, setup of necessary operating parameters may be a major problem. Currently, this problem may be solved more efficiently and faster than in past applying specialized simulation programs.

By development of proprietary simulation program intended for less complex axially symmetric parts one condition for better preparation of induction hardening process has been provided. The simulation program has been tested for the case of a simple cylindrical part, and achieved results were within limits of acceptable deviations. Further investigation should be directed to enhancement of the simulation program for the more complex axially symmetric parts.

6. REFERENCES

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