RECENT ADVANCES IN HEAT-TREAT TECHNOLOGY

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HOW *RECENT* IS RECENT ?

There is always a scope of ambiguity in interpreting a topic dealing with recent advances. Hence, it is imperative that the framework within which the topic is going to be discussed, be expounded at the very outset.

The most logical option would be to specify a timeframe. However, this may prove to be too rigid and may often turn into a historical account. Further, in a subject as large as that of heat treatment, advancements have occurred in diverse areas, some of which are truely path-breaking, while others may really be classified as modernization. It would not be fair, if all such advances are given the same weightage. It would be too long a discourse if all were discussed anyway. A certain amount of subjectivity, therefore, must invariably be applied while defining recent advances.

INTRODUCTION

In the last ten to fifteen years, heat treating technology has witnessed a lot of advances. The introduction of new alloys, like duplex stainless steel, micro-alloyed steel, HSLA steels, low-cobalt maraging steels, austempered ductile iron, directionally solidified and single crystal superalloys, aluminium-lithium alloys, various metal matrix composites *etc.*, have called for new heat treatments based on structure-property correlations. There have also been changes in heat treatment processes, including improvements in continuous annealing, induction heating, and surface hardening operations using laser or electron beams, establishment of the commercial viability of plasma-assisted case-hardening processes, and advances in thermo-mechanical processing. However, the most dramatic advances have taken place in the area of newly developed tools for improving process characterization and process control. Notable amongst such developments are the improved instrumentation for controlling furnace temperature, furnace atmosphere, and surface carbon content, the practical application of statistical process control (SPC), the application of computer modelling for prediction of hardness profiles, quantitative modelling of tempered on case hardened properties, and the computer-assisted object oriented selection of materials and their heat treatment processing. Many of the advances listed above are being covered in some of the other lectures in this workshop. A selection of the items mentioned above are discussed in a general manner in this paper.

LASER SURFACE HEAT TREATMENT

Laser surface hardening is widely used nowadays to harden localized areas on steel components. In this process[§], a laser beam is focused on to the workpiece surface, which absorbs the heat to undergo selective austenitization of local surface regions; these regions subsequently transform to martensite due to rapid cooling by the conduction of heat into the bulk of the workpiece (self-quenching). Control must be exercised on the amount of heat transmitted by the laser beam by controlling the residence time of the beam so that local melting is prevented. As a matter of fact, laser surface melting is another process of laser surface engineering and in order to differentiate the laser surface hardening process from it, the latter is often called laser transformation hardening. It is emphasized that there is no change in chemistry during laser transformation hardening, and the process like induction and flame hardening, provides an effective technique to harden ferrous material selectively. In laser surface hardening, narrow surface zones are heated and cooled rapidly to produce fine martensitic microstructures. The case depth which can be achieved without surface melting is reported to be about 0.75 - 1.0 mm. A high surface hardness and good wear resistance, with less distortions, result from this process therefore. The process has become very popular for selective hardening of wear and fatigue prone areas on irregularly shaped machine components like camshafts and

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[§] P.J. Oakley, The Welding Institute Research Bulletin, **22** (1981), 4.

crackshafts. For treating shafts and bores, a spiral travel pattern is often used since this results in higher efficiency.

The laser method of surface hardening differs from induction and flame hardening in that the laser source can be located at a distance from the workpiece, as opposed to proximal placement of the heat source for the conventional hardening processes. Also the width of the heating spot or track can be easily controlled via the focusing lens and reflection mirrors. The flexibility of the laser delivery system is another advantage with this method. However, because the absorption of laser radiation in cold metal is low, laser surface hardening often requires energy absorbing coatings on surfaces. Molian[¶] lists some such coatings and also tabulates the characteristics of fifty applications of laser surface hardening. An informative review of the laser hardening process has been made by Hick[†].

Other than for transformation hardening, laser is also used for other surface treatments. Laser surface melting has been mentioned previously. In laser surface alloying, alloying elements are added to the melt pool to change the composition of the surface. Fig.1 shows the various laser surface modification processes characterized by their power densities and interaction time.

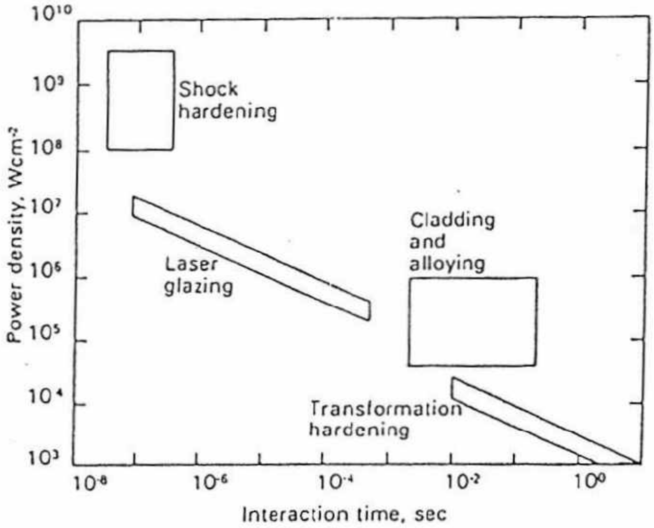

Fig.1 : Various laser surface modification processes

[¶] P.A. Molian, "Engineering applications and analysis of hardening data for laser heat treated ferrous alloys", *Surf. Engg.*, **2** (1986), 19-28.

[†] A.J.Hick, "Rapid surface heat treatments —— a review of laser and electron beam hardening", *Heat Treatment of Metals*, **1983.1** (1983), 3-11.

ELECTRON BEAM HARDENING

Electron Beam (EB) hardening is similar to laser surface hardening, but employs a concentrated beam of high-velocity electrons as an energy source to heat the selected surface area. Electron emitted by a source are accelerated and formed into a directed beam by electrical lenses, before being suitably deflected by deflection coils to fall on the surface of the workpiece. To prevent oxidation in the region where the electron beam is emitted and to avoid scattering in the region where the electrons are being accelerated, a high vacuum of 10^{-5} torr is needed. Like the laser hardening process, EB hardening does not require a quenchant. However, a sufficient workpiece mass of about 8 times the EB hardened volume is required to surround the target surface to induce self-quenching. Unlike the laser process, EB hardening does not require energy-absorbing coatings. It is thought that, although still expensive, the EB process is more economical than the laser hardening process. The EB hardening process has gained popularity recently due to the coupling of dedicated computer control system with the EB equipment[$][#]. Fig.2 gives a schematic of such a computer controlled EB hardening set-up. An useful comparison of the laser and EB hardening methods has been given by Hick[§], which is reproduced in Table 1.

SELECTIVE SURFACE HARDENING THROUGH ION IMPLANTATION

Ion implantation is a surface modification process in which ions with very high energy are driven into a substrate. Theoretically ions of any atomic species can be implanted. However, nitrogen ions are widely used for implantation, mainly for improving the corrosion resistance and tribological properties of steels. Hochman[†] gives a general account of the process.

[$] C.L. Gilbert, *Industrial Heating*, **45** (1978), 16-18

[#] C.A. Fiorletta, *Heat Treating*, **12** (1980), 28-32

[§] A.J. Hick, previously cited

[†] R.F. Hochman, in : "Metals Handbook", **9th ed., Vol.5**, ASM, 1982, p.422-426.

Table 1 : Comparison of the laser and electron beam hardening processes

Item	Electron Beam	Laser
Bore size limitation	Line of sight at 35° impingement	1 in. dia. and up — no limit, 1/4 in. to 1 in. — using small spot size
Part contamination	Parts should be clean	Parts should be clean at reaction area
Focused spot size	Hard vacuum, 0.02in dia soft vacuum, 0.03 in dia	Varied — depends on system and optics
Heat treat pattern	Shape and density controlled by computer or function generator	Shape limited to mirror deflection capabilities, density averaged.
Beam deflection	Electromagnetically 30° included — two axes	Water cooled reflecting optics — mechanical or integrating
Effect of vacuum on cycle time	Production system pre-pumped – no effect, low volume system – min. 5 sec. pump down, but depends on chamber size	No effect
Part size limitation	Limited by chamber size and motion required	No limit
Power available	100 kW +	15 kW max.(commercial) 100 kW + (experimental)
Conversion efficiency	>90%	<10%
Operating costs	Low	High due to gases and low efficiency
Surface preparation	None	Requires absorptive coating
Investment	Lowest on high power applications	Lowest on low power applications.

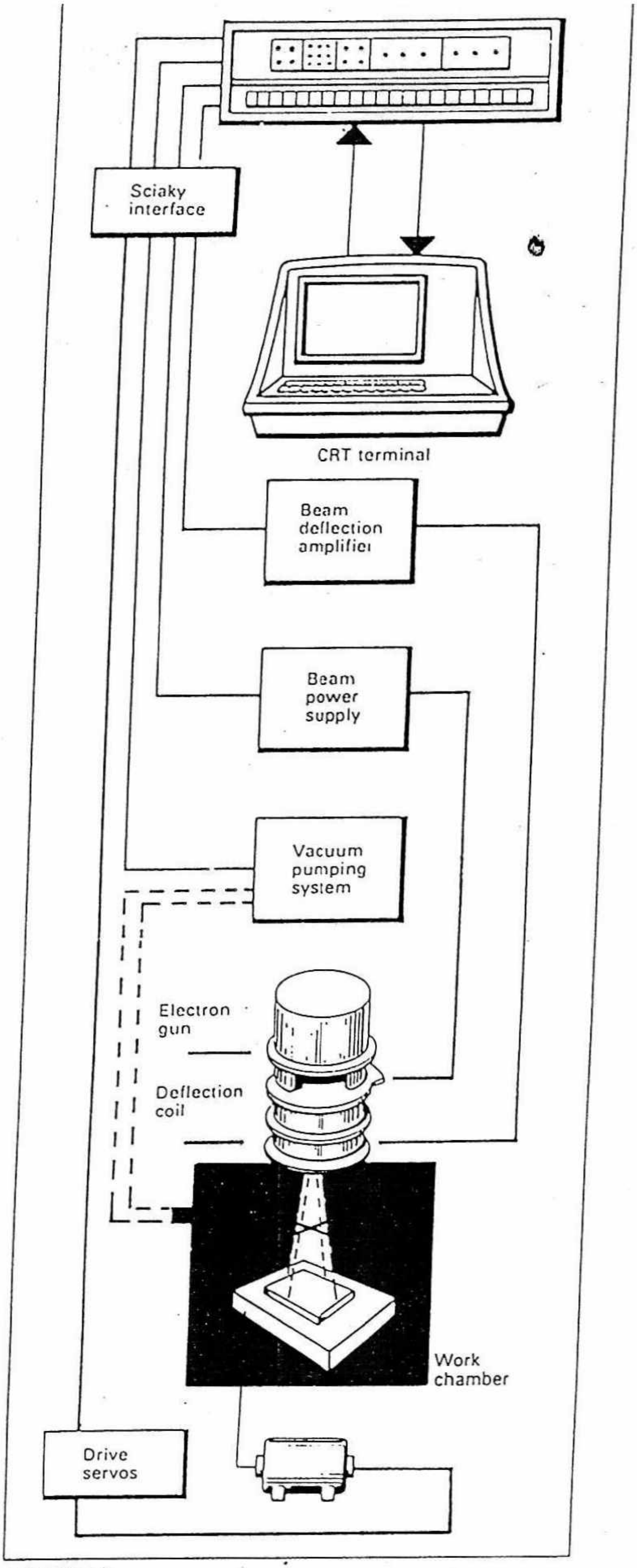

Fig.2 : Schematic representation of computer controlled electron beam heat treatment system

For ion implantation, ions generated by a special source, are accelerated to energies from 30 to 500 keV, at which they impinge on the surface of the workpiece. These ions penetrate the workpiece and by the dissipation of their energy through the collision and cascade theory[¶] come to rest at depths of 10-200nm. The concentration of the implanted species shows a Gaussian distribution, as shown in Fig.3, reported by Pollock[$]. The whole process must be carried out in high vacuum of the order of 10^{-5} torr at ambient temperatures. As ion-implantation is a line-of-sight process, the workpiece may need manipulation to cover a wider area. The advantages and limitations of the ion-implantation process are listed below in Table 2.

Table 2 : Advantages and limitations of ion implantation.

	Advantages		**Limitations**
1.	Implants any species into any substrate	1.	High capital outlay ($150,000)
2.	Clean vacuum process	2.	Line-of-sight process
3.	Applicable to finished products with no dimensional change	3.	Shallow treatment layer
4.	Conservative use of implant species	4.	Sample manipulations required in vacuum
5.	Reliable; precise alloying possible	5.	Cannot be used for high temperature applications, as implanted specie may diffuse out

Ion implantation can be used to form sub-surface metastable and amorphous phases. Thus it is possible to alloy species which would normally segregate during solidification or would not thermally diffuse,

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[¶] P.D. Townsend, J.C. Kelly and N.E.W. Hartley, "Ion implantation, sputtering and their applications", Academic Press, London, 1976

[$] J.T.A. Pollock, "Durability of Ion-implanted surfaces : a review", *Materials Forum*, **9** (1986), 127-136 eg. Cr into Cu[†] . In fact, it has been shown[§] that solid solubility rules are greatly widened when applied to ion implantation process.

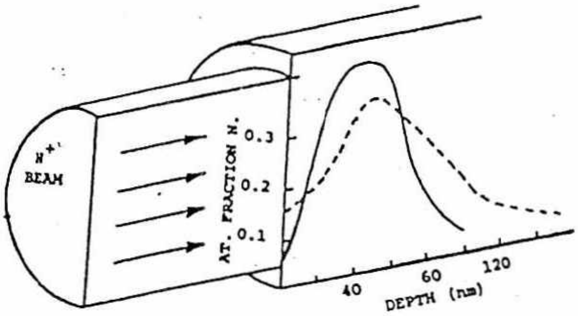

Fig.3 : Comparison of ideal (solid line) and determined (broken line) implant profiles for N-implanted mild steel. Implant conditions : 65 keV, 3 x 10 ion m^{-2} (Pollock, 1986)

Due to sputtering, prolonged implantation can only achieve a atom concentration of <50 atom%. If implantation is carried on beyond saturation limit, the Gaussian distribution of atomic concentration is skewed towards the surface. A benefit of the sputtering limitation is that component dimensions are accurately maintained.

Ion implantation has been used for surface hardening of razor blades and knives, a variety of tool steel applications and the implantation of 521000 and 440C bearings with titanium and/or nitrogen to improve rolling contact fatigue resistance.

PLASMA ION CARBURIZING AND NITRIDING

Plasma ion carburizing and plasma ion nitriding are relatively recent and non-conventional methods of carburizing and nitriding that are gaining wide acceptance. Both the processes are based on the glow-discharge phenomena in which the process gas is ionized under plasma-forming

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[†] M. Baron, J. Gueggi and J. Schreurs, in "Metastable materials formation by ion implantation", *eds.* Picraux and Choyke, North Holland, 1981, p.43.

[§] D.K. Sood, *Phys. Lett.*, **68A** (1978), 469 conditions and the ions discharge on the workpiece emanating a characteristic glow.

Fig.4 gives the typical voltage and current characteristics for glow discharge and Fig.5 shows a schematic arrangement for plasma ion carburizing or nitriding. In the processes, the workpiece is heated to a suitable temperature at which carburizing or nitriding is to be carried out, and the process gas is admitted into the reaction chamber. The pressure inside the chamber is maintained at 1-20 torr. In the presence of the process gas, the workpiece is maintained at a high negative potential (-500 to -1000 V) with respect to the vessel which is grounded or with respect to an anode inserted into the chamber. Under the influence of the pressure, temperature and voltage, the process gas ionizes and forms a plasma. Ions from this plasma are attracted towards the workpiece. Within a short distance of the workpiece, the positively changed ions acquire electrons from it and emit photons. This photon emission results in the visible glow discharge. The elemental species then strike the workpiece, converting its kinetic energy into heat, and reacts and diffuse into it, forming a hardened surface and case. The thickness of the glow envelope can be altered by pressure, temperature, gas mix and current, and controls the nature of hardening that results.

The glow-discharge or plasma-ion method of carburizing or nitriding significantly reduces the time taken to complete a job. This is mainly because surface saturation of carbon is quickly attained and results in faster diffusion kinetics. The plasma methods produce a very uniform case depth[†][¥] , mainly because the glow-discharge plasma can be controlled to closely envelope the specimen surface following its contours[¥]. An additional advantage in plasma nitriding it that the surface is cleaned by sputtering.

[†] B.Edenhofer, M.H.Jacobs and J.N.George, "Industrial processes, applications and benefits of plasma heat treatment", in **Plasma Heat Treatment, Science and Technology**, PYC edition, 1987, p.399-415.

[¥] W.L.Grube and J.G.Gay, "High rate carburization in a glow-discharge methane plasma", *Met. Trans. A*, **91** (1987), 1421-1429

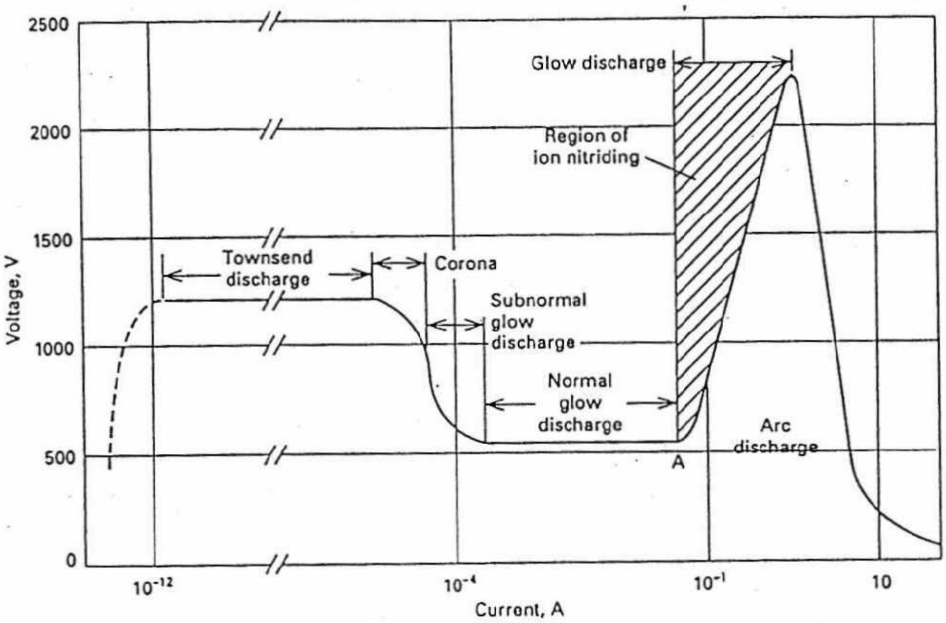

Fig.4 : Voltage-current characteristics for glow discharge processes.

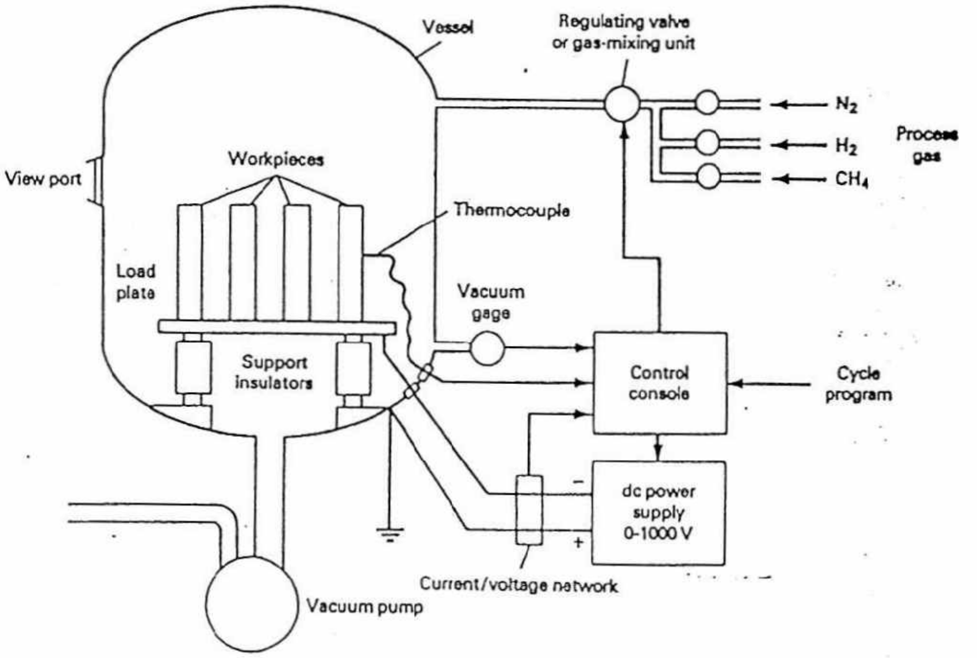

Fig.5 : Schematic arrangement for plasma-ion processes.

THE TOYOTA DIFFUSION PROCESS

The Toyota Diffusion (TD) coating process was first developed in Japan in 1971[#][$], and since then has been further developed to be known currently as the Thermoreactive Deposition/Diffusion (TRD) process[¶]. In this process, steel parts of sufficient carbon content are case-hardened by the intentional build-up of a refractory carbide layer of 5-12 μm on the surface by heating the parts in electric salt bath furnace containing molten borax $Na_7B_4O_4$ and appropriate ferro-alloys at about 1000°C for a few hours. The refractory carbide layer formation on the outer surface occurs by a reaction between carbide forming elements, such as Ti, V, Nb, Mo, W, Hf, and Cr dissolved in the molten borax bath, and carbon atoms diffusing from the bulk of the steel body. In many cases, the steel parts can be directly hardened from the salt bath employed for the TRD process. A final tempering treatment is often given for better dimensional stability and minimal distortion[§]. A schematic of a typical TRD processing cycle is shown in Fig.6.

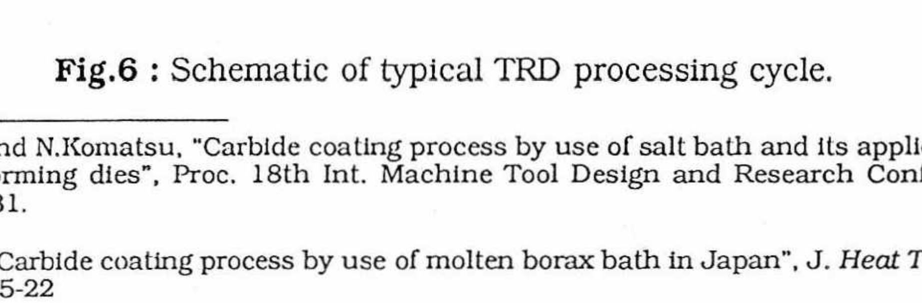

Fig.6 : Schematic of typical TRD processing cycle.

[#] T.Arai and N.Komatsu, "Carbide coating process by use of salt bath and its application to metal forming dies", Proc. 18th Int. Machine Tool Design and Research Conf., 1977, p.225-231.

[$] T.Arai, "Carbide coating process by use of molten borax bath in Japan", J. *Heat Treat.*, **18** (1979), 15-22

[¶] T. Arai and S. Harper, "Thermoreactive deposition/diffusion process", ASM Handbook, 1st ed.,Vol.4, 1991, p.448–453

[§] H.C.Child, *Met. Mater. Technol.*, **13** (1981), 303-309

The TRD process is limited to elements which have a larger free energy of oxide formation than that of B_2O_3 and a relatively small free energy of carbide formation. Carbon is provided by diffusion from the substrates, thus limiting the use of the process to carbon containing substrates. For carbon-deficient materials, for example, iron and nickel alloys, the TRD process can be used after carburization.

The main advantages of the TRD process are:

1] Exceptionally high surface hardness (1200-4000 DPH) and fatigue life.
2] Excellent wear and thermal shock resistance.
3] Much better seizure properties against many running materials.
4] Improved corrosion and oxidation resistance, the latter being found upto 800°C in the presence of Cr_7C_3 carbides.
5] Absence of cracks, spalls, peels or flakes, even after oil quenching.

ADVANCED CONTINUOUS ANNEALING

Continuous annealing was originally developed in the 1960s and the 1970s and was mainly used for tinplate steels for which formability is not a critical requirement. However in more recent years, the continuous annealing process has been extended to the production of high formability steel sheets.

The change from ingot casting to continuous casting has increased production efficiency and reduced energy consumption. In additions, direct hot rolling immediately after continuous casting has eliminated slab reheating. Compared with batch annealing, continuous annealing makes the same economic contribution as continuous casting. In recently developed continuous process@ for production of cold-rolled steel sheets, all the processes from pickling to temper rolling occur in one production line, including continuous annealing, as shown in Fig.7. It is in such situations that continuous annealing provides the greatest advantages.

@ K.Fudaba, O.Akisue, Y.Tokunaga, Int. Symp. on Ladle Steel making and Furnaces, Montreal, 1988, Canadian Inst. Min. Metall., p.290-304

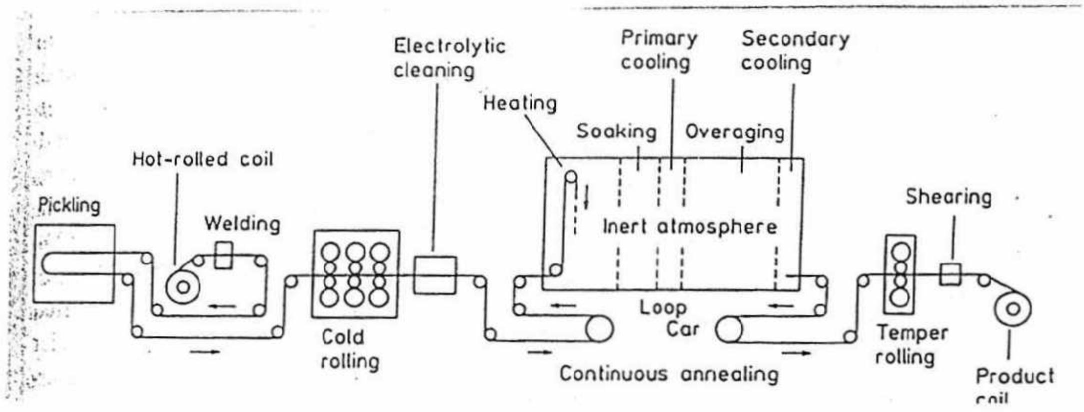

Fig.7 : Newly developed continuous line to produce cold rolled, continuously annealed products.

Continuous annealing thus provides a potential for faster response to customer requirements. Also, for a properly planned and optimized process, more consistent mechanical properties, improved flatness, a cleaner surface and a lower unit cost as compared to batch annealed process, may be engineered.

Continuous annealing typically provides a short annealing time (about 100 sec.) and a rapid rate of both heating and cooling (about 10°C/sec.) during the annealing cycle. Sufficient grain growth cannot be obtained in the short annealing time, especially for Al-killed steels, and the rapid heating does not permit Al-killed steels to improve the deep-drawability. The rapid cooling after annealing may result in a deterioration in ductility because of the large amounts of dissolved residual C. All of the above points are not conducive to the production of high formability sheets, which have therefore been conventionally produced by batch annealing.

In advanced continuous annealing, the above negative effects of continuous annealing are countered by using specially prepared scavenged steels, proper considerations for the hot coiling temperature and using post-annealing overaging treatments to reduce the dissolved C. The candidate materials for high formability deep-drawing type of applications are usually unkilled (rimmed and capped), Al-killed and interstitial free (IF) steels. These steels can be prepared by scavenging impurities out of them through the addition of alloying elements, so that in effect a more pure steel is produced[$] . The scavenging action can be assisted by the hot coiling temperature. For example, in rimmed and capped steels, impurities such as O and S are scavenged by Mn after hot coiling at 750°C. In Al-killed steels, Al scavenges O during steel making, whilst N is scavenged by Al after high temperature coiling at about 750°C. For B containing Al-killed steels and IF steels, high temperature coiling is not necessary as N is scavenged by B in the former and both C and N are scavenged by Ti in the latter before hot rolling. By providing a purer matrix, the $\bar{r}$ value (the average plastic strain ratio or the average Lankford value, which characterizes deep-drawability) is enhanced by optimal control of scavenging and hot-coiling, and this makes the steel suitable for processing through continuous annealing. Another requirement for good formability is an overaged microstructure, particularly for unkilled and Al-killed steels, which shows enhanced ductility. As in continuous annealing, the cooling rate is higher, a supersaturated microstructure results. Therefore in advanced continuous cooling, an overaging treatment (above 300°C to prevent temper embrittlement) is appended after the annealing.

USE OF COMPUTERS IN HEAT TREATMENT

Computer usage in heat treatment processing has made a significant impact in recent years. It is thought, that in the future, computers are going to exert a still greater influence on heat treatment technology.

The areas of heat treatment technology in which computers are being used regularly are :

1) Storage and retrieval of databases
2) Modelling of transformation processes
3) Prediction of microstructures and properties
4) Process analysis and optimization
5) On-line process monitoring and control

Through the development of computer-based storage and retrieval systems for material composition, material properties, the effect of

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[$] B.L.Bramfitt and P.L.Mangonon (eds.), Metallurgy of continuous-Annealed sheet steel, Warrendale : Metall. Soc. AIME, 1982, p.35-47, p.51-81, p.133-153 processing variables on material properties, CCT and TTT informations for various alloys *etc.*, heat treatment technologist can assess the effect of material selection on heat treatment and its final properties very easily. Thus an assessment of the material and processing alternatives available can be readily made and executed. Using computers, it is now possible to model a heat-treatment process accurately enough so that the effect of the processing variables can be analysed. Therefore, it may not be necessary to perform costly and lengthy experiments in order to study the effect of processing variables and instead a computer-based optimization of the process can be performed. Computers have been extensively used for on-line process monitoring and control during heat treatment. This has largely been brought about by the development of solid state transducers. On-line heat treatment softwares are particularly suitable for monitoring energy consumption, which is an important issue nowadays. Lastly, the computer is an important tool to obtain solution of heat transfer and deformation behaviour problems. These are directly related to the situations encountered during heat treatment which can, therefore, be analysed and studied in detail for development of heat treatment processes and prediction of heat treated properties. Table 3 lists some of the computer softwares available commercially, alongwith informations of their most important features, which are of interest to heat treatment technologists.

Table 3 : Available computer programs and data bases on steel selection, microstructure, properties and heat treatment technologies.

Name of the software	Availability	Features
Mat.DB	ASM International, U.S.A	Materials data base management program containing the designations, chemical compositions, forms (sheet, bar and so forth), and properties (up to 40 properties). It is designed to select alloys on the basis of many characteristics.
EQUIST 2.0	SACIT Steel Advisory Centre for Industrial Technologies, Hungary	Contains the chemical compositions, mechanical properties, application fields, and the international comparison (equivalent steels) of 6500 standard steels from 18 countries.

Database SteelMaster	Dr. P. Sommer, Werkstoffechnik, GmbH, Germany	Contains compositions, mechanical properties, heat-treatment parameters, CCT diagrams, tempering charts for commonly used German structural and tool steels. The heat-treatment technologies designed by the use of the software can be stored and retrieved.
FERITUS	Matsel Systems Ltd., Great Britain	This data base provides engineers with up-to-date information about the range of materials from traditional metals to new polymers. The range of information: mechanical and physical properties, environmental resistance, material forms, processing methods, trade names and standards.
AMETA	SACIT Steel Advisory Centre for Industrial Technologies, Hungary	This data base of individual measured steel properties contains data collected from laboratories of industry quality control departments, range of data: steel designation, heat number, dimensions of the machine part, composition, heat treatment of the part, results of tensile tests, impact test results, measured Jominy curve of the heat, and other tests. The system makes statistical analysis of the data.
KOR	SACIT Steel Advisory Centre for Industrial Technologies, Hungary	KOR is a corrosion information system, which contains a data base of 300 corrosive media, more than 15000 individual corrosion datasets, metallic structural materials, and 200 isocorrosion diagrams. Structural material selection is possible according to prescribed mechanical, physical, technological properties, or it is possible to find a suitable resisting material for a corrosive medium with given temperature and concentration. The system will also accept the user's own data.
PREDIC & TECH	SACIT, Steel Advisory Centre for Industrial Technologies, Hungary	Simulates the cooling, transformation of austenite in cylindrical, plate-shaped workpieces, Jominy specimens made of case-hardenable and quenched and tempered low-alloy steels and calculates the microstructure and mechanical properties in any location of the cross section of the workpiece taking into account the actual chemical composition, dimensions, austenitizing temperature, durations, cooling intensity of quenchant, tempering, and time. The same program works as technology planning program if the prescribed mechanical properties and composition are given.
AC3	Marathon Monitors Ltd., Great Britain	Hardenability model designed to predict the response to quenching of through-hardening and carburized low-alloy steels in terms of microstructure and hardness distribution.

CETIM-SICLOP	Centre Technique des Industries, Mechaniques PROGETIM, France	Contains a steel data base for the selection of structural and tool steels and calculates the mechanical properties along the cross section of workpieces
SteCal	Comline Engineering Software, Great Britain and ASM International	Calculates the heat-treatment response and properties of low-alloy steels from composition.
PREVERT	Creusot-Loire Industries, France	Calculates the mnicrostructure and mechanical properties of quenched and tempered low-alloy steels from composition and heat-treating parameters.
CHAT	International Harvester Company, U.S.A.	CHAT is a two-part system for selecting the optimum steel composition to be used where heat treating is performed to develop required engineering properties.
MINITECH	Minitech Limited, Canada	The Minitech Alloy Steel Information System consists of twelve computer programs which generate a series of hardenability-related properties of steels, such as Jominy curves, hardenability bands, mechanical properties of hot rolled products, hardness distributions for quenched and tempered and carburized products.
PREDCARB	SACIT, Steel Advisory Centre for Industrial Technologies, Hungary	This computer program determines the gas carburizing technology and calculates the carbon profile and hardness distribution in the case and core on the basis of chemical composition, dimensions of the workpiece, cooling intensity of the quenchant, prescribed characteristics of the case.
SIMULAN	Lammar, Ensam Bordeaux, France	Simulates the gas carburization and induction hardening process, and calculates the carbon and the hardness profile.
CARBCALC	Marathon Monitors Ltd., Great Britain	Simulates the carburizing reactions between a steel and surrounding atmosphere. It calculates the carbon profile.
CARBODIFF	Process Electronic, Germany	Monitoring of carbon profile during carburizing and prediction of hardness distribution after quenching of case-hardened steels.
Carbo-O-Proof	Ipsen Industries Ltd., U.S.A.	This software is able to optimize the carburizing process, calculates continuously the carbon profile, and regulates the process in accordance with program target values.
SYSWELD	Framasoft, Great Britain	This system is based on finite-element technique and simulates the transformation processes in steel during heat treatment or welding. The program calculates the temperature distribution, microstructure, hardness and stresses.

CLOSURE

A few of the recent advances in heat treatment technology have been discussed in this paper. It has not been the intention to be exhaustive while describing the advances. Interested readers are directed to go through the references cited in the text and the list of selected readings appended at the end.

Future prospects in heat treatment lie in further development of some of the newer processes that have been proposed. Large scale integration of operations, as in continuous processing from steel casting to heat-treated products, is possibly going to receive more attention. The use of computers in heat treatment will be increasing. But perhaps, the most important issues facing heat-treaters will be those of energy conservation and environment friendliness. This will result in better furnaces, better control of processes and the development of newer processes altogether. The Chinese have already progressed in this direction by proposing the use of concentrated solar energy for selective surface hardening†.

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† Industrial Heating, "Chinese investigation of surface hardening of steel and iron by solar energy", **49** (1982), 34-35