Acta Mechanica Slovaca **29 (2): 54 - 58,** June **2025**
https://doi.org/10.21496/ams.2025.019

Acta Mechanica Slovaca
ISSN 1335-2393
www.actamechanica.sk

Design of a Device for Recycling Metal Hydride Alloys Prior to Melting

Peter Čurma [1,*], Marián Lázár [1], Natália Jasminská [1], Peter Milenovský [1]

[1] Technical University of Košice, Faculty of Mechanical Engineering, Department of Power Engineering, Vysokoškolská 4, 042 00 Košice

Abstract: The present article deals with the recycling of metal hydride alloys, as part of the melting process, conducted with the use of a newly-designed prototype device. Individual induction heating parameters that affect the efficiency of the process of melting metal hydride alloys are analysed. The induction heating method, its effects on the melted metal hydride alloy, and potential optimisation of the recycling process are analysed in detail. The article also presents specific designs of the induction heating apparatus, including a crucible. The construction of the oscillator module, the source module, and the water-cooling module that are required for controlling the melting process are described in detail.

Keywords: metal hydride alloy, induction heating, recycling.

1. Introduction

Metal hydride alloys exhibit nucleophilic, electrophilic and radical behaviour. Behaviour specifics typical for a particular metal hydride complex are determined by its chemical properties, primarily the bond-dissociation energy od the M-H (metal-hydride bond) and the nature of the other reactant [1].

Out of a wide range of heating technologies, high reactivity and high melting points (1,300–1,500 °C) of metal hydride alloys determine only a small number of techniques that are applicable in the process of melting metal hydride alloys in an inert atmosphere (nitrogen, argonium) or in a vacuum. Those techniques include induction heating, photothermal heating, electron beam heating, or plasma heating [2]. The use of induction heating in the process of melting metal hydride alloys offers multiple advantages compared to the other heating methods. The first and undisputable advantage is that such technology is cheaper and less difficult to operate from the technological point of view. Since the thermal energy is generated directly in the material and not in the surrounding environment, the process efficiency is higher than the efficiency of conventional methods. Heating is targeted on the desired area only, and thus the undesired heating of the surrounding components is limited and the risk of material degradation is reduced. Induction heating is very fast as the energy is transferred directly into the material through the electromagnetic field, and that minimises the heat loss. Due to the fact that induction heating facilitates accurate regulation of the temperature, the rate of impairment of metal hydride alloys is lower. With correct heating parameters, the process may be run in an inert atmosphere (in a chamber or by active blowing) or in a vacuum. That minimises oxidation and increases the purity of melted metal hydride compounds. During induction heating, the heat applied is evenly distributed; therefore, temperature gradients are lower and so is the probability of internal tension and the consequent material disintegration. With regard to those advantages, induction heating is often a preferred method in the processing of metal hydride alloys, primarily in applications that require high purity and efficient

*** Corresponding author:** Peter Čurma, ***E-mail address:*** *peter.curma@tuke.sk*

temperature regulation. Therefore, the device presented in this paper is an air-core transformer, while the induction furnace coil is the primary coil and the heated object is the secondary coil. Changes in the magnetic field induce the formation of heat losses inside the heated object so the object is actually heated by those losses. The useful heat is therefore generated directly in the heated material [2], [3].

In the process of induction heating of metal materials, two types of electric losses occur – eddy current losses and hysteresis losses. The eddy current losses are caused by the currents induced inside the heated object, i.e. the loop currents. Since the material inserted in the furnace has a non-zero electrical resistance, eddy currents cause electric losses that are transformed into the required useful heat. The hysteresis losses in ferromagnetic materials are caused by alternating magnetisation and demagnetisation of the object inserted in the induction furnace. The magnitude of those losses depends on the area in the hysteresis loop of the material and the magnetic field frequency. Hysteresis losses are also transformed into useful heat directly in the heated object. This means that in the case of paramagnetic materials, the heat is generated as a result of eddy currents only. The effect is that Joule heat is generated in the parts in which electric currents are induced; it may be expressed in differential form as follows (1):

$$\mathrm{d}Q = \rho \cdot J^2 \cdot \mathrm{d}V \cdot \mathrm{d}t\,(\mathrm{J}), \tag{1}$$

wherein ρ is the electrical resistivity of the crucible material (Ω·m), J is the current density (A·m^{-2}) and $\mathrm{d}V$ is the elementary volume (m^3) [4].

2. Design of the Experimental Device

With regard to relatively high temperatures that must be achieved in order to melt a metal hydride (MH) alloy, it is also important to develop an optimal design of the crucible, which must be made of a suitable material. Even though metal hydrides are metal compounds, their fine structure with multiple edges causes that they exhibit high electrical resistance that hinders the induction heating of the alloy as such. A solution to that problem is the choice of a metal crucible. Wolfram crucibles are ideal for induction heating, especially in cases when extreme thermal resistance and stability at very high temperatures are required, while the purity of the melted alloy must be guaranteed. Wolfram is chemically inert to many aggressive materials that might react with other metals or ceramic materials at high temperatures. Wolfram is also paramagnetic; it means that hysteresis losses do not occur during induction heating. The dimensions of the custom-manufactured crucible are shown in Fig. 1 [5], [6].

The skin depth parameter δ corelates with the skin effect and depends on the frequency. In induction heating, δ expresses the distance from the surface of the heated object to which the electromagnetic energy penetrates and is transformed into heat. Thin materials are heated using a high frequency at which a short skin depth is practically not applied. On the other hand, in the case of thick materials, a low frequency should be used since the skin depth is longer and hence the material is heated more evenly. However, in real life, thick materials are sometimes heated with the use of high frequencies, for example, when only a thin layer on the surface must be heated in a very short time. Therefore, when choosing the working frequency, it is necessary to consider the object to be heated. The skin depth is expressed as follows (2):

$$\delta = \frac{1}{\sqrt{\pi f \sigma \mu}}\,(\mathrm{m}), \tag{2}$$

wherein f is the oscillator frequency (Hz); σ is the conductivity of the heated object material (S·m^{-1}); and μ is the magnetic permeability of the heated object material (H·m^{-1}).

Figure 1: Wolfram crucible dimensions in mm.

The power required may be expressed as follows, provided that the temperature of the crucible and the temperature of the charge immediately before and after the heating are identical (3):

$$P_i = \frac{(m_t \cdot c_t + m_v \cdot c_v) \cdot (T_1 - T_0)}{t} (\mathrm{W}), \tag{3}$$

wherein m_t is the mass of the crucible (kg); m_v is the mass of the charge (kg); c_t is the specific heat capacity of the crucible material (J·kg^{-1}·K^{-1}); c_v is the specific heat capacity of the charge (metal hydride) (J·kg^{-1}·K^{-1}); T_0 is the initial temperature (K); and T_1 is the final temperature (K).

With regard to the experimental purpose of the apparatus, which was used with only a small amount of the charge, the process of induction heating was carried out, due to practical and economic aspects, with the use of a commercially available Zero Voltage Switching (ZVS) driver of the maximum input power of 1 kW and the input voltage of 12–48 VDC [8].

The ZVS driver is a modified Royer oscillator with a sinusoidal output. The working frequency of the oscillator when idle is determined by the capacity of the resonant capacitor and the inductance of the primary coil [9].

The primary coil, in the shape of a solenoid with 7 turns, a height of 54 mm and the identical mean diameter, was comprised of a thin-wall copper tube with an outer diameter of 6 mm and a 1 mm thick wall. The self-inductance of the solenoid may be expressed as follows (4):

$$L_0 = \frac{\mu_0 \cdot N^2 \cdot A}{l} = \frac{\mu_0 \cdot N^2 \cdot \pi \cdot D^2}{4 \cdot l} = \frac{1.26 \cdot 10^{-6} \cdot 7^2 \cdot \pi \cdot 0.054^2}{4 \cdot 0.054} = 2.618 \cdot 10^{-6}\ H \tag{4}$$

wherein μ_0 is the vacuum permeability (1.26·10^{-6}H·m^{-1}); N is the number of turns of the primary coil (1); A is the cross-sectional area of the solenoid in the radial plane (m^2); D is the mean diameter of the solenoid (m); and a l is the length of the coil (m). Formula (4) is derived under the assumption that the coil length is significantly greater than its diameter. In the present context, this condition is not fully met, which introduces a degree of inaccuracy.

The working frequency of the idle oscillator may thus be expressed as follows (5):

$$f_0 = \frac{1}{2\pi \cdot \sqrt{L_0 \cdot C}} = \frac{1}{2\pi \cdot \sqrt{2.618 \cdot 10^{-6} \cdot 1.98 \cdot 10^{-6}}} \approx 69.9\ \text{kHz}, \tag{5}$$

wherein C is the capacity of the resonant capacitor (F) [10,11].

When the crucible is inserted into the primary coil, its inductance decreases, and hence the resonant frequency of the ZVS driver increases [12].

For practical and safety reasons, the induction heating apparatus was segmented into 3 modules. The first module (Fig. 2) consists of the ZVS oscillator and the primary induction coil. The panel contains the outlets of the water-cooling system and 4 mm banana connectors. A 10K NTC (negative temperature coefficient) thermistor is glued with thermally conductive glue to the outer shell of the exit part of the induction coil. Its terminals are connected to the panel through a C01 industrial connector.

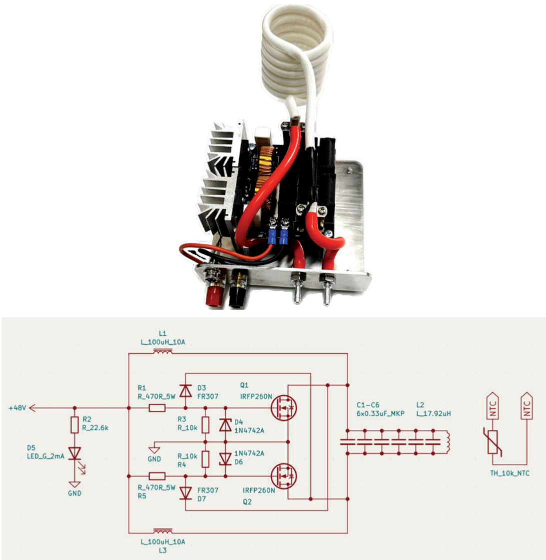

Figure 2: Module 1.

The second module (Fig. 3) consists of the powered source 48V 21A. The source has a fan for forced convection. Power is supplied through a C14 power connector. The power supply to the source may be interrupted using a two-position button. Since the circuit protection is integrated in the source, a 20A fuse was installed in the low-voltage section. Since the voltage and current conditions indicate a risk of an arc discharge, a 200A battery disconnector was used as an emergency stop. Voltage indicators are installed on the panel. 4 mm banana jacks were used as the output terminals.

Module 3 (Fig. 4) is a water-cooling module. The fan provides the forced convection of the heat from the cooler into the surrounding environment. The required pressures were achieved by using an expansion vessel with an integrated 10W pump for active circulation. Similarly to Module 2, power supply was ensured through a C14 connector. The power supply to the

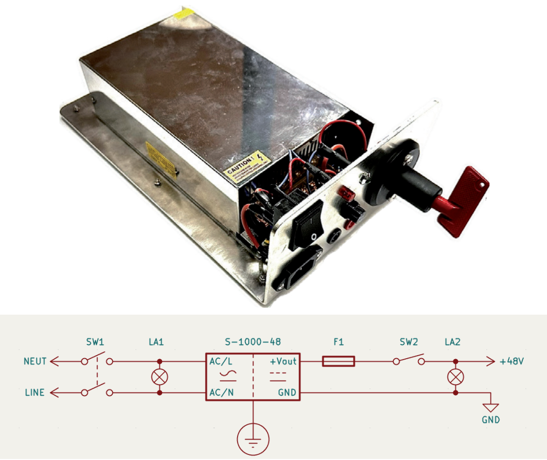

Figure 3: Module 2.

source may be interrupted using a two-position button and power supply indicators are installed on the panel. The thermistor is connected via a C01 connector. The pump, the fan and the thermostat are powered by the 12V 2A power source. The pump ensures constant circulation, while the fan is actuated by the thermostat as soon as the temperature on the outer shell of the output of the induction coil exceeds 40 °C. The device is turned off while taking into account the required hysteresis in the case of a temperature drop to 35 °C. 10% aqueous solution of ethylene glycol containing biocidal and anticorrosive additives is used as a heat-

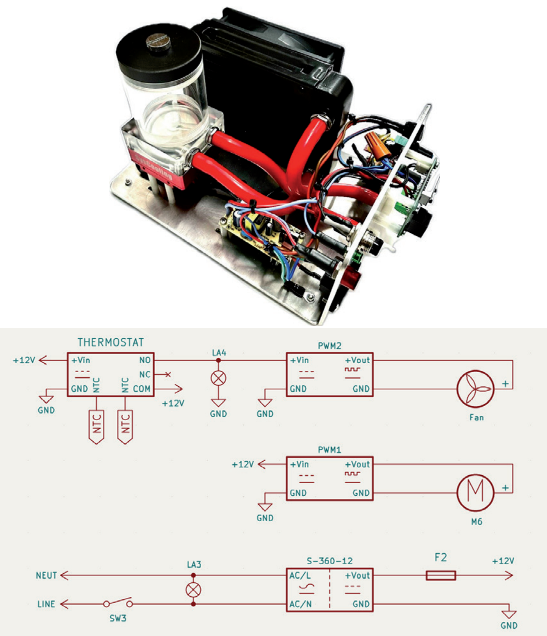

Figure 4: Module 3 diagram.

carrying medium.

As mentioned above, the heating was regulated through inserting the crucible into the primary coil and pulling it out. Accurate monitoring of the temperatures of the charge was facilitated by a Type C thermocouple.

3. Discussion

Skin depth δ depends not only on the frequency, but also on the temperature of the heated material, while the skin depth increases as the temperature rises. The low-frequency range of 1–50 kHz is suitable for deep penetration of heat into the object material. The mid-frequency range of 50–200 kHz is a compromise between the skin depth and the efficient heating. The high-frequency range of 200 kHz – 1 MHz is suitable for surface heating and is primarily applied in the process of surface hardening.

When choosing a working frequency, it is also necessary to consider the fact that the working coil not only exhibits reactance, but also comprises a parasitic resistance arranged in series. The coil reactance depends on the frequency, but the resistivity practically does not change as the frequency changes. At a low frequency, when the reactance is low, voltage drops mostly occur on that parasitic resistance. In those cases, majority of the output is transformed into heat inside the coil turns and the output is not transferred to the heated material. Therefore, induction furnaces are typically powered by high-frequency sources with a frequency of tens to hundreds of kHz [3], [4], [6].

Common challenges that must be faced in the foundry sector also include adhesion. In the process of melting metal hydrides, particularly mechanical and chemical adhesion causes problems. Mechanical adhesion is conditioned by the penetration of the melt into the pores of a wolfram crucible manufactured by the sintering technology. At high temperatures, the crucible material may react with the melt. Diffusion process also represent a hazard since in certain conditions the melt may wet the crucible wall. The aforesaid problems may be avoided by applying separation barriers, such as boron-nitride- or yttria-based coating.

For the purposes of the herein presented method of melting MH alloys, the most appropriate alternative is the use of a thin layer of boron nitride (BN). BN is thermally stabile, chemically inert, and does not affect the melt quality. The most costefficient method is the application of such a layer in the form of a spray or suspension, which is subsequently dried. Prior to the application of the coating, the surface must be thoroughly cleaned and degassed. After the application, additional burning is recommended at temperatures of 500–800 °C [7].

4. Conclusion

Based on the conducted analysis of induction heating methods and the subsequent designing of the induction heating device, it is possible to state that induction heating is an efficient method of melting metal hydride alloys for recycling purposes. By optimising the heating parameters and choosing optimal structures of the individual modules of the system, it is possible to achieve high efficiency of the heating process and extend the recycling options. The outcomes of the present paper provide important information for the further development of induction heating technologies used in the processing of metal hydride materials. The technological apparatus described in this paper offers a prospective potential for further optimisation and industrial applications.

Acknowledgments

This work was supported by the Slovak Research and Development Agency under the Contract no. APVV-23-0266 and APVV-21-0274, by internal grant IVG-25-01 and the VEGA granting agency within the Project No. 1/0224/23.

References

1. Evans, M. 2.6: Metal Hydrides. Available at: https://chem.libretexts.org/Bookshelves/Inorganic_Chemistry/Organometallic_Chemistry_(Evans)/02%3A_Organometallic_Ligands/2.06%3A_Metal_Hydrides.
2. Pickering, L. et al (2018). Induction melted AB 2 -type metal hydrides for hydrogen storage and compression applications. In: Materials Today: Proceedings, DOI: https://doi.org/10.1016/j.matpr.2017.12.378.
3. Nacar, S. et al (2022). Induction heated metal hydride tube for hydrogen storage system. In: Pamukkale University Journal of Engineering Sciences, DOI: https://doi.org/10.5505/pajes.2021.97692.
4. Lucia, O. et al (2014). Induction Heating Technology and Its Applications: Past Developments, Current Technology, and Future Challenges. In: IEEE Transactions on Industrial Electronics, DOI: https://doi.org/10.1109/TIE.2013.2281162.
5. Fashu, S. et al (2020). A review on crucibles for induction melting of titanium alloys. In: Materials & Design, DOI: https://doi.org/10.1016/j.matdes.2019.108295.
6. De Vaux, S. R. et al (2017). Influence of skin depth on convective heat transfer in induction heating. In: Magnetohydrodynamics, DOI: https://doi.org/10.22364/mhd.53.4.3.
7. Rudolph, S. (2013). Boron Nitride Release Coatings. In: WHITELEY, Peter R. (ed.). Aluminium Cast House Technology. Hoboken, NJ, USA: John Wiley & Sons, pages 163-170. ISBN 9781118806364. DOI: https://doi.org/10.1002/9781118806364.ch16.
8. AMAZON. ZVS Driver 1000W ZVS Induction Heating Module Low Voltage Induction Heating Board Module Tesla Coil Heating Power Supply Module 12V-48V Flyback Driver Heater DIY. Available at: https://www.amazon.com/induction-Heating-Voltage-Induction-Flyback/dp/B0BMF638YT.
9. Zin, R. M. et al (2017). Zero voltage switching driver and flyback transformer for generation of atmospheric pressure plasma jet. In: AIP Conference Proceedings, 1883, 020023, DOI: https://doi.org/10.1063/1.5002041.
10. Park, S. M. et al (2020). Optimal Design of High-Frequency Induction Heating Apparatus for Wafer Cleaning Equipment Using Superheated Steam. In: Energies, DOI: https://doi.org/10.3390/en13236196.
11. Truong, Ch.T. et al (2024). Improved ZVS Criterion for Series Resonant Converters. In: IEEE Access, DOI: https://doi.org/10.1109/ACCESS.2024.3350437.
12. Barman, B. et al (2024). Parameter Determination of a Multi-layered Induction Heating Coil: Analytical, Simulation and Experimental Studies. In: Journal of The Institution of Engineers: Series B, DOI: https://doi.org/10.1007/s40031-024-01000-7.