LEP - Laboratory for Electroheat of Padua University

The Laboratory for Electroheat of Padua University, LEP, is the only Italian academic group that researches about electroheating. LEP was founded about 40 years ago by prof. Di Pieri, it was leaded for many years by prof. Lupi and now it is directed by prof. Dughiero. Actually, about 10 people are working in the group. It is also the organizer of the conference ‘HES’. Heating by Electromagnetic Sources, whose 6th triannual edition will take place this year in May.

In the paper, the latest research activities of LEP are presented, mostly with reference to the fields where LEP concentrates its research activity: innovative technologies for the through heating of non ferrous billets, contour induction hardening, silicon melting and crystallization, microwave heating and biomedical application of electromagnetic fields.

HISTORICAL BACKGROUND
The first years after the second World War have seen in Italy an increasing interest for all induction heating applications, mostly due to the fast development of the automotive industry. The main center of this interest was Padua, where a wide research activity was initiated and developed at the University by the emeritus Prof. Ciro Di Pieri.

In 1931 he graduated at the University of Padua and started his activity at the Institute of Electrotechnics. From 1943 he oriented his research on frequency converters, medium and high-frequency heat treatments and, in general, all induction heating applications.

He dedicated his scientific interest not only to the theoretical research but also to industrial realizations as technical director of the company SIATEM - Società Italiana Apparecchiature Termo Elettromeccaniche, establishing a very close and fruitful link between university and industry and a new school on induction heating at the University.

An important step forwards for the research activity was made by prof. Di Pieri in 1969 with the foundation of the "Laboratory of the Institute of Electrotechnics and Electronics of the University of Padua for researches and tests in the field of induction heating and hardening"; the laboratory was equipped with a 100 kW motor-generator at 9800 Hz and a 90 kW HF generator at 450 kHz.

From 1983 till his retirement in 2010 the activity of the laboratory has been directed by the emeritus prof. Sergio Lupi. The main research activities till 2010 are extensively described in [1,2,3].

Nowadays, all the facilities available in the Laboratory have been replaced with modern solid state generators: a MF generator, 200 kW – 2 to 30 kHz and a HF one, 200 kW to 200 kHz.

MAIN RESEARCH ACTIVITIES
PMH – Permanent Magnet Heating
The mass heating of billets before hot metal forming plays a major role among industrial induction heating applications as regards the number of installations, unit rated power of the heaters and energy consumption. The efficiency of induction process, i.e. the ratio between the power transferred to the work piece and the power supplied to the inductor, is around 50 % for aluminum or copper billets. For these materials, a DC induction heating concept has been proposed to improve the process efficiency. In this approach the billet is forced to rotate inside a transverse DC magnetic field by means of an electric motor. Due to the change of magnetic flux an induced current distribution reacts to the driving torque during the rotation and generates thermal power within the billet. The distribution of the average heating power and its dependence on the applied field and angular velocity have been demonstrated to be identical to those of conventional longitudinal flux AC induction heating, even if induced current paths are geometrically different (azimuthally directed in traditional longitudinal flux heaters while currents are mostly longitudinal in rotating heater). Recently, LEP has proposed a rotating system of permanent magnets as sketched in Fig. 1.

This solution looks very promising because it allows to reach high efficiency, that depends mostly upon the efficiency of the motor drive, without using an expensive superconductive system [a_3]. An industrial scale prototype (Fig. 2) has been recently realized and several tests have been carried out. The prototype has been designed to heat 200 mm diameter, 500 mm length aluminum billet of an approximate weight of 42 kg. The motor drive has a rated power of 55 kW at a rated speed of 2,500 rpm, while the magnetic field is produced by SmCo, rare earth permanent magnets.

The preliminary tests showed the robustness of the design of permanent magnet heater (Fig. 3). Several tests have been carried out up to around 400 °C, at various rotational speed: the global process efficiency (i.e. the ratio between the amount of heat supplied to billet and the total electric energy consumption) is around 70 %.
Electroheat and photovoltaic

The reduction of the environmental impact of electrical energy generation is nowadays a key issue for the electrical energy community. Photovoltaic (PV) is one of the most important sources for clean electricity and costs related to this technology are continuously going down, but the photovoltaic community needs further technological improvements to achieve a cleaner production of cells, cost competitive and less energy intensive.

The possibilities to develop electrothermal processes for industrial PV applications are numerous and LEP currently works on two projects related to PV: an induction DSS furnace for crystalline silicon casting and a thermal process for recycling end of life modules.

iDSS

The production of silicon ingots and wafers from raw polysilicon is one of the most cost and energy intensive process in the whole crystalline silicon solar panels production chain. Multi-crystalline silicon ingots and solar wafers are usually made using directional solidification system (DSS) furnaces with resistive heating (Fig. 4). While this technology is well established and mature, it has some drawbacks that can be hurdles for the competitiveness of the multi-crystalline silicon PV technology in the fast changing solar energy market.

The knowledge acquired by the Laboratory of Electroheat at Padua University on induction heating processes and the need for the photovoltaic industry to develop innovative solutions for keeping this industry competitive has pushed the start of the iDSS project: a DSS furnace based on an induction heating system.

The advantages of adopting induction heating systems, in substitution of resistors, range from the possibility to induce directly the heat to the hot zone of the system (e.g. the graphite susceptors inside the thermal insulation layers), thus reducing drastically the thermal losses of the system, to a better control of the temperature distribution during the melting and solidification process, allowing an active control of the process and producing silicon ingots and wafers with better physical characteristics.

Fig. 1: Concept of rotating permanent magnets heater; (a) Schematic of the rotating permanent magnet induction heater, (b) Induced current distribution in the billet and equiflux lines as result of a FEM calculation.

Fig. 2: Industrial scale laboratory prototype installed at LEP

Fig. 3: Arrangement of the permanent magnets inside the steel rotor

Fig. 4: Industrial scale laboratory prototype: 350 kg Multi-crystalline silicon ingot
A full-scale induction DSS furnace has been built by an Italian company in collaboration with LEP and a smaller 120 kg lab-scale furnace (Fig. 5) has been designed and built at Padova University in the framework of the project “Polo del Fotovoltaico della Regione Veneto”. This will allow to make experimental tests on silicon crystal growth and to develop and promote the use of induction heating systems in silicon casting applications.

PV Recycling
Most of the materials used in photovoltaic solar modules, (i.e. silicon, glass, metals and aluminium) can be easily recycled and reused in the solar panels production chain. The separation of these materials from end of life crystalline silicon solar panels, though, is a real technological challenge; in fact the polymeric materials used as encapsulant between solar cells, glass and backsheet layer act as a strong adhesive and don’t allow them to be mechanically separated (Fig. 6).

The recovery of silicon and glass from end of life c-Si solar panels is usually done manually after the incineration of the polymeric materials of the panels at high temperature in incinerating ovens with big environmental impact due to the emission of hazardous fumes.

At LEP a low temperature thermal process has been developed for the separation of glass from the solar panels. This de-lamination process is based on dielectric heating using radio-frequency and allow to heat directly the polymeric material used as encapsulant (EVA); heating EVA at temperature lower than 80 °C leads to the reduction of its adhesive strength and the possibility of mechanical separation of clean glass from the panel with no harmful emissions after the thermal treatment. This possibility has been demonstrated experimentally; further tests and multi-physics simulations are currently carried out for developing a full scale de-lamination system for the separation of glass and silicon from end of life c-Si photovoltaic panels.

Induction hardening of gears
Induction heating has been widely used by the heat treatment industry, i.e. in the wind-power and automotive sectors, in particular for hardening purposes, in a broad range of applications; main benefits of switching to induction hardening of gears are related to a significant reduction in process steps and fabrication costs, ease achievement of compressive residual stress, and lower distortions, in order to eliminate the grinding process. Though, traditional furnace-based case hardening still represents the choice of reference when performance requirements are particularly demanding, either for the critical operating conditions or safety-related issues.

An accurate optimization of the induction treatment by numerical means can speed-up the process development and help meeting design specifications and mechanical requirements (Fig. 7).

During induction hardening an high intensity magnetic field is generated by a contour single-turn coil, and high intensity currents are induced, heating the treated workpiece by Joule effect.

The induced power density distribution is mainly function of the material’s properties and frequency/ies of the exciting magnetic field.

The hardening process is generally carried out in two phases: a medium frequency (i.e. 5 to 20 kHz) pre-heating stage, in which the root of the gear is brought to a temperature close to 500 °C, and a high frequency (i.e. 100 to 400 kHz) heating stage that give the characteristic contour profile to the gear, reaching a superficial temperature of 1,000 to 1,100 °C in few tenths of second (Fig. 8). In this way, it is possible to localize the treatment only in a superficial layer, generally thinner than a millimeter.

An electromagnetic and thermal coupled numerical simulation (FEM) can be developed in order to predict the temperature distribution during the heating process.

LEP is working about induction hardening with several industrial partners. LEP also participates to the EU project ‘ESPOSA’, together with other 39 companies and research institutions from 15 European and non-European countries.

Magneto Fluid Hyperthermia
Magneto Fluid Hyperthermia (MFH) is one technique among clinical applications of hyperthermia for the tumor treating. MFH uses magnetic NanoParticles (NPs) dispersed in a fluid in order to heat locally a tumor mass. This technique provides a temperature rise that can
damage tumor cells because heating a tumor up to 42 °C can induce the cell apoptosis.

In this technique magnetic NPs are injected in the human tissues and heated by means of an external AC magnetic field. The target of MFH treatment is to heat uniformly and locally the tumor region. In order to improve the effectiveness of this kind of therapy, our laboratory has evaluated new designs of the heating systems by means of numerical simulation and optimization algorithms (Fig. 9). These numerical simulations are mostly intended to optimize the thermal source depending upon the NPs dimension and concentration.

The proposed solution is based on Loney’s solenoid scheme, that gives the possibility of adapting the induction coil shape to the various physical conformations of different patients and to the different region to treat (e.g. thorax or leg).

The final goal of the research is the design of the full therapy treatment planning.

**Electrochemotherapy**

Electrochemotherapy (ECT) is a cancer therapy that uses pulses of electric field in order to open some "pores" on cell membrane that improve the delivery of chemotherapeutic drugs into cancer cells (Fig. 10a). It is well known that, if the electric field strength overcomes a suitable threshold, it induces the reversible cell membrane permeabilization. In standard clinic therapy, the electric field is applied to tumor tissues by means of needle electrodes suitably positioned in the target volume.

Therapy optimization is searched in order to improve effectiveness. A multiobjective optimization method based on NSGA algorithm has been used to search optimal positioning of needles in the tumor mass to maximize the sub-volume where the electric field overcomes the electroporation threshold and preserve healthy or critical area. Fig. 10b shows an optimized electrode configuration and the electric field intensity on tumor (T) and healthy (H) tissue.

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**Fig. 8:** Temperature distribution at the end of high frequency stage; isotherm at 950°

**Fig. 9:** Color shade of temperature for optimized MFH treatment planning and optimized position of the inductors (Loney’s solenoid)

**Fig. 10a:** Electrochemotherapy (ECT) mechanism

**Fig. 10b:** Optimized electrode configuration and electric field intensity
Microwave Heating

LEP has recently started to research about applications of microwave heating (Fig. 11). Nowadays microwave ovens for household use and industrial installations at 2.45 GHz frequency band use magnetrons as a high power sources of microwave energy. Those bulky and old-fashioned devices characterize with limited efficiency of energy conversion from power supply to microwaves. They are also difficult to control, which leads to mismatch losses due to significant changes in reflection characteristics of the resonant cavity caused by large variations of load parameters (permittivity, loss tangent) as a function of its temperature.

New semiconductor technologies allow us for building innovative high power microwave sources. They exhibit great advantages over magnetrons like a precise frequency, phase and output power level control ability.

It is clear that the absorption of microwave energy in foods is dependent on both the electromagnetic fields and the microwave penetration pattern in the food material. The field distribution is in turn strongly influenced both by the type of cavity, the waveguide system, as well as by the type, shape and distribution of the food inside the oven.

Although traditionally extensive experimentation was the major technique exploited in the development of microwave (MW) applicators, it has been recently realized that advanced computer simulation could make the design of the MW heating systems more intelligent and thoughtful, shorten the development time, and reduce the project’s cost.

LEP is also involved in a EU FP7 project, ‘High efficiency electronic cooking systems HEECS’, which main goal is the design of an experimental set-up for microwave heating measurements, on the right: the simulation of microwave heating of a agar sample.
innovative microwave oven in cooperation with industrial and academic partners.

**OTHER ACTIVITIES**

**High performance computation for numerical modeling**

In most industrial cases, induction heating processes involves many different fields of physics, i.e. electromagnetic fields, thermal exchange, mechanical stresses, metallurgical phase transitions, fluid dynamics and other aspects. Thus, it is necessary to analyze multi-physics phenomena, not only by taking into account all the physics but also the correct interaction among them. This kind of virtual prototyping yields to very complex numerical simulations, characterized by a rapidly growing computational cost, in terms of very long computing time and large need of numerical memory.

With the purpose of reducing the computing time, and to facilitate the design and optimization of new processes, the most recent parallel hardware architectures and the most advanced numerical methods and parallelization techniques have been exploited to reduce the solution time of a commercial Finite Element software.

Thanks to fruitful cooperation with software houses (a special mention has to be done to Cedrat s.a., the French software house that develops Flux2-3D and INCA software) and international research teams, the computing time and memory needs have been considerably reduced and now results of complex multi-physics simulation of induction heating processes can be obtained in a reasonable time.

**International Collaborations**

LEP intensively collaborates with several Academic Intuitions worldwide. In particular, we acknowledge the active and fruitful scientific and didactic collaborations with Leibniz University of Hannover (Germany), University of Silesia in Katowice (Poland), École de Technologie Supérieure in Montreal (Canada), Saint Petersburg Electrotechnical University "LETI", Samara Technical University, Novosibirsk Technical University (Russia).

LEP collaborates also with University of Pavia, prof. DiBarba, in the field of inverse problems and optimization techniques.

**HES-13**

Since 1998, LEP and the Department of Industrial Engineering organize in Padua the triannual International Symposium HES - Heating by Electromagnetic Sources (Fig. 12).

The HES conferences have become a traditional appointment for all the researchers in the field of electroheating technologies, encouraging the meeting of Industries and Academic Institutions.


During the conference, authors coming from about 20 different countries will present the latest results of research and industrial development activities in the field of: Induction, Conduction, Dielectric, Microwaves Heating and EMP (Electromagnetic Processing). LEP invites you to attend the conference!

**LITERATURE**


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Authors:
F. Dughiero
M. Forzan
M. Bullo
F. Bressan
A. Doni
C. Pozza
E. Sieni
M. Spezzapia
A. Tolomio

Contact:
University of Padova
Dept. of Industrial Engineering
via Gradenigo 6/a
35131 Padova, Italy
www.dii.unipd.it