Editorial

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Biographical notes: Janez Grum is a Professor of Materials Science at the University of Ljubljana, Faculty of Mechanical Engineering. He is also the founder and editor-in-chief of a new journal *International Journal of Microstructure and Materials Properties – IJMMP* and has been editor of the *Journal News of Society for Nondestructive Testing*, Slovenian Society for Non-Destructive Testing, Ljubljana, Slovenia since 1994. He is editor of the six NDT Conference Proceedings, two ASM and Marcel Dekker book chapters and five books with several reprints. He has also published more than 100 refereed journals and more than 300 conference papers on heat treatment, laser materials processing and materials testing including non-destructive testing.

Valery Rudnev, FASM, is one of the leading global figures in induction heating technology. He is known among induction heating professionals as 'Professor Induction'. Formerly, he was an associate professor at several universities. Since 1993, he has been on the staff of the Inductoheat Group serving as Chief Scientist (1993–2001) and Director of Science and Technology (2001–present). He was involved in several hundred projects that required advanced and divers knowledge in applied electromagnetics, metallurgy, material science, heat transfer, failure analysis and computer modelling. Dr Rudnev has 28 years of practical experience and his credits include numerous 'know-how', 16 patents and 128 scientific and engineering publications.

The present special issue of the *International Journal of Materials and Product Technology* (*IJMPT*) comprises 21 papers on induction heating, hardening and welding.

In agreement with the editor of the journal, Dr M. Dorgham, this special issue was edited to comprise the papers received on a special invitation from authors well known in the respective fields. The first invitations were distributed as early as 2004, i.e. on the occasion of the International Symposium on Heating by Electromagnetic Sources taking place in Padua, Italy. Such symposia have become traditional. The symposium in Padua was organised under the patronage of the International Union for Electricity Applications (UIE) and the IEEE-North Italy Joint Chapter, with the participation of the Italian Association of Electronics and the University of Padua.

Articles selected to be published in this issue reflect appreciable scientific/engineering achievements obtained by world-recognised experts in the field of induction heating, hardening and welding. Information regarding novel approaches in developing advance induction heating, hardening and welding technologies will be provided here as well. Materials presented here will be useful for engineers and scientists involved in related technologies as well as being suitable as a study aid for undergraduate students and in particular for postgraduate students.

The papers presented can be classified into two groups, the first covering induction heating and hardening and the second covering welding, including a paper on electro-erosion treatment.

The basic phenomenon of induction heating is quite simple. An alternating voltage applied to an induction coil or inductor results in an alternative current flow in the coil circuit. An alternative coil current produces, in its surroundings, a time-variable magnetic field that has the same frequency as the coil current. This magnetic field induces eddy currents in the electrically conductive bodies located in close proximity to the induction coil. Induced eddy currents have the same frequency as the coil current; however, their direction is opposite to the coil current. Eddy currents produce heat by the Joule effect and hysteresis heating.

One of the most common applications of induction heat treating is the hardening of steels and cast irons. Due to the electromagnetic skin effect, induced eddy currents flow within well-defined surface layers. A typical hardening procedure involves heating the alloy up to the austenising temperature, holding it at that temperature for a period long enough for completion of the formation of austenite, then rapidly cooling the metal to below a certain critical temperature where martensite starts to form. The goal in surface hardening is to provide a martensitic layer on specific areas of the workpiece to increase hardness, wear resistance and other important properties, while allowing the remainder of the part to be unaffected by the process. Developing a desirable distribution of residual stresses represents another goal of induction heat treating.

Induction surface hardening offers a number of advantages over other heat treatment methods, including a short cycle time, good repeatability, minimal distortion, decarburisation and oxidation. Induction hardening offers good possibilities for automation and can be easily incorporated into a production line.

There are two basic techniques for induction surface hardening of machine parts: 'single shot' and 'scanning'. The former employs selective static heating and quenching to harden a specific area or areas of the machine part in one operation. The latter is typically applied to progressively harden long sections, such as shafts, bars, rods, spindles, etc. With scanning techniques, the part or inductor is moving. Scan heating is usually followed by the quench arrangement, which is often an integral part of the inductor (i.e. MIQ-coils).

The mode of heating may be influenced by the workpiece geometry, its arrangement in the inductor as well as by the required heating pattern. Induction heating is suited to small, medium, and large, as well as extremely large, machine parts.

Since conventional induction systems comprise an induction coil, a high or medium frequency generator, cooling/quenching arrangements, and the heated workpiece itself, there are a number parameters influencing the induction heating process.

The course of induction surface hardening depends on:

- the type of steel or cast iron
- prior microstructure
- electrical, magnetic and thermal properties of the material
- the time/temperature relationship in induction hardening and tempering
- the selection of power density and current frequency
- geometry of the workpiece, induction coil, tooling and magnetic flux concentrator if applied
- selection of appropriate process recipe
- selection of appropriate type of induction coil circuit and quenching techniques (if applied).

In induction hardening, it is necessary to carefully plan individual design steps and manufacture phases, which are:

- design of a machine part from a blank to its final shape taking into consideration subsequent final grinding
- technique and specific conditions of induction heating
- particularities of quenching techniques
- part tempering after hardening
- final machining of the machine part by grinding.

Process optimisation allows the development of highly effective control recipes in terms of optimising transient and steady-state process parameters, obtaining an optimal combination of mechanical properties, microstructures and residual stresses.

In general, the optimisation process for induction heating/hardening is characterised by the following steps:

- definition of the appropriate problem-oriented mathematical model of the heating and quenching stages
- formulation and validation of the optimisation criteria
- formulation and validation of the technological constraints and control functions
- selection of the process parameters to be optimised
- definition of the disturbances existing in the real-life system
- solving the optical control problem.

The process of welding also introduces specific features. Since the properties and integrity of the weld metal depend on the solidification microstructure, a verified quantitative understanding of the weld pool solidification behaviour is essential. At present, our knowledge of the chemical and physical reactions occurring during solidification of fusion welds is limited. This situation arises mainly from a complex sequence of reactions caused by the interplay between a number of variables, which cannot readily be accounted for in a mathematical simulation of the process. Nevertheless, it will be shown that it is possible using the approaches suggested to rationalise the development of the weld metal solidification microstructures with models based on well-established concepts from casting and homogenising treatments of metals and alloys.

Grum provided a survey of the technical literature on induction surface hardening. The discussion is focused on the dependence of the heating rate and the temperature required for homogeneous austenitising from the heating time. Author described modes of quenching and the related changes of internal stresses and occurrence of residual stresses utilising computer modelling predictions and experimental measurements.

Rudnev discussed different computer modelling approaches tailored to the needs of particular groups of induction heating and heat-treating applications. The pros and cons of the most popular numerical techniques (including the finite difference method, finite element analysis, mutual impedance technique, boundary element method, etc.) were evaluated in respect to developing subject-oriented and user-friendly induction heating software that can be effectively used in industry.

Bay and co-authors presented 'Induction heating processes modelling: optimisation procedure and parallel computing'. The aim of their paper is to present direct modelling and optimisation of induction heating process. The problem comprises the determination of an optimal process or control parameters, such as current intensity and frequency, in order to get the suitable temperature distribution that is essential for particular technological process requirements. They have developed and implemented a parallel computation strategy for the direct model and the optimisation procedure.

Boyarevics and co-authors discussed a numerical model of cold crucible melting, based on the coupled electromagnetic, temperature and turbulent velocity field calculation accounting for the magnetically confined liquid metal shape continuous change. The model is applied to investigate the process energy efficiency dependence on the critical choice of AC power supply frequency and an optional addition of a DC magnetic field. The behaviour of the numerical model at high AC frequencies is instructively validated by the use of the electromagnetic analytical solution for a sphere and temperature measurements in a commercial-size cold crucible furnace.

Kurek and co-authors discussed computer simulation of the superficial induction hardening process. They presented a basic model that takes into account electromagnetic and thermal field coupling, interrelations between temperature changes and phase transitions, nonlinearity of material properties, and their effect on obtaining the desired mechanical properties of a machine part. Computer programmes based on the finite elements method were applied to hardening-process simulation. The method presented included the selection of electrical parameters, the inductor's geometry cooling modes, and other process conditions, in order to assure proper induction hardening. The results obtained were verified experimentally.

Zgraja discussed simulation of induction heating and hardening of flat parts, such as a cutter knife and a grey-cast iron lathe bed. An inverse method was used for determination of heating and quenching conditions. The simulation was conducted in respect to an induction circuit that comprised an induction coil, load and a series transistorised inverter. The simplified 3D model of the moving inductor-load system for determination of heating parameters was tested.

Lepeshkin and co-authors conducted numerical simulations of different induction heating process recipes and cooling conditions in order to predict the formation of certain phase transformations and residual stresses for highly intensive surface hardening. They presented a novel software package for the calculation of electromagnetic field process parameters, transient thermal and thermo-elastic–plastic states during the heating and cooling stages and finally a residual stresses analysis, after hardening, using the finite element method. Recommendations for choosing process parameters for induction surface hardening of machine parts were provided.

Pleshivtseva presented transportation problems of time-optimal induction heating prior to metal hot and worm forming. Specifics of developing the optimal control formulations of the induction heating processes, taking into consideration the most typical technological constrains, are discussed here as well. Special optimal control techniques have been developed for solving such problems. The examples of optimisation presented demonstrate the high effectiveness of the novel optimal control methods and can be effectively used to obtain cost-effective solutions in the forging industry.

Domínguez-Tortajada and co-authors treated optimisation of electric field uniformity in microwave heating systems by means of multi-feeding and genetic algorithms. The aim of microwave heating deals with obtaining uniform heating patterns in certain regions of the applicator. The authors proposed a solution for achieving electric field uniformity based on design requirements and determining the configuration of the feeding system by means of Genetic Algorithms. Results for the curing of epoxy resin over a marble slab are presented.

Plaza-González and co-authors presented the utilisation of a coupled electromagnetic-thermal model for a 2D analysis of thermal runaway. Both static and mode-stirred microwave ovens were analysed together with their influence on electric field and temperature profiles. Comparisons of using continuous and pulsing heating modes of the microwave power source were also discussed.

Pedreño-Molina and co-authors presented a learning architecture based on neural networks for modelling the electric field pattern along an axis of a multimode microwave-heating cavity that contains dielectric materials. This model, based on radial basis functions (RBF) and polynomial structures, allows the fitting of the electric field as a function of the dielectric parameters. Advantages of the proposed learning model, with respect to traditional methods, are the reduction of computational resources and possibilities of implementation in integrated devices.

Grum presented a method for heat treatment process optimisation entitled 'Input and output control of steel intended for induction surface hardening'. In the experimental part of the study, the starting point was the analysis of steel hardenability according to the Jominy test. On this basis, the conditions for induction hardening were prescribed for a worm gear tooth. The experiments on heat treatable carbon steels, C35, with different histories have shown that by using existing heat treatment conditions it is not possible to achieve the microhardness profile required by the user. The following paper, by the same author, presents experimental research work titled 'Influence of induction surface heating and quenching on residual stress profiles, followed by grinding'. It has been shown that residual stresses after induction surface hardening are closely linked to hardness variation and microstructure in the transition zone of the hardened layer and base material. Additional grinding deteriorates the stress in the surface layer, and has always induced tensile stresses. Proper selection of the grinding wheel and grinding conditions will contribute to smaller tensile residual stresses and will avoid the deterioration of the favourable residual stress state after induction surface hardening.

In contrast to heat treating, welding can be defined as joining of similar or dissimilar materials into a whole or a structure. The joints obtained can have a carrying nature or a carrying and tensile nature, e.g. vessels and reservoirs in chemical and processing industries. Occasionally other specific requirements are set for welded joints or surface layers, such as wear resistance, corrosion resistance, etc. Appreciable variation of chemical composition and microstructures of welded joints and surface layers, as well as variation of their mechanical and physical properties in comparison to the parent metal, takes place after welding.

Joining most often involves only local heating of the materials, which means that different temperatures can occur at different weld areas and their vicinity. This could result in noticeable microstructural changes. Due to temperature and microstructure differences, deformations of the welded parts usually occurs. These phenomena are typical for fusion welding processes, where heating is very intense.

Fusion welding processes include surfacing, high-productivity processes characterised by increases in filler-material melting rate and welding speeds, as well as processes ensuring deeper penetration. This can be accomplished by modifying the distribution of heat energy that effects the process of crystallisation and metallurgical interactions among the molten pool, slag and gas phases. Therefore, the conditions at an electrode, in an arc or a flame and at the parent metal are often monitored. All of these are functions of welding parameters that include the temperature and the atmospheric composition.

Welding processes, such as arc welding, gas welding, as well as laser welding and electron-beam welding, employ electric power sources. Since the properties and integrity of the weld depend on the solidification microstructure, a verified quantitative understanding of the weld pool solidification behaviour is essential. At present, our knowledge of the chemical and physical reactions occurring during solidification of fusion welds is limited. This situation primarily takes place due to a complex sequence of reactions caused by the interplay between a number of variables that cannot readily be accounted for in a mathematical simulation of the process. Nevertheless, it will be shown that it is possible to rationalise the development of the weld metal solidification microstructure with models based on well-established concepts from casting and homogenising treatment of metals and alloys.

Golob and Köveš suggested fuzzy logic based quality monitoring in gas metal arc welding. The paper deals with options of an analysis of weld quality by means of measurable electric signals emitted during welding. A simple fuzzy inference system was realised which could efficiently assess the weld quality on the basis of time variations of welding parameters in a certain time window.

Langus and co-authors optimised welding parameters in pulsed MIG/MAG welding using width-controlled sine-wave current pulses.

The first part of the paper discusses the determination of a general synergic equation and normalised parametric diagram with adequate welding range. Research was focused on a theoretical derivation of a general synergic equation of pulsed MIG/MAG welding with width-controlled sine-wave current pulses that relates a mean welding current with pulsed welding parameters. On this basis a normalised parametric diagram with welding range is defined permitting welding process optimisation of pulsed welding parameters.

The second part of the paper discusses the determination of optimum material transfer through the arc and control method. In the second part, research was focused on an analysis and optimisation of the material transfer through the arc using a limiting criterion determined by an iso-parametric equation. The results show that a parametric analysis determines the optimum welding region for a chosen droplet volume transferred through the arc.

Grum and co-authors studied the influence of workpiece adjustment and energy input on the quality of the resistance projection weld. The study is supported by a description of parameters of resistance projection welding that assure good quality of the product. The experimental part includes a description of welding with front and edge adjustments and choosing of the most suitable welding process parameters. The results of a quality evaluation of welds obtained by visual examination, mechanical welding and a metallographic analysis allow choosing of optimal resistance welding conditions.

Gliha researched the effect of small flaws on the fatigue strength of the heat-affected zone at the weld toe. Different artificial flaws were produced in the specimens by indenting them with a Vickers pyramid at different loads as a single or series indentation. The size of artificial flaws did not exceed austenitic grain size that is one of the most relevant microstructural units. The dependence of the experimentally determined bending fatigue strength of the treated coarse grain in the heat-affected zone of materials on the properly evaluated size of the artificial flaws was compared.

Kejžar and co-authors describe arc welding in different shielding gases in the paper titled 'New findings in welding of structural steels'. Particular attention was paid to the ability to obtain smooth and uniform metal transfer in a very wide range of welding parameters with certain gas mixtures. In pulsed arc welding the degree of penetration can be effectively affected by a pulse shape, energy and base current.

Kejžar and co-authors investigated the influence of different welding parameters on surface refining from the productivity point of view. Alloyed agglomerated fluxes can affect surfacing quality, especially of wear-resistant and corrosion-resistant cast irons on unalloyed structural steels.

In order to achieve a high removal rate and low electrode wear, when roughing by the sinking electrical discharge machining process, appropriate surface power density is required in the gap between the workpiece and the electrode. Valentinčič and co-authors presented a system for online selection of the rough machining parameters according to the given machining surface. The selection of the machining parameters is based on the acquisition of only the percentage of short-circuit discharges, which represents a noticeable improvement compared to known systems.

We would like to express our gratitude to all contributors to this special issue of the *IJMPT*. Our sincere thanks to Mr Franc Ravnik and Ms Nevenka Majerle, who provided enormous help in selecting papers, coordinating the reviewers and the authors, and in preparing the papers for publication.

Finally, we wish to thank the journal, *IJMPT*, and the Editor Professor Dr Dorgham, who accepted and endorsed our invitation to prepare this special issue. Many thanks are also due to the team at Inderscience Publishers for the assistance offered in preparing the materials published here.

We sincerely hope that the papers presented on induction heating, hardening and welding will be a valuable source of information to researchers and engineers in their professional activities.