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Development of Customized Solutions – an Interesting Challenge of Modern Induction Heating

Jens-Uwe Mohring and Elmar Wrona
HÜTTINGER Elektronik GmbH + Co. KG, Freiburg
Germany

1. Introduction

Induction heating is a reliable and innovative technology which conquered a fix place in the most different markets. Today the fields of application run from the classical heat treatment in the metallurgical industry to modern crystal growing processes in the semiconductor industry. It is characterized by the fact that the required energy is non-contacting transmitted into the work piece where the transformation into warmth energy finally takes place. The most important advantages of induction heating against heat transmitting applications are reachable high rates of heat up speed, high efficiency, excellent reproducibility, and the possibility of automation of the process. For an extensive use of these advantages, it is necessary to have both the possibility to develop a suitable induction coil design and an innovative technique for the used power supply. These two aspects of the modern application development shall be highlighted in this report.

2. Effective development of customized solutions for industrial application

2.1 Definition of efficiency rates

The solution of a heating task for a given application starts with a calculation of the required usage power P_u which depends on the weight of material which has to be heated up in a certain time. In processes where the work piece is moved the time unit can be assigned to the mass of material instead of the temperature increase per time. An additional power which is necessary for the thermal heat losses by radiation and convection at the surface has to be considered for the whole required thermal power P_{th}. Up to 100°C the convection losses are dominant. Since the radiation losses depend on the temperature to the 4^{th} over 900°C the convection can be neglected. The ratio between the usage and the thermal power/energy is the thermal efficiency rate η_{th} which is a time dependant value (see Figure 1). To reduce the energy costs the heating time should be as low as possible. On the other hand, the installation costs rise with a shorter heating time. At last, the customer has to take into account the usage ratio of the system. For defining the optimal size he has to balance the three aspects.
For an induction heating application the required generator power P_G is the summation of the thermal power P_{th} and the ohmic loss power within the induction coil P_I which has to be

removed by the cooling water. The ratio between P_{th} and P_G is the electrical efficiency rate ηI of the induction coil. The value of η_I is strongly influenced by the material properties of the work piece and the design of the induction coil. Typical values can vary between 0.2 for materials like copper and 0.9 for magnetic steel below the Curie point. The generator itself has to deliver the power P_G and is supplied by the main with the power P_N. The ratio between P_G and P_N is the efficiency rate of the generator η_G. A modern electronic power supply can achieve a value of $\eta_G > 0.85$.¶

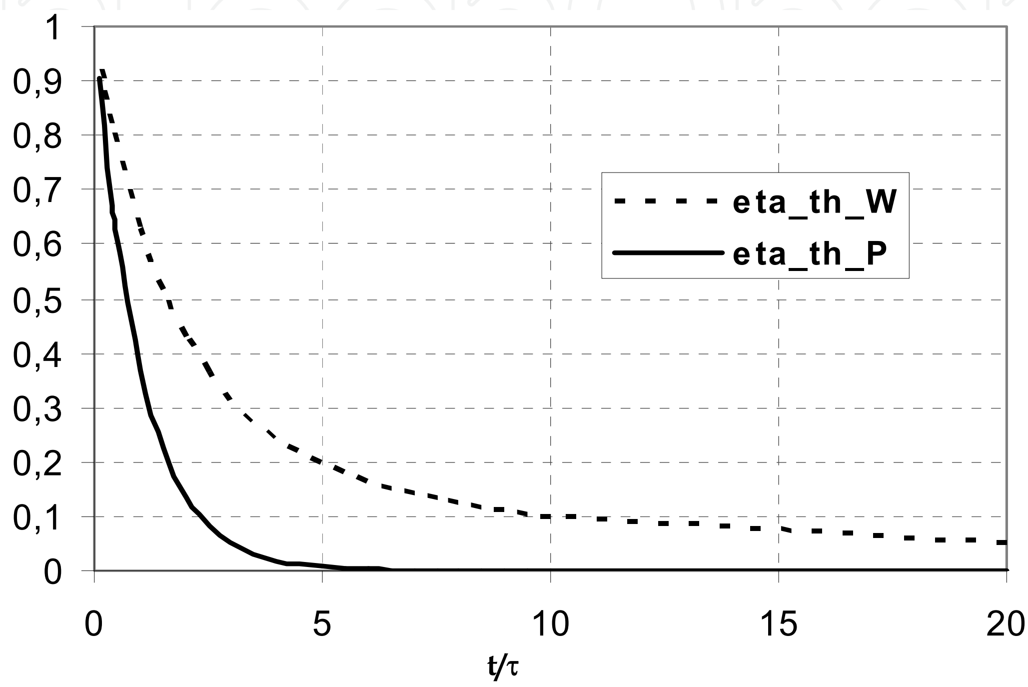

Fig. 1. Thermal efficiency rate for power (η_{th_P}) and energy (η_{th_W}) vs. t/τ. t is the heating time and τ is a constant time characterized by the work piece. Radiation losses are neglected.

2.2 Specifying the coil design

The most important and difficult part during the development of an induction heating application is to specify the optimal coil design. Solving this task the application engineer has to consider the aspects of reaching the heating goal, of maximising the efficiency rate η_I, and of optimising the load impedance of induction coil and work piece for the generator output. A classical cylindrical induction coil is defined by its number of turns, its length and its inner diameter. There is no possibility to calculate these parameters directly. The calculation can only be performed in one direction: from a certain coil design to the resulting heating of the work piece. Therefore, an iteration loop has to be passed to find suitable parameters of the induction coil. There are three different methods: the analytical calculation, the numerical calculation and the performance of experiments. Analytical methods for the calculation of cylindrical arrangements of coil and work piece are described by Nemkov [1] and Sluchotsky [2].

Meanwhile, for more sophisticated geometries the numerical calculation has developed to an essential tool for the application engineer. There are a couple of commercial software packages on the market using the method of Finite Elements (FEM), and since the personal computers have become very powerful in the last few years numerical calculations can be

performed quickly. Nevertheless, for an efficient and short-time development of induction heating application the engineer has to do some simplifications. For industrial needs in the most cases it is advantageous to calculate as accurate as necessary and not as accurate as possible. Typical simplifications are the use of geometrical symmetry planes to reduce the number of elements and the negligence of dependencies of material properties on temperature and/or electromagnetic field strength in case of magnetic materials. The last point makes sense since these material properties are very often unknown. For a lot of applications a precise knowledge of the local temperature distribution is not necessary too. Thus the resulting temperature field can be estimated by a calculation of the specific power losses distribution. So the computing time can be rapidly reduced. Hence, there are heating tasks which have to be computed by considering the temperature dependent material properties, e.g. hardening and soldering. Because of the greater complexity of such problems the performing of these calculations should be done in scientific laboratories.
The third method to develop customized solutions is to perform experimental tests. This way offers three important benefits. At first, the heating results can be directly controlled and measured at the real work piece. At second, after performing successful experiments a suitable induction coil design has been obtained. And the last not least, the heating effect can be impressively presented in combination with the generator to the customer. Recently, we can observe the trend that more and more customers tend to use this opportunity. Therefore, to have the facility of a well-equipped application laboratory with experienced engineers is a big advantage for the supplier of induction heating systems.

3. Investigation of a System for Crystal Growing by Epitaxy

3.1 Crystal Growing by Epitaxy

The crystal growing by epitaxy is used in the semiconductor industry, e.g. for the production of light emitting diodes (LEDs). Mostly planetary reactors (see Figure 2) are used, which basically consist of a water cooled stainless steel chamber and a replaceable graphite susceptor. The susceptor is the support plate for rotating carrier discs - so called satellites - with the substrates on it.

Fig. 2. Typical reactor arrangement for epitaxy processes

The customer has three basic demands. At first he wants to have a reliable heating system which delivers the necessary process power over many years. Furthermore, to reach good process results, the susceptor has to be very homogeneously heated up to temperatures of more than 1000°C in the region where the satellites are located. And nevertheless, the third demand of the operator is preferably low energy consumption and respectively a high efficiency factor. Therefore, the two main components of an induction heating system – the generator and the induction coil – must perfectly play together. The generator has to deliver very reliably his full power at chosen frequency. Moreover, it should be able to work over a wide frequency range so that the customer has a couple of opportunities to match different arrangements of coils and work pieces. The internal power losses should not exceed 15% of the nominal output power. The product family TruHeat MF 3010 – 7040 fulfils these requirements.

3.2 Dimensioning of a typical system

We want to present the different opportunities to develop an induction heating system for a typical arrangement for an epitaxy process. The susceptor to be heated is a slice of graphite with a thickness of 8 mm and a diameter of 320 mm. The induction coil has to be located at its lower side. At first we have to calculate the required power. For a goal temperature of 1100°C the convective heat losses can be neglected against the losses by radiation. With an emission rate of 0.92 we find a loss power of around 30 kW. This power has to be induced at least in the graphite to hold the temperature during the process. A suitable induction coil for a flat work piece is a so-called pancake coil (see Figure 3). It is a helical wound copper profile ($\gamma = 58{\cdot}10^6$ S/m) in one layer. We chose a coil with 6 turns made of a 15x10 mm tube with a wall thickness of 1 mm. The connection end of the inner winding is located at the lower side of the turns. The graphite slice ($\gamma = 70000$ S/m [3]) has a coupling gap of 10 mm to the coil surface.

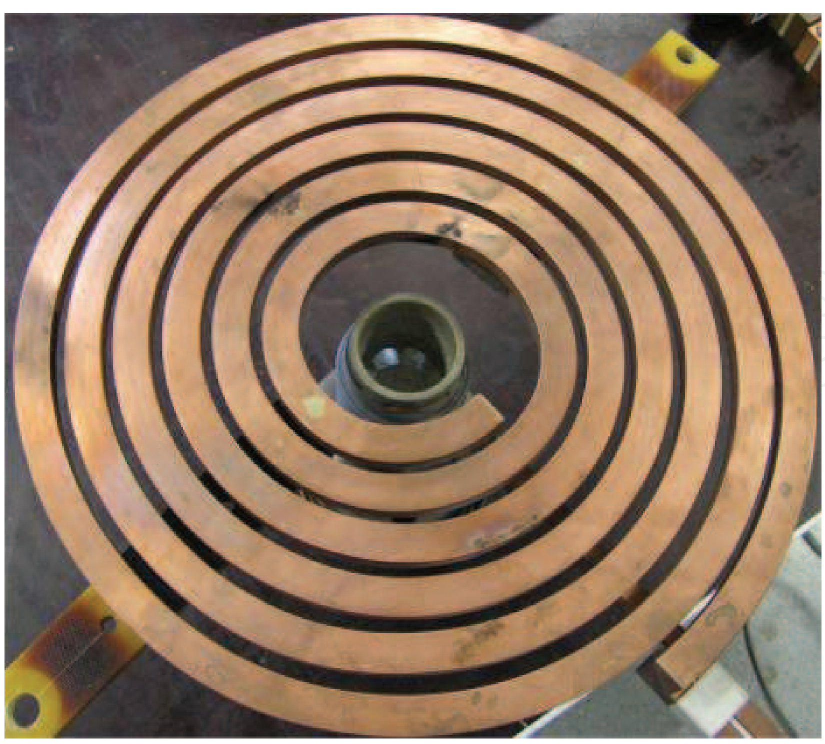

Fig. 3. Pancake coil

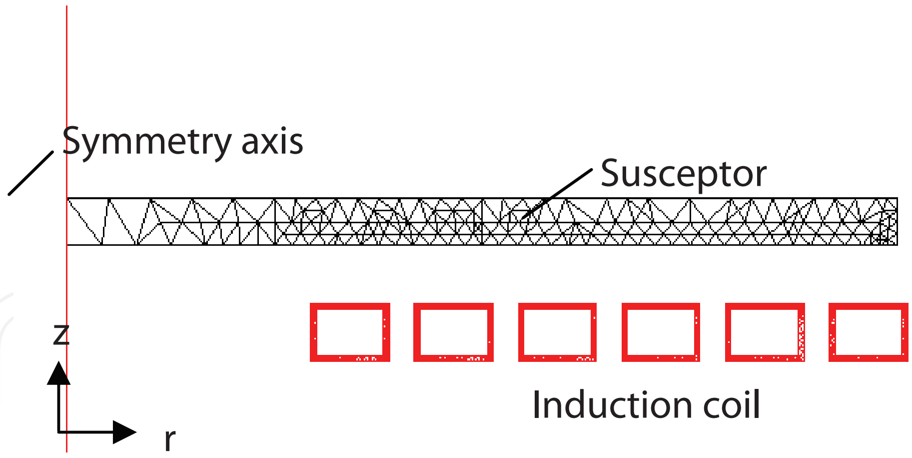

Fig. 4. Numerical 2d model with finite element mesh

To find out a suitable power supply we have to calculate the ohmic resistance R and the inductivity L of the coil and the work piece at the coil ends. The most effective and accurate way to obtain these values is by performing a numerical simulation of the electromagnetic field distribution. Since the turns of the coil are not circular there is no exact symmetry in azimuthally direction. But we neglect this small disturbance and only have to solve an axisymmetric problem in the (r,z) plane. The geometry mesh is represented in Figure 4. The numerical simulation is performed with the commercial software package MAXWELL. At the beginning we chose a certain current I of a certain frequency f in the coil, e.g. I=100 A and f=50 kHz.

From the simulation we obtain the integral parameters of the total electrical power P and the magnetic energy W_m. So we find the total ohmic resistance R and the inductivity L by:

$$R = P/I^2, \; L = \frac{2W_m}{I^2} \tag{1a,b}$$

The resulting load Z is a complex serial impedance of R and L:

$$\underline{Z} = R + j\omega L \quad \text{with} \quad \omega = 2\pi f \tag{2a,b}$$

Now we consider that our generator works with a parallel oscillating circuit, i.e. a capacity C is switched parallel to the induction coil in the tank circuit. We have to calculate C with the used frequency f by:

$$C = \frac{1}{\omega^2 L + \frac{R^2}{L}} \tag{3}$$

Since the system works at the resonance frequency the resulting load R' for the generator is given by:

$$R' = R(1 + Q^2) \quad \text{with} \quad Q = \omega L/R \tag{4}$$

The factor Q is called quality of the oscillating circuit. The suitable nominal power P_G of the generator is obtained from the required power in the work piece P_{th} and the electrical efficiency rate of the coil η_I which can be calculated from the power values. The nominal load R_G of the generator depends on the nominal output voltage U_G and P_G and should be equal to R'. In case of $R'>R_G$ we decrease f, if $R'<R_G$ we increase f and repeat the simulation until we find $R'\sim R_G$ and $C = n\cdot C_p$ where C_p is an available size of capacitors, e.g. 0.66 µF. At a frequency of 85 kHz we find a load which is good matched to a TruHeat MF 3040 generator which is presented in the next chapter. At a voltage of 82% (492 V) we have a generator current of 93% (68 A) and an induced power in the susceptor of more than 31 kW. The efficiency rate of the coil ηI is more than 90%. Figure 5 shows the distribution of the density of Joule heat sources p_V in the susceptor which is defined by:

$$p_V = \frac{J^2}{\gamma} \tag{5}$$

In Fig. (5) J is the current density. We can make out three areas of different values of p_V. In the centre of the susceptor a region of low intensity exists which comes from the type of the used coil. The current flows circularly in the slice and is equal zero in the axis. The second zone is the most important for the process because the satellites are located in this region. For the success of the process this zone should have a homogeneous temperature distribution. In the third zone at the outer perimeter of the susceptor the highest power density is induced. This is advantageous because of the higher radiation losses at the edge.

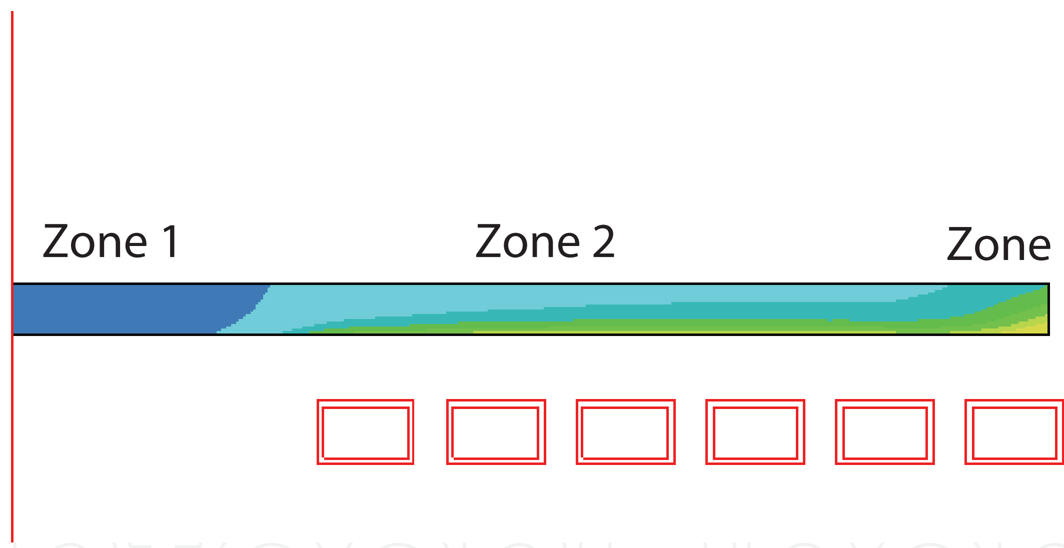

Fig. 5. Distribution of the density of Joule heat sources

3.3 Validation of the Numerical Model

To validate the results of the numerical simulation we performed measurements of the temperature distribution at the surface of the susceptor using an infrared camera system. The 2d-solver of the used software package MAXWELL only offers the possibility to compute steady state temperature fields. Therefore, we performed an experiment at a reduced generator voltage (20% of the nominal output voltage U_G). At this voltage (120 V) the susceptor surface was heated up to steady state temperature below 500°C. These values can also be reliably measured with our infrared camera system. At first we had to determine the emission rate of the graphite surface by comparing the temperatures measured with both a pyrometer and a thermocouple. We found a value of 0.92. For the numerical simulation we had to recalculate the distribution of the heat sources with the real current through the coil I_I at the chosen generator voltage U. The current can be calculated by (6) from the results of the former calculation since the values of R and L are independent on the voltage.

$$I_I = U / \sqrt{(R^2 + \omega^2 L^2)} \tag{6}$$

The 2d modeller of MAXWELL allows a direct coupling between an eddy current and a thermal simulation. In this feature the distribution of the Joule heat sources are directly imported by the temperature field solver. Due to the temperature dependence of the conductivity of graphite we calculated the value at 400°C (γ = 99200 S/m [3]). At the surface of the susceptor the boundary condition was set as radiation and convection while at the surface of the water-cooled coil a constant temperature of 25°C was defined. The convection coefficient was set to 7.1 W/m2K [4]. Figure 6 shows the calculated and the measured temperature distribution along the diameter of the susceptor. The measured curve was obtained after heating up the susceptor over a time of 12 min with a constant generator voltage of 120 V. We see a good qualitative agreement between both curves but a reasonable difference along the diameter of the slice. The measured temperatures are lower than the computed. We see two reasons for that. During the measurement the convection coefficient could be increased in comparison to the theoretical value because of air flows in the laboratory.

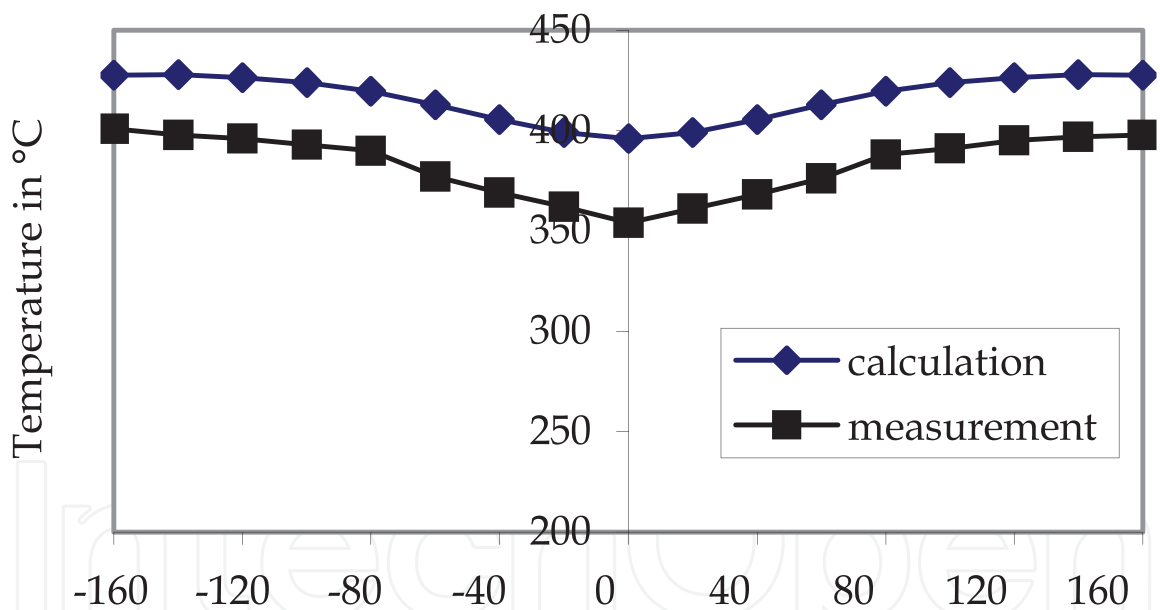

Fig. 6. Temperature distribution along diameter

Furthermore, we can assume that the steady state temperature distribution had not been reached after the heating time of 12 min. Considering this facts the numerical model seems to have a good accuracy. For the process of epitaxy the distribution is not homogeneous enough due to the temperature drop between the highest and the lowest value of nearly 10%. It is possible to decrease this value by changing the coil geometry. The application engineer has the opportunity of a local modification of the coupling gap and/or the distance between the turns of the coil. The effects of these modifications can be conveniently investigated with numerical simulations. In this manner an optimal solution for the customer can be developed.

4. Product Family TruHeat MF 3010 - 7040

4.1 General Information

The experimental investigations were done with the innovative induction heating generator TruHeat MF 3010 - 7040. This product family is available with 10, 20, 30 or 40 kW output power. The frequency range reaches from 5 to 100 kHz. The user has the possibility to operate at any frequency from 5 to 30 kHz or from 20 to 100 kHz. The TruHeat MF 3010 - 7040 was designed for mains voltages from 400 to 480 V. The generator works at any frequency in this range.

Three different variants of the TruHeat MF 3010 - 7040 are available. The basic version is the 19-inch plug-in module, designed for integration in a 19-inch rack (see Figure 7). This very compact variant offers the possibility to integrate the power supply very easy into the facility, e.g. in machines for modern crystal growing by epitaxy. This variant already offers the full functionality of the product family. The second version is the tabletop unit, which is the ideal heating equipment for stand alone operation. This variant is the best choice for laboratories, universities or companies with low amount of space. The third version is the cabinet. This is the traditional variant for industrial environment with a high protection class IP54. This enables the use even in rough conditions, e.g. in the field of induction hardening.

Fig. 7. TruHeat MF 3040, 19-inch plug-in

4.2 Technical specification

The 6-puls rectifier is connected directly – without using a relatively space consuming mains transformer – to the mains. This saves space and money.

The DC output voltage of the rectifier is controlled by a chopper unit, which enables to vary the output power (voltage or current) from almost 0 to 100 %. Therefore, the TruHeat MF 3010 – 7040 is ideal for high power as well as for low power applications, or for processes which need the full power range, e.g. to reach special temperature profiles.

The inverter is operated by an advanced control unit. It recognizes the frequency of the oscillating circuit and chooses the control parameters for the different frequency ranges by itself. As a result, the whole TruHeat MF 3010 – 7040 family needs only one inverter control board.
The output transformer fulfils two functions. It separates the mains potential from the application area and adapts the load to the power supply. The output voltage of the transformer can be switched from 600 to 300 V or vice versa very easy. Using this feature, the user has the full flexibility to solve different application tasks.
The described components are integrated in the power supply. It is connected with power cables to a parallel oscillating circuit, which has two main advantages in comparison to a serial oscillating circuit. The current in the induction coil – thus the electromagnetic field – can be increased by incrementing the factor Q. In addition to that, the matching of the generator and the load can easily be done by changing the capacity. An overview of the features and benefits of TruHeat MF 3010 – 7040 is shown in Figure 8.

Features	**Benefits**
■ Compact design, high power density	■ Low space requirement for easy system integration
■ Mains voltage of any value between 400 V -10% and 480 V +10%	■ Application in almost every country possible
■ One MF-transformer for 300 V and 600 V output voltage	■ Full flexibility to solve different application tasks
■ Parallel oscillating circuit	■ Quick process adaptation by changing the capacity ➔ low set up time and high flexibility in use
■ Control of the process power from almost 0 % to 100 %	■ Ideal for temperature controlled processes

Fig. 8. Features and Benefits of the TruHeat MF 3010 - 7040

5. Conclusions

The induction heating is an innovative technology which offers important advantages against heat transmitting application. For an extensive use of these advantages it is necessary to have both the possibility to develop a suitable induction coil design and an innovative technique for the used power supply. We have highlighted these two aspects in the report. We have discussed three methods for analyzing induction heating systems, and have shown that the numerical simulation of electromagnetic and thermal fields has been developed to an essential tool for the application engineer. Together with the possibility to perform measurements it allows the effective and quick development of customized solutions. Our generator family TruHeat MF 3010 – 7040 can deliver its nominal output power over a wide frequency range. Because of its low space requirement and its high flexibility in use it is the ideal power supply for modern induction heating application.

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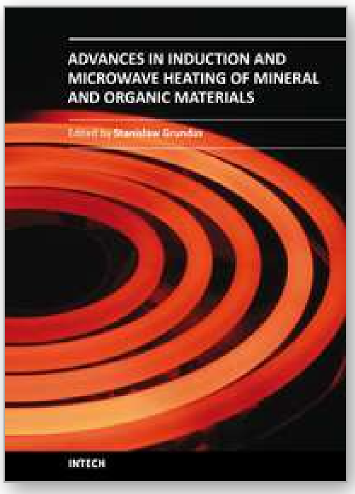

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The book offers comprehensive coverage of the broad range of scientific knowledge in the fields of advances in induction and microwave heating of mineral and organic materials. Beginning with industry application in many areas of practical application to mineral materials and ending with raw materials of agriculture origin the authors, specialists in different scientific area, present their results in the two sections: Section 1-Induction and Microwave Heating of Mineral Materials, and Section 2-Microwave Heating of Organic Materials.

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