© Strojniški vestnik 45(1999)7/8,267-277 © Journal of Mechanical Engineering 45(1999)7/8,267-277
ISSN 0039-2480 ISSN 0039-2480
UDK 621.785.6:681.51 UDC 621.785.6:681.51
Predhodna objava (1.03) Preliminary paper (1.03)

Razvoj modela procesa in strukture krmilnega sistema delovne enote za indukcijsko kaljenje

The Development of a Model for the Process and Structure of a Control System for an Induction Hardening Cell

Franjo Cajner - Josip Grilec - Darko Landek

Da bi dosegli kakovostnejše in bolj prilagodljivo izvajanje postopka indukcijskega kaljenja, je potrebna računalniško podprta priprava in krmiljenje procesa. Prispevek opisuje in določi model procesa indukcijskega kaljenja, s katerim, ob zahtevanih parametrih postopka, dosežemo predpisano kakovost zakaljenega sloja. Nadalje obravnava vplivne dejavnike, ki opredelijo in uvajajo krmilni sistem, s katerim vodimo proces indukcijskega kaljenja v prilagodljivi delovni enoti.

(Ključne besede: kaljenje induktivno, modeliranje procesov, sistemi krmilni, celice fleksibilne)

In order to achieve higher quality and a more flexible execution of the induction hardening process, a computer assisted program for undertaking and controlling of this process is needed. This paper proposes and describes a model for the induction hardening process, the application of which achieves a specified quality of the hardened layer, within all the parameters of the process. All the influencing factors, which define and implement the control environment used in the application of the process within the flexible working cell, are systematically analyzed.

(Keywords: induction hardening, process modelling, control systems, flexible cell)

0 UVOD

Indukcijsko kaljenje je postopek površinske toplotne obdelave, med katerim se, zaradi elektromagnetne indukcije, tanek površinski sloj na določenih površinah jeklenega obdelovanca hitro segreva do temperature avstenitizacije, nato pa se z gašenjem doseže želeni martenzitna mikrostruktura in trdota. S tem se zagotovi obrabna odpornost torno obremenjenih površin obdelovanca brez strukturnih sprememb v jedru obdelovanca ([1] do [3]).

Da bi dosegli želene lastnosti, mora biti površinski sloj predpisane oblike, predpisana pa sta tudi globina kaljenja in površinska trdota. Pri tem ne sme priti do sprememb izmer in oblike obdelovanca. Za dosego teh zahtev je treba razviti [4]:

- matematični model za optimizacijo oblike induktorjev in simuliranje procesa,
- ustrezno bazo podatkov za spremljanje lastnosti materiala in delovnih karakteristik opreme,
- krmilne algoritme procesa za določen material, geometrijsko obliko obdelovanca in enofrekvenčno (ali dvofrekvenčno) obdelavo, ki omogoča želeno kakovost zakaljenega sloja.

0 INTRODUCTION

Induction hardening is a process by which thin surface layers, at specified areas of the steel workpiece, are heated rapidly to an austenitization temperature by electromagnetic induction, and the desired hardness and the martensitic structure is achieved by quenching. Thus, at the workpiece's contact surfaces the wear resistance is achieved while allowing the rest of the material to be unaffected by the process ([1] to [3]).

To achieve these properties the hardened surface layer has to be of a predefined shape, predefined depth of quench hardening and predefined surface hardness. To meet these requirements and produce quality results, it is necessary to develop [4]:

- computational models for the optimal shape of inductors and for the simulation of the process,
- appropriate database systems for observing the properties of the material and the working characteristics of the machinery,
- control algorithms for the application of the process to a given material, to the geometric shape of the workpiece and to the monofrequency (respectively dualfrequency) treatment, which will result in the desired quality of the hardened layer.

V članku so prikazana načela in osnutek bodoče programske podpore projektiranju tehnologije indukcijskega kaljenja, posebej za obdelovance zahtevnejših oblik. Podan je prikaz nadzornega in diagnostičnega algoritma, ki omogoča povezavo z generatorjem, obdelovalnim sistemom, sistemom za gašenje in krmilnim sistemom za prilagodljivo delovno enoto.

1 OSNUTEK RAZVOJA PROGRAMA ZA SIMULIRANJE IN OPTIMIZACIJO INDUKCIJSKEGA KALJENJA

Podatke o materialu in izmerah obdelovanca ter podatke o induktivni delovni enoti je najbolje organizirati v modularno povezane operativne in povezovalne baze podatkov. Računalniški programi, ki se uporabljajo za obdelavo tovrstnih podatkov, že obstajajo in so lahko dostopni. Za uporabo simulirnega programa indukcijskega kaljenja in programa za optimizacijo oblike induktorja so potrebne tri operativne baze podatkov:

1. baza podatkov o tehničnih značilnostih in vzdrževanju indukcijske delovne enote;
2. baza podatkov o lastnostih materiala;
3. izhodiščna tehnološka baza, tj. uspešno izvedenih in preverjenih optimizacij za posamezne materiale in obdelovance.

Izvedensko znanje o procesu indukcijskega kaljenja in rešenih tehnoloških primerih je shranjeno v izhodiščni tehnološki bazi. V njo se po uspešni optimizaciji induktorja ter simuliranja indukcijskega kaljenja shranijo podatki o obliki in izmerah induktorja, parametrih segrevanja in ohlajanja ter rezultati metalografske analize preskušanca. S tem se ob vsakem reševanju problemov pri indukcijskem kaljenju razširi in poglobi znanje, kar vpliva na proces učenja in pridobivanje izkušenj.

Algoritem za numerično simuliranje indukcijskega kaljenja in optimizacijo induktorja (sl. 1), je definiran na podlagi vpogleda v poročila in rezultate uporabe posameznih komercialnih in raziskovalnih simuliranj programa ([3] do [5]).

Kakovost indukcijsko zakaljenega sloja - zaradi katere se izvaja simuliranje procesa in optimizacija induktorja - je definirana z obliko zakaljene cone, globino kaljenja in s površinsko trdoto.

Vhodne veličine simulirnega programa morajo zbirati najpomembnejše vplive, ki odločajo o kakovosti zakaljenega sloja. Popis vplivov in njihov učinek na posamezne lastnosti sloja je prikazan v preglednici 1. Optimizacijski algoritmi, ki naj bi bili vgrajeni v omenjeni program, bodo upoštevali vplivnost navedenih dejavnikov in opozarjali uporabnika na njihovo ustrezno uporabo.

This paper describes the principles and the concept for a future system support program for the design of induction quench hardening technology. It focuses in particular on the hardening of complex shapes. Furthermore, it illustrates the control and the diagnostic algorithm that enables linking of the power supply, the workhandling system, the quenching system and the process control and monitoring system in the flexible work cell.

1 THE CONCEPT OF PROGRAM DEVELOPMENT FOR THE SIMULATION AND OPTIMIZATION OF INDUCTION HARDENING

It is important to organize all the data relating to the material, about the dimensions of the workpiece to be treated and the induction work cell, into a modular and operationally related database. Readily available computer programs already exist for the design of such data. To use the induction hardening simulation program as well as the inductor shape optimizing program, three operational databases are necessary.

1. A database relating to the technical characteristics and maintenance of the induction work cell.
2. A database of material properties.
3. A technological initialization base, i.e. of successfully carried out and verified optimization for single materials and workpieces.

Expert knowledge about the induction hardening process and case by case technical solutions are stored in the technological initialization base. After successfully completing the optimizing of the inductors, and the simulation of induction hardening, the following data are then fed in to the technological base: details about the shape and the dimensions of the inductor, the heating and cooling parameters, and the results of the metallographic analysis of the experimental sample. Thus, with each solution to problems that relate to the induction hardening, the knowledge system grows and improves and acquires more elements of technical expertise.

The algorithm for a numerical simulation of the induction hardening and the optimization of the inductor is defined on the basis of information received from individual research and commercial simulation programs ([3] to [5]) (Fig. 1).

The quality of the induction hardened layer - the assurance of which is the reason for undertaking the simulation of the process and the optimization of the inductor- is defined by the shape, the depth and the surface hardness of the quench hardened zone.

The initial scope of the simulation program must include the factors which most influence the quality of the quench-hardened layer. These factors and their significance with respect to individual cases are listed in Table 1. During the development, optimizing algorithms will be included into the above mentioned program and will take into consideration the influence of the specified factors, so the user will be well informed about their adequate use.

Ob začetku izvajanja simuliranja je treba določiti porazdelitev vira toplote (spremenljivo v času in prostoru) z reševanjem elektrodinamičnih enačb magnetnega polja pri podanih robnih pogojih. Postavljeni model obsega obdelovanec, induktor in zračno režo med njima.

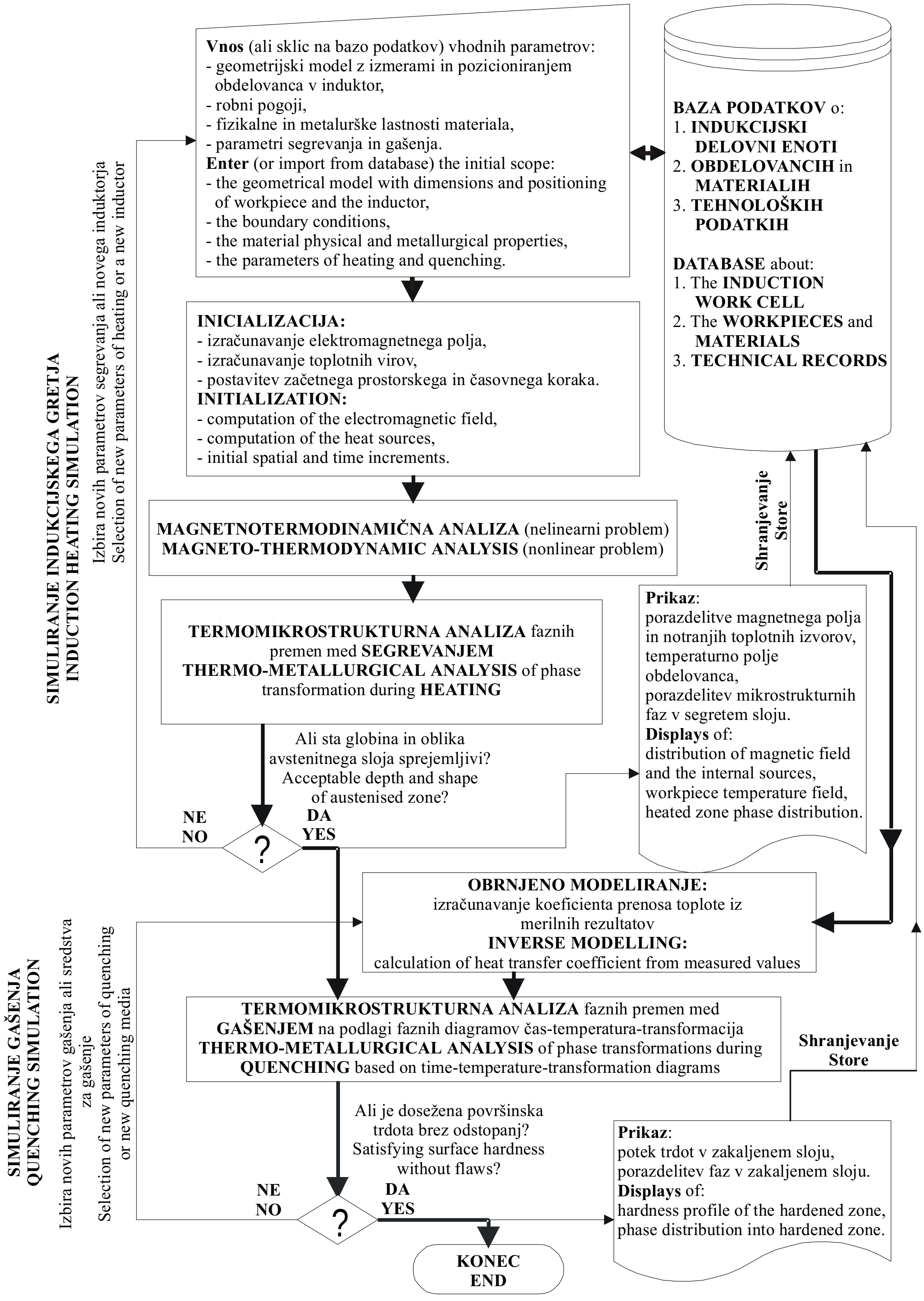
Začetna porazdelitev polja toplotnega vira pomeni vhodno spremenljivko za izračun neustaljenega temperaturnega polja in z njim povezanih faznih premen v času pregrevanja. Spremenljive fizikalne lastnosti materiala, ki so odvisne od temperature, so v modelu popisane z ustreznimi interpolacijskimi temperaturno odvisnimi zlepki, ki izhajajo iz rezultatov prejšnjih preskusov ali iz literature. Omenjena odvisnost lastnosti od temperature vnaša nelinearnost v magnetno-termodinamičen proces, kar terja iterativno izračunavanje razvite moči z uporabo numeričnih metod (npr. metodo končnih elementov, metodo robnih elementov) ([3] do [7]).

At the start of the simulation procedure the heat source distribution (variable according to time and place) should be determined by solving the electrodynamic magnetic field equations for the established boundary conditions. The corresponding model includes the workpiece, the coil and the air gap.

The initial distribution of heat sources represents the input variable for the computation of the nonstationary temperature field and the interacting phase transformation during heating. The changeable physical properties of the material which depend on temperature are included in the model via corresponding spline temperature dependent functions, derived from experiments or literature sources. The dependence of properties on temperature produces nonlinear data in the magneto-thermal procedure, thus necessitating iterative calculations of the dissipated power using numerical methods (i.e. Finite Element method, Boundary Element Method etc.) ([3] to [7]).

Preglednica 1. *Veličine, ki vplivajo na obliko zakaljenega sloja, globino kaljenja in potek trdot po zakaljenem sloju in jih popisujejo vhodni parametri simulacijsko optimizacijskega modela*
Table 1. *Influencing factors on the appearance of the quench-hardened area, the depth and hardness of the hardened area included in the initial scope of the simulation optimizing model*

VPLIVNE VELIČINE kot VHODNI PARAMETRI MODELA **INFLUENCING FACTORS as THE INITIAL SCOPE OF THE MODEL**	**PARAMETRI, KI OPREDELJUJEJO KAKOVOST ZAKALJENEGA SLOJA CHECK MARKS OF THE QUENCH-HARDENED ZONE**		
	Oblika zakaljenega sloja Shape of the zone	Globina kaljenja Depth of hardness	Trdota površine Surface hardness
Oblika in izmere obdelovanca The shape and dimensions of the workpiece	**X**		
Kemijska sestava materiala Chemical composition of the material		**X**	**X**
Toplotne lastnosti materiala obdelovanca Thermal properties of the workpiece material	**X**	**X**	
Električne in magnetne lastnosti materiala Electrical and magnetic properties of the material	**X**	**X**	
Temperatura avstenitizacije pri hitrem segrevanju Austenitizing temperature due to rapid heating Zgornja kritična hitrost gašenja Upper critical quenching speed		**X**	**X**
Poprejšnja toplotna obdelava in izhodiščna mikrostruktura Previous heat treatment and initial microstructure	**X**	**X**	**X**
Postopek indukcijskega kaljenja Method of induction hardening	**X**		
Lega induktorja glede na obdelovanec Workpiece to induction coil location	**X**	**X**	
Izhodna oblika, izmere in material induktorja The initial shape, dimensions and material of the inductor	**X**	**X**	
Delovna frekvenca Working frequency	**X**	**X**	
Moč, napetost in tok induktorske tuljave Power, voltage or current of the induction coil	**X**	**X**	
Čas segrevanja ali premik obdelovanca Heating time or the scan speed of the workpiece	**X**	**X**	
Podatki o gašenju (sredstvo, temperatura, čistost in koncentracija) Quench data (media, temperature, purity, concentration)		**X**	**X**
Pretok ali tlak sredstva za gašenje Flow or pressure of the quench media Koeficient toplotne prestopnosti Heat transfer coefficient		**X**	**X**



Sl.1. *Algoritem simuliranja indukcijskega kaljenja*
Fig. 1. *Induction hardening simulation algorithm*

Da bi določili doseženo globino avstenitizacije, izračunamo temperaturno polje z upoštevanjem faznih premen pri hitrem segrevanju v časovno-temperaturnem diagramu avstenitizacije (TTS) pri podanem izhodiščnem mikrostrukturnem stanju. Če je dosežena globina pregretja neustrezna, se znotraj določenih meja najprej spremenijo parametri segrevanja (delovna moč induktorja, trajanje, pomik), šele nato spremenimo velikost in obliko induktorja.

Z upoštevanjem temperaturne porazdelitve po procesu segrevanja, se izvedeta simuliranje in optimizacija gašenja. Za natančnejše določanje hitrosti ohlajanja je treba poprej razrešiti inverzni termodinamični problem [6] in izračunati spremembo koeficienta prestopa toplote α (W/m^{2}K) v odvisnosti od temperature. Z uporabo faznih diagramov TTT in enačb fazne kinetike se izračunajo krivulje ohlajanja in po njih nastala mikrostruktura in njena trdota. Ta postopek je uporaben v primeru enojnega indukcijskega kaljenja. Za simuliranje je treba hkrati analizirati indukcijsko kaljenje, segrevanje in hlajenje.

Zaradi napak v izračunavanju lastnosti materiala in nenatančnosti matematičnega modela procesa, je potrebna eksperimentalna potrditev modela. Izvedemo jo s snemanjem časovnega spreminjanja temperatur med procesom in z merjenjem dosežene mikrostrukture in trdot po kaljenju. Pred podrobno raziskavo in optimizacijo postopka za novo obliko obdelovanca in induktorja je priporočljivo potrditi model [7]. Overitev ni potrebna, če uporabimo podoben induktor ali obdelovanec. Modeliranje in simuliranje je priporočljivo izvajati s posebnim programom, ki ga lahko razširimo z lastnimi moduli.

Za vsakdanjo tehnično uporabo in preliminarne raziskave zadostujejo enodimenzionalni računalniški programi (samo za reševanje elektromagnetnih in termodinamičnih problemov). Drugi korak simuliranja se izvaja z dvodimenzionalnimi in tridimenzionalnimi programi, ki so natančnejši pri načrtovanju in simuliranju [7]. Uporaba računalniških programov ne izključuje sodelovanja s tehnologom za indukcijsko kaljenje, ki mora uporabljati lastne izkušnje in intuicijo med izvajanjem kritičnih progamskih korakov (posamezni izbor po ustrezni analizi). Na ta način dosežemo optimalno temperaturno in mikrostrukturno porazdelitev v najkrajšem času in z najmanjšo potrebno močjo. Po določitvi geometrijske oblike induktorja, vrste sredstva za gašenje in intenzitete gašenja, se parametri indukcijskega kaljenja shranijo v bazo podatkov za krmiljenje procesa in izhodiščno tehnološko bazo.

Izstopne veličine simulacijsko-optimizacijskega programa, ki se hkrati postavljajo kot referenčne veličine krmiljenja, so prikazane v preglednici 2.

In order to determine the achieved depth of austenitization, the temperature field must be calculated. All the phase transformations, according to the Time-Temperature-Austenitizing diagrams, for a given initial microstructure must also be taken into account. Should an unsatisfactory depth of austenitisation be reached, initially the parameters which relate to heating (the power, voltage or current of the induction coil, the heating time, or scan speed) would be modified, within their boundaries. Should these modifications prove inadequate, the size and the shape of the inductor must be altered.

Starting from the temperature distribution after heating, the quenching phase is simulated and optimized. In order to exactly establish the rate of cooling, after solving the inverse thermodynamic problem first, the alteration of the heat transfer coefficient α (W/m^2 K) which depends on the temperature has to be calculated [6]. The cooling curves are calculated using the phase transformation and the phase kinetics Time-Temperature-Transformation diagrams. This procedure is suitable in the case of single-shot induction hardening. For simulation the scanning induction hardening, heating and cooling must be analyzed simultaneously.

Because of errors in the calculation of the properties of the material and a faulty mathematical model of the process, an experimental confirmation of the model, by recording the time-sequence temperatures during the process as well as the obtained microstructure and hardness after treatment, becomes necessary. It is advisable to verify the model before any detailed research and optimization of the procedure for a new shape of workpiece or inductor is undertaken [7]. This is not necessary for a similar inductor or workpiece. To execute a new model or simulation it is advisable to use a special software program which is expanded with self-development modules.

For everyday technical use and preliminary research 1-D computer programs are adequate (for solving only electromagnetic-thermodynamic problems). The next simulation step is done via 2-D and 3-D programs for better predictability and a more accurate simulation. The use of computer programs does not, however, exclude the induction hardening technician, who must rely on his experience and intuition (making choices after adequate analysis), in the critical programming steps, to achieve the optimal temperature field and microstructure distribution at the surface layer, in the shortest time with the minimum consumption of power. After the inductor geometry has been determined, the parameters of the induction quench hardening are stored into the process control database and the technological initialization base data.

The application range of the simulation-optimization program, which is also used as the reference range for the controller, is illustrated in Table 2.

Preglednica 2. *Izstopni parametri optimizacijsko simulacijskega programa, ki so hkrati krmiljene veličine med izvajanjem procesa indukcijskega kaljenja in mesta merjenja teh parametrov*
Table 2. *Application range of the simulation-optimization program also used as the range of control in the induction hardening process and their measuring points*

IZSTOPNE KRMILJENE VELIČINE **APPLICATION CONTROL SCOPE**	**Generator in induktorska tuljava** **Power supply and inductor coil**	**Vpenjalni in pomični sistem** **Workhandling system**	**Sistem za gašenje** **Quenching system**	**Obdelovanec** **Workpiece**
Lega obdelovanca v induktorski tuljavi Position of workpiece within the induction coil		**X**		
Vhodna moč induktorske tuljave Induction coil input power	**X**			
Tok in napetost induktorske tuljave Coil current or voltage	**X**			
Čas segrevanja Heating time	**X**			
Hitrost pomika obdelovanca Workpiece scanning speed		**X**		
Koncentracija in čistost sredstva za gašenje Concentration and purity of the quench media			**X**	
Tlak in pretok sredstva za gašenje Quench media flow and pressure			**X**	
Temperatura sredstva za gašenje Quench media temperature			**X**	
Površinska temperatura obdelovanca po postopku gretja Workpiece surface temperature after heating process				**X**
Globina zakaljenega sloja, ki jo izmerimo z vrtinčnimi tokovi Depth of workpiece surface hardening verified by eddy current testing				**X**

2 KRMILNI SISTEM DELOVNE ENOTE ZA INDUKCIJSKO KALJENJE

Računalniško podprt krmilni sistem je zasnovan na merjenju krmiljenih parametrov procesa in primerjavi z referenčnimi parametri. To je osnutek krmiljenja procesa s t.im. “zapisom procesnih parametrov” (procesni diagrami) optimalno izvedenega procesa. Če kateri od opazovanih parametrov izstopi iz tolerančnega polja, krmilnik signalizira stanje procesa in zahteva njegovo prilagoditev referenčnemu procesu. Znotraj tolerančnega polja krmilnik sam usklajuje potrebne parametre procesa [8].

Pri indukcijskem kaljenju se dandanes, tako kakor pri drugih običajnih postopkih kaljenja, za krmiljenje moči induktorja, premik obdelovanca (ali induktorja) in parametre gašenja, uporabljajo programljivi logični krmilniki (PLK). Običajno se opremi za indukcijsko kaljenje doda večji mikroprocesor. Referenčni (krmilni) parametri in preostali podatki, potrebni za delovanje enote za

2 THE OPERATING SYSTEM OF THE INDUCTION HARDENING CELL

The computer driven control system is based on the comparison between the range of tolerances of the process and the size of the frame of references. This is the process conducting concept according to the so called “recorded process range” (process diagrams) of the optimally conducted procedure. As soon as one of the elements of the observed range steps out of the field of tolerances, a controller signals the status of the procedure and instructs its adaptation to the process frame of references [8].

The execution of induction as well as conventional hardening processes use programmable logical controls (PLC) for the operation of the power of inductor, the mobility of the workpiece and the parameters of quenching. It is customary to add to the induction hardening equipment a host-microprocessor. The operating range and other information for the functioning of the system are programmed into the operation database. They are programmed indukcijsko kaljenje, so shranjeni v operacijski bazi podatkov, iz katere jih v realnem času in po potrebah nadziranja procesa razbira enota PLK. Zaradi obdelave signala na digitalnem računalniku morajo biti analogni parametri poprej spremenjeni v digitalne z uporabo A/D pretvornikov na kartici PLK.

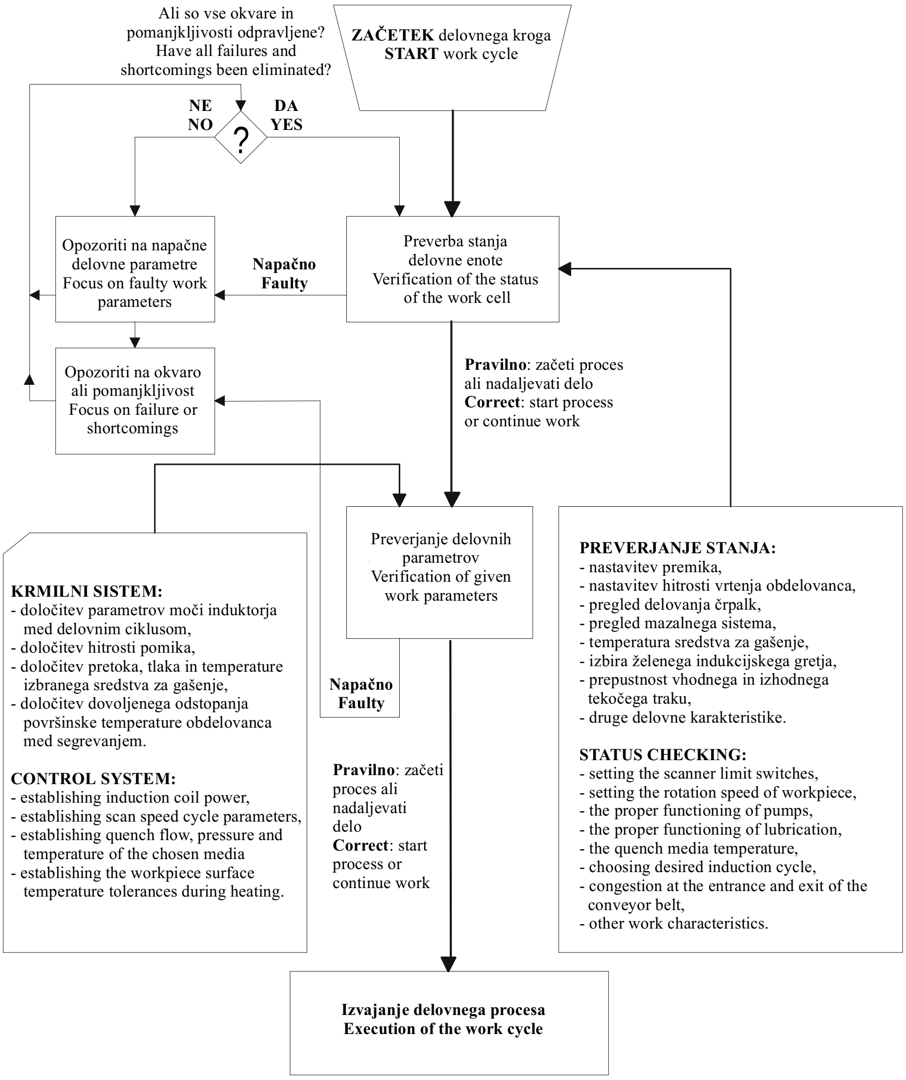
2.1 Diagnostika procesa

Pred začetkom delovnega kroga je treba overiti stanje in delovne parametre vseh podsestavov delovne enote. V primeru manjših in starejših delovnih enot diagnostiko procesa izvaja operater enote. Ob izvajanju poprej računalniško simuliranega indukcijskega kaljenja je nujno potrebno avtomatsko krmiljenje delovnega kroga ob spremljanju minimalnega števila delovnih parametrov na zaslonu (video display terminal - VDT). Primer tipičnega avtomatskega diagnostičnega algoritma delovne enote za indukcijsko kaljenje za delo v avtomatski proizvodni liniji prikazuje (slika 2) ([8] in [9]).

into the PLC according to the real time needed for the execution of the procedure. Because of the computation of the signal on a digital computer (measurable information in the feedback), analog signals have to be first converted into digital via an analog/digital converter-card on a PLC.

2.1 Process diagnostic

Before the start of the work cycle, it is necessary to verify the condition and the functionality of all the supporting parts of the work cell. In the case of smaller and older work cells the diagnostic work is performed by the operator of the cell. To first conduct a computer simulation of the induction hardening process, an automated work cycle has to be initiated observing the minimal number of operating functions on a VDT (video display terminal). A typical diagnostic algorithm for an induction hardening work cell, designed for an automated production line, is shown in Fig. 2 ([8] and [9]).



Sl. 2. *Diagnostični algoritem za indukcijsko delovno enoto*
Fig. 2. *Representation of the diagnostic algorithm for the induction work cell*

Pred začetkom delovnega kroga diagnostični sistem preveri stanje delovne enote in izvede primerjavo znanih parametrov z vnesenimi. Primerjava se izvaja tudi med procesom kaljenja. Če odstopanja parametrov presežejo vnaprej določene meje, sistem obvesti operaterja in zahteva njegovo posredovanje pri reševanju nastalega problema.

2.2 Krmilni algoritem

V večini delovnih enot za indukcijsko kaljenje nadzorujemo dva parametra: relativni premik med induktorjem in obdelovancem ter moč indukcijskega generatorja. Drugi parametri enote ostanejo nespremenjeni oziroma jih skušamo ohranjati nespremenjene. Krmiljenje lahko izvajamo ročno (z nastavljanjem ustreznih potenciometrov) ali avtomatsko (spreminjanje krmilne napetosti, dovedene z računalnika prek D/A pretvornika na kartici PLK). Krmilne napetosti, podane z računalnikom, običajno pripravljamo s prosto izbiro krmilnih operacij ali pa jih pripravljamo kot vhodne podatke, pridobljene iz datotek simulirnih programov po določenem operacijskem zaporedju.

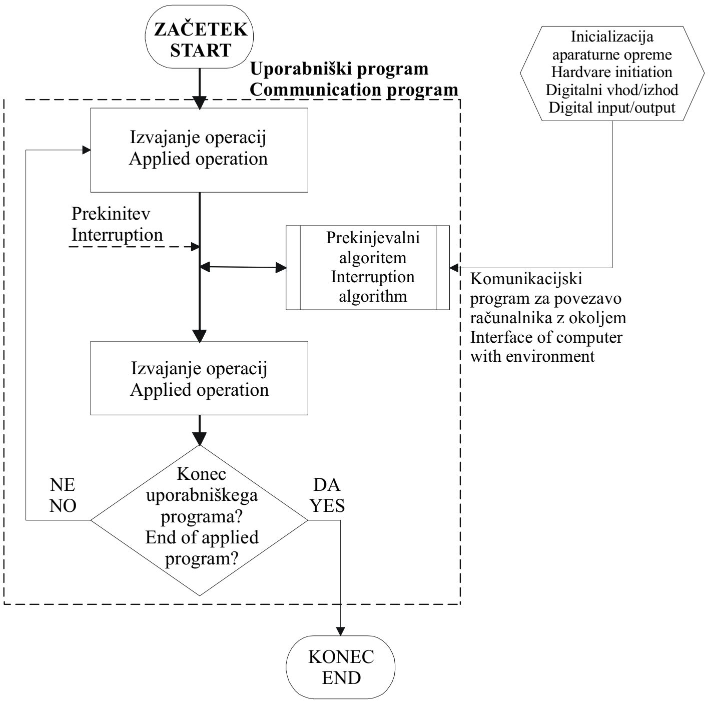
Pri enostavni krmilni zanki se razbiranje vhodnih podatkov iz A/D pretvornika izvaja diskretno. Po izvedbi krmilnega algoritma se na D/A pretvorniku pojavijo novi podatki. V ozadju teh dejavnosti lahko računalnik izvaja druge opravke, npr. prenos in obdelavo podatkov. Diskretizacija omogoča ustavitev glavnega uporabniškega programa s skokom na postopek za ustavitev krmilnega algoritma. Princip dela za ustavitev je shematsko podan na sliki 3.

Before the start of the work cycle, the diagnostic system verifies the status of the work cell, and compares the existing parameters with the new ones. In the where case the new parameters exceed the defined parameters, the operator is called and asked to solve the problem.

2.2. Control algorithm

In most conventional work cells for induction hardening the operation is based on two variables: the scan speed of the intake mechanism and the power of the induction generators. Other aspects of the work cell are made unalterable or are maintained as such. The operation can be manual (an adjustment of corresponding potentiometers) or automatic (altering the control voltage via computer through the D/A converter on the PLC card). Controlled voltages fed by the computer are usually program generated with a free choice in a controlled operation, or generated through the input of data obtained from databases of simulation programs in sequential operation.

In a basic control loop the input of data from the A/D channel is performed during selectivity, and after the execution of the control algorithm new information is fed into the A/D channels. In the background during these operations, the computer can perform other tasks such as the transfer and organization of data. Selectivity enables the interruption of the main running program in order to leap to the routine executing of the control algorithm. The principle of performing the routine interruption is illustrated in Fig. 3.



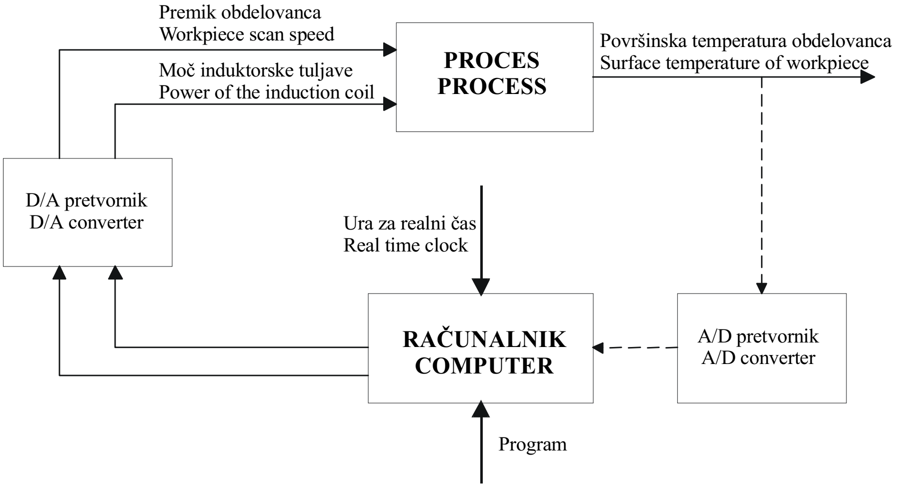
Sl. 3. *Diagram poteka programa z uporabo prekinjevalnega postopka*
Fig. 3. *Program flowchart with interruption routine*

Med programiranjem krmilnih aplikacij je treba posebno pozornost posvetiti vodenju sistema v realnem času, zbiranju podatkov z vhodov A/D pretvornika, njihovi obdelavi in na podlagi tega krmiljenja krmilnih parametrov prek izhodnih kanalov D/A pretvornika.

Krmilne aplikacije je priporočljivo izdelati v programskem jeziku, ki je soroden zbirnemu jeziku (assembler) in ki hkrati vsebuje tudi lastnosti višjih programskih jezikov (programski jezik C in njegove nadgradnje). Takšni programi so prenosljivi, njihove izvirne kode pa se brez sprememb lahko izvajajo na različnih računalnikih in z različnimi operacijskimi sistemi. Reševanje problemov pri krmiljenju se izvaja z uporabo podprogramov, ki jih lahko logično poenotimo pri gradnji krmilnih programov. Poenostavljena shema digitalnega krmiljenja procesa (izhodna moč indukcijskega generatorja in premik obdelovanca) je prikazana na sliki 4.

During the programming of control applications special attention should be paid to the control of running the system in real time, to gathering information from the A/D input, its treatment and on the basis of this perform the control scope through the output D/A channels.

It is recommended that the control applications should be performed using a program language which is close to that of the assembler which has the ability of many languages, similar to human languages (e.g. program language C, or C++). Such programs have a very high degree of transferability and the resultant codes can be used with various computers under different operational systems. The control program is produced by the use of subprograms and their logical unification. For the simplification of the digital process control (e.g. the outgoing induction generator power and the workpiece scanning speed) see Fig. 4.



Sl. 4. *Poenostavljena shema digitalnega krmiljenja procesa*
Fig. 4. *The simplification of the digital process control diagram*

2.3 Problemi uvajanja digitalnega krmilnega sistema

Digitalni krmilni sistemi so diskretni sistemi v pogledu amplitude in časa. Vhodno izhodni parametri digitalnega krmilnega sistema lahko zajemajo le določene celoštevilčne vrednosti, katerih razpon je določen z A/D in D/A pretvorniki. Te pretvornike je treba izbrati tako, da njihove karakteristike (hitrost, ločljivost) omogočajo krmiljenje procesa v realnem času.

Z namenom, da bi omogočili krmiljenje z uporabo računalnika, je eden od prednostnih problemov povezava računalnika z realnim indukcijskim procesom. Ker računalnik deluje pod nizkim energetskim nivojem (istosmerna napetost do 12 V), ga moramo z izoliranimi ojačevalniki galvansko ločiti od indukcijskega procesa (napetosti anode visokofrekvenčnega generatorja znašajo tudi do 12 kV).

2.3. Problems in the implementation of the digital control system

Digital control systems are discrete in terms of time and amplitude. The input/output power of a digitally controlled system can accept only integers whose support is defined by the A/D and D/A converters. The converters should be chosen based on their ability to perform the control process (speed, resolution) in real time.

In order to make the computer control possible, the problem of the link-up between the computer and the real induction hardening process becomes a priority. Since the computer functions only at low energy levels (direct current of up to 12V) it has to be completely insulated and well separated from the induction process (the power of a HF generator anode can reach levels of 12 kV).

Pri diskretizaciji signalov moramo veliko pozornosti posvetiti hitrosti vzorčenja merjenih parametrov z namenom, da bi diskretizirani signal ustrezno ponazoril stalni signal. Pogosto je treba prilagoditi krmilni signal (z ojačitvijo na potreben energijski nivo), da bi lahko vplivali na objekt krmiljenja v skladu z algoritmom krmiljenja in vektorjem referenčnih parametrov.

3 SKLEP

Za kvalitetno indukcijsko kaljenje je treba analizirati procese segrevanja in ohladitve z računalniškim simuliranjem in zagotoviti avtomatsko krmiljenje celotnega procesa.

Zaradi pospešitve tehnološke priprave pri oblikovanju induktorja zadošča simuliranje segrevanja obdelovanca z eno od uporabnih numeričnih metod s komercialno razvitimi enodimenzionalnimi računalniškimi programi. Za napovedovanje površinske trdote in porazdelitve zaostalih napetosti po kaljenju je treba simulirati nastale fazne premene in mehanske napetosti pri gašenju, kar pomeni zapleteno nalogo in terja veliko računalniškega časa ter uporabo dvo- in tridimenzionalnih programov.

Simulirni programi se izkažejo za koristne pri uporabi oblikovno podobnih ali enakih obdelovancev, za katere je potrebno popolno razumevanje fizikalnih pojavov v procesu in pravilno izvedbo simuliranja. Pomemben prvi pogoj za natančnost simuliranja je tudi pravilna izbira robnih pogojev in dobro poznavanje lastnosti materialov obdelovancev.

Za simulirne programe je treba organizirati operativne podatkovne baze, ki se uporabljajo med izvajanjem programov in za shranjevanje rezultatov izračunov. Dobro organizirane podatkovne baze rabijo kot vir znanja in pridobljenih izkušenj pri vsakem novem reševanju problemov indukcijskega kaljenja. Z uporabo računalniških simuliranj je čas projektiranja postopka indukcijskega kaljenja znatno krajši. Induktor, oblikovan za določen obdelovanec, ima lahko, poleg specifične oblike indukcijske zanke, tudi koncentrirana mesta magnetnega pretoka, kar zahteva razvoj posebnih diagramov sprememb procesnih parametrov in ustrezni krmilni algoritem delovne enote.

Izhodni parametri simulirnega programa, ki definirajo procesne diagrame (npr. spremembe delovne moči generatorja in spremembe premikov obdelovanca med delovnim krogom) zahtevajo avtomatsko krmiljenje z uporabo PLK. Za diagnostiko delovanja indukcijske enote in za spremljanje parametrov procesa je koristno krmilne parametre prikazati na zaslonu.

When selecting of the signal, special attention has to be paid to the speed induced pattern of the measured volume so that the selected signal matches closely the continuous signal. It is often necessary to approximate the controlling signals (amplifying them to reach the required energy level) in order to affect the controlled system so that it conforms with the algorithm of control and the vector of the reference parameters.

3 CONCLUSION

For quality quench hardening induction, it is necessary to analyze the heating and quenching operations by means of a computer and insure the automatic control of the entire process.

To speed up technical preparations for the shaping of the inductor, it is sufficient to simulate the heating of the sample workpiece with one of the available numerical methods and with the help of some commercially developed 1-D computer programs. To predict the surface hardness and the profile of residual stresses after hardening, a simulation of the resulting phase transformations and mechanical stresses at the quenching stage become necessary. This is a complex task requiring considerable computer time and 2-D and 3-D programs.

Simulation programs are usually well suited for a selected group of similar or identical tasks. It is, however, necessary to completely understand the physical outcomes of the process in order to design and conduct a successful operation. The important preconditions for an accurate simulation are the setting up of an adequate framework and knowledge of the material properties of the sample.

For simulation programs, the operative database must be organized for the servicing of the program and storing of the results of the calculations. By organizing a database it is possible to classify a system of knowledge with each solution to an induction hardening problem, that provides the simulation program with elements of learning. Using computer simulation, the time for the design of the induction hardening operation can be significantly shortened. The inductor, formed for a concrete task other than the specific induction angle shape, could have concentrators and magnetic flow screens that demand specifically developed diagrams, changed processing parameters and a compatible work cell control algorithm.

The application scope of simulation programs that define process diagrams (e.g. the change in the working power of the generators and the changes in the mobility of the sample during the work cycle) require an automatic control and a PLC driven process. For the diagnosis of the work of the induction cell, as well as for the observation of the process parameters, it is useful to show the control parameters and the metering scope with a VDT diagram.

Krmiljenje znanih indukcijskih sistemov starejše izvedbe z ročnim in polavtomatskim krmiljem je mogoče posodobiti z uporabo ustreznih krmilnih algoritmov. Pri novih in sodobnih indukcijskih sistemih se bodo simulirni programi uporabljali predvsem za hitro dimenzioniranje induktorjev in za definiranje optimalnih procesnih parametrov indukcijskega segrevanja oz. kaljenja.

The existing induction hardening equipment of an older generation with manual or semi-automatic controls could be made more reliable by adapting applicable control parameters and by designing an adequate control algorithm. When purchasing new and contemporary induction equipment, future state of the art programs could be built-in for a successful and quick sizing of the inductors and for defining the optimal processing parameters for high frequency hardening.

4 LITERATURA
4 REFERENCES

[1] Hassell, P.A., N. V. Ross (1994) Induction heat treating of steel. *ASM Handbook Part 4. 9th edition*, Metals Park, Ohio, USA, 164-202.

[2] Liščić, B., Stupnišek, M., Cajner, F., T. Filetin (1992) Toplinska obradba - praktikum. *FSB Sveučilišta u Zagrebu*.

[3] Rudnev, V.I. et. al. (1997) Induction heat treatment. Steel heat treatment handbook, ed. by G. E. Totten, M. A. H. Howes, *M. Dekker Inc.* USA, 765-871.

[4] Kelly J.B. (1995) Intelligent induction hardening. *Advanced Materials & Process*, 12/95, 36Q-36R.

[5] Schopfel, A., K. Strorzel (1997) Optimization of process parameters for induction heat treating by means of numerical simulation. *Proceedings of the 17th Heat Treating Society Conference and Expositions, and 1st International Induction Heat Treating Symposium*, 15.-18. September, Indianapolis, Indiana, USA, 595-600.

[6] Liščić, B., Tensy, H., W. Luty (1995) Theory and technology of quenching. *Springer-Verlag*.

[7] Nemkov, V.S. et. al. (1997) Computer simulation on effective creative tools for development of induction heat treating processes. *Proceedings of the 17th Heat Treating Society Conference and Expositions, and 1st International Induction Heat Treating Symposium*, 15.-18. September, Indianapolis, Indiana, USA, 786-792.

[8] Baines, A.P. (1988) Induction heating quality assurance monitoring systems. *Report 10th ASM Heat Treating Conference & Expositions in Heat Treatment of Metals 1988.1*, 9-10.

[9] Myers, R. (1992) Diagnostic - a powerful tool for induction heating. *Advanced Materials & Processes, 7/92*, 41-43.

Naslov avtorjev: prof.dr. Franjo Cajner
mag. Josip Grilec
Darko Landek
Fakultet strojarstva i brodogradnje
Sveučilišta u Zagrebu
Ivana Lučića 5
10000 Zagreb, Hrvaška

Authors' Address: Prof.Dr. Franjo Cajner
Mag. Josip Grilec
Darko Landek
Faculty of Mechanical Engineering
and Naval Architecture
University of Zagreb
Ivana Lučića 5
10000 Zagreb, Croatia

Prejeto:
Received: 17.11.1998

Sprejeto:
Accepted: 15.9.1999