

On the Suitability of Induction Heating for the Manufacture of Reinforced Aluminum Foam Structures

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Abstract. Thanks to an intriguing combination of properties, aluminum foams are becoming materials useful for applications in several industrial fields and can be of great interest as core of reinforced structures. Starting from previous studies of the authors, this research work investigates the feasibility of using the induction heating, a fast, clean, and localized source of energy, to produce structures on aluminum foam, also reinforced; in the last case, by means of an innovative single-step process based on the powder compact melting technique, which considers a steel wire mesh-grid as reinforcement and as a mold. In particular, the aim of the work is a screen of the potential of the induction heating to manufacture plain and reinforced aluminum foam structures.

Introduction

Usually, sandwich structures based on aluminum foams present metal sheets or composite materials as skins; instead, the authors proposed the manufacture of structures with a core of aluminum foam and a steel wire mesh-grid as reinforcement and, also, as a mold. In doing so, they developed an innovative single-step process based on the powder compact melting technique, carried out in a muffle furnace [1]. This last solution presents some limits, in terms of speed and localization of heating. On the other side, induction heating (IH) is a non-contact heating method widely used in different industrial applications thanks to its high heating efficiency, easy automation, flexibility, and safety [2]. Furthermore, IH is an ideal energy source due to its high heating rate related to the unique characteristic of this heating method: the localized heating inside the workpiece without affecting the outside interested area [3,4].

Thanks to these characteristics, IH is applied in a wide range of industrial processing such as melting [5], brazing [6], sintering [7], welding [8,9] and additive manufacturing [10].

Electromagnetic IH is based on the eddy currents and hysteresis phenomenon. When a ferromagnetic or electrically conductive material is immersed in an alternating magnetic field, energy is directly targeted to the material and locally transformed into heat.

Two different dissipation phenomena convert energy into heat, whose occurrence depends on the nature of the materials: the Joule heating due to eddy currents occurring on electrically conductive samples and the hysteresis heating in the case of ferromagnetic materials.

The eddy currents flow on the workpiece's surface, resulting in molecular excitations inside the metals with subsequent heat generation. If the workpiece is realized with a ferromagnetic material, the heat is also produced by magnetic hysteresis. In this case, the magnetic field constrains the magnetic domain of the material to flow in the same direction of the magnetic line and this phenomenon generates heating [11].

This work aims to investigate the possibility to use IH to produce structures of plain and reinforced aluminum foam, starting from strips of extruded precursor. Concerning the idea of foaming by IH, it is worth highlighting that this system has been already used to produce aluminum foams. For example, Jeon et al. [12] considered the induction as the heating method in the foaming process of aluminum by complex stirring; they highlighted the capability of a good temperature control with this heating method.

In this work, foamable-solid precursor and stainless-steel wire mesh-grid were employed. Specimens of plain precursor and of precursor locked in a box of mesh-grid, used both as reinforcement skin and mold, were prepared and foamed by using an IH system with different coils and configurations. Before presenting the experimental campaign and showing the main results, the following subsection introduces the IH system.

Induction Heating System. An IH system, of which the principle is schematized in Fig. 1, consists of three main components: power supply, control panel and induction coil. The control panel makes possible to modify the process parameters, such as current, power, and heating time.

The induction coil is a fundamental part of the induction system; it is generally realized with copper, a material characterized by high thermal conductivity and low electrical resistivity compared to the other metal alloys.

The heating profile induced inside the material depends on the induction coil's dimension and geometry, which affect the heating rate, effective heat length, and heat penetration depth.

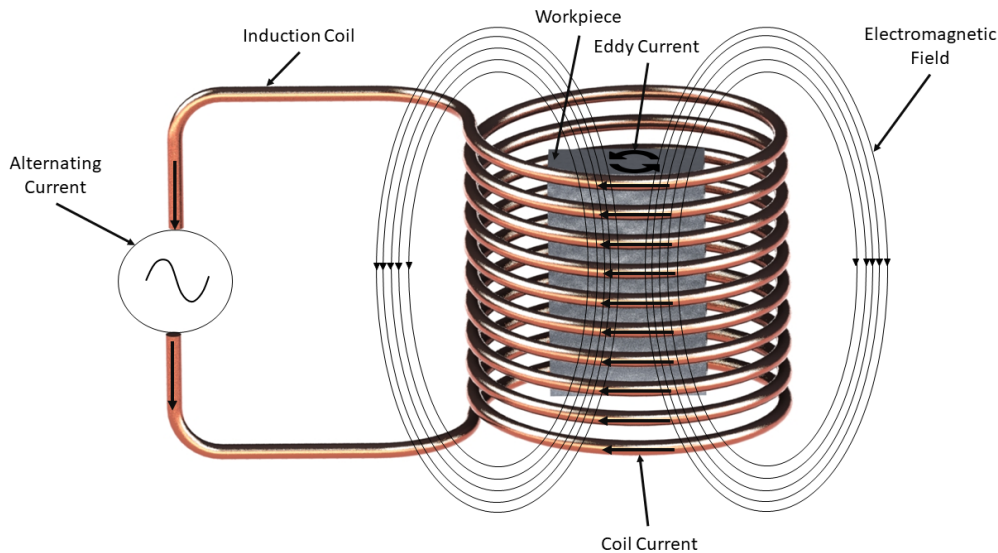


Fig. 1. IH principle.

In the metal alloys case, the heating depth of penetration can be obtained by Maxwell's equations [13], the formula of which is as follows (Eq. 1):

$$\delta = \sqrt{\frac{\rho}{\pi \mu f}} \quad (1)$$

where ρ is the resistivity of the material [$\Omega \cdot m$], μ is the magnetic permeability [H/m], and f is the frequency [Hz]. Thus, the depth of heat penetration depends on the material's characteristics and the frequency of coil current.

An IH presents a generator; the frequency at which it oscillates is the resonance between the inductance of the connected coil and the capacitance of the capacitor placed inside the generator. The formula to apply is (Eq. 2):

$$f = \frac{1}{2\pi\sqrt{LC}} \quad (2)$$

where L is the inductance [H], and C is the capacitance [F].

The value of the inductance depends on the geometrical features of the inductor such as the length l , the section A of the spire, and the number of turns N (span density $n = N / l$).

Finally, the current density generated in the workpiece thickness can be estimated by Eq. 3 [11]:

$$J = J_0 y \delta \quad (3)$$

where J is the current density at the distance y from the surface, J_0 is the current density at the workpiece surface, and δ is the penetration depth.

Materials and Methods

The aluminum foam precursor used in this study was supplied by *Alulight Company* (Austria). This commercial material is in the form of extruded strips, with a cross section of $20 \times 5 \text{ mm}^2$ (see Fig. 2, left); it is based on a mixture of Al and Si (10 wt.%) powders, and contains 0.8 wt.% of TiH_2 powder as the foaming agent [14]. A 0/90 stainless-steel wire mesh grid (6 mm \times 6 mm grid, wire diameter of 0.8 mm) was employed, an elastoplastic material with isotropic hardening. The main properties of both these constituents are reported in [15].

Heating tests were performed with an induction generator EGMA 30R, designed and developed by *Felmi* (Italy). While the frequency is kept constant, the power and the voltage can be tuned; the power can be set up to 30 kW, from 20% to 100% ranging, while the max value of the voltage is 500 V. Moreover, the coil distance, the maximum temperature, and the holding time can also be varied for each heating run process. The IH system is shown in Fig. 3. The experimental tests were performed selecting two different coil geometries, labelled D100_coil and D40_coil:

- D100_coil: Diameter of 100 mm, 5 turns, and total length of 65 mm;
- D40_coil: Diameter of 40 mm, 4 turns, and total length of 30 mm.

The generator controls the current frequency by an automatic coupling system called “auto-tuning system”, depending on the geometry characteristics of the coil used. The frequency at which the generator oscillates is calculated by Eq. 2; the value of the two coils used are characterized by two different values of frequency: 70 kHz for the D100_coil and 130 kHz for the D40_coil. The actual frequency was verified by the display of the generator used for the tests. In addition, the display shows the operating parameters of the machine, such as coil current and voltage.

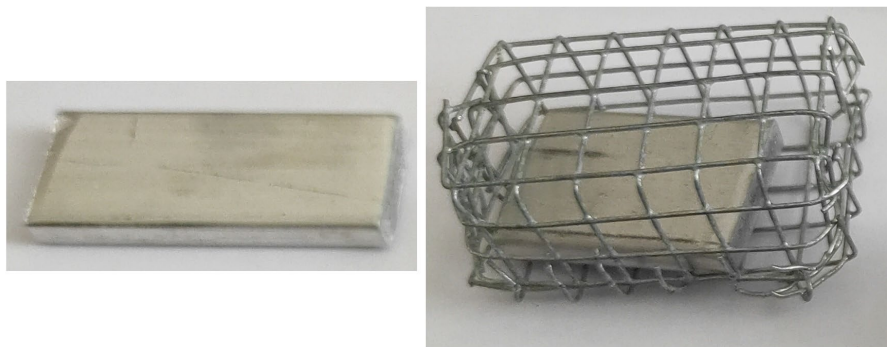


Fig. 2. Foam precursor and sample with precursor in a box of mesh-grid.



Fig. 3. IH test equipment.

Results and Discussion

Before showing the results of the tests, some considerations on the IH system are reported. Increasing the frequency, the amount of heat generated is more significant and the heating rate increases but, based on Eq. 1, the value of depth penetration of the heat inside the material decreases. The lower frequency inductor produces slower heating and is characterized by a greater penetration depth, increasing the value of the skin effect, resulting in slower but more uniform and controlled heating. Moreover, as reported by Rudnev [11], the magnetic field is maximum inside the coil (see Fig. 1).

Preliminary tests were carried out on pieces of precursor, to only investigate if the IH system can determine their foaming. They were positioned in different ways with respect to the coils. In the follow-up, the most interesting results are reported and discussed.

The first tests were with the precursor kept by a plier and positioned along the axis of the coil; both the coils allowed the foaming. Fig. 4 reports a foaming test with the precursor ($10 \times 20 \times 5 \text{ mm}^3$ in dimensions) along the axis of the more efficient coil, that is the D40_coil; the foamed precursor is reported in the lower-left corner of the figure. For this case, the foaming was obtained after a time of about 15 seconds at a voltage of 200 V; the cooling was in air (so as all the tests carried out in this experimental campaign). The cons of this solution can be attributable to the geometrical limits imposed by the internal dimensions of the coils, the necessity of a positioning and containment system and the eventuality of short-circuit of the system in the case of contact between the foam and the coil.

Successively, the feasibility of tests with the precursor outside the coils was evaluated. The solution with the precursor along the lateral surface of the coil resulted inefficient, both varying the process parameters and the coil; on the contrary, the tests with the precursor at the base of the coil were conducted with success (see Fig. 5, reporting a case with D100_coil and a piece of precursor of $20 \times 20 \times 5 \text{ mm}^3$ in dimensions). Compared to the case of Fig. 4, this last case presents higher foaming times. The results reported above are in line with [11]; in fact, when the precursor is placed inside the coil, the heating is more efficient.



Fig. 4. Foaming test of plain foam with the precursor along the axis of the coil and foamed precursor.



Fig. 5. Foaming test of plain foam with the precursor at the base of the coil.

Finally, tests with the precursor locked in a box of mesh-grid were conducted (see Fig. 2, right), to simulate the manufacture of reinforced structures with the grid acting both as reinforcement and mold. A piece of extruded strip with a length of about 30 mm was inserted in a parallelepiped box, $20 \times 25 \times 35 \text{ mm}^3$ in dimensions.

The setup used for the test is reported in Fig. 6a. Fig. 6b reports the result of this test, in which it is possible to note that the foaming process takes place into the box; in this case, the foam was obtained after 20 seconds at a voltage of 500 V. As already verified in [1], the box acted as a mold; in fact, the molded material did not come out of it. Concerning geometrical considerations, the foamed precursor occupied about the 50% of the box volume, and this translated into a relative density of the foam equal to about 0.35. In the light of the last considerations, future works can consider the optimization of some features, like the positioning and sizing of the precursor, as well as the control of the temperature and the cooling phase, in order to improve the quality of foaming and to avoid the coalescence and collapse of the gas bubbles [16].

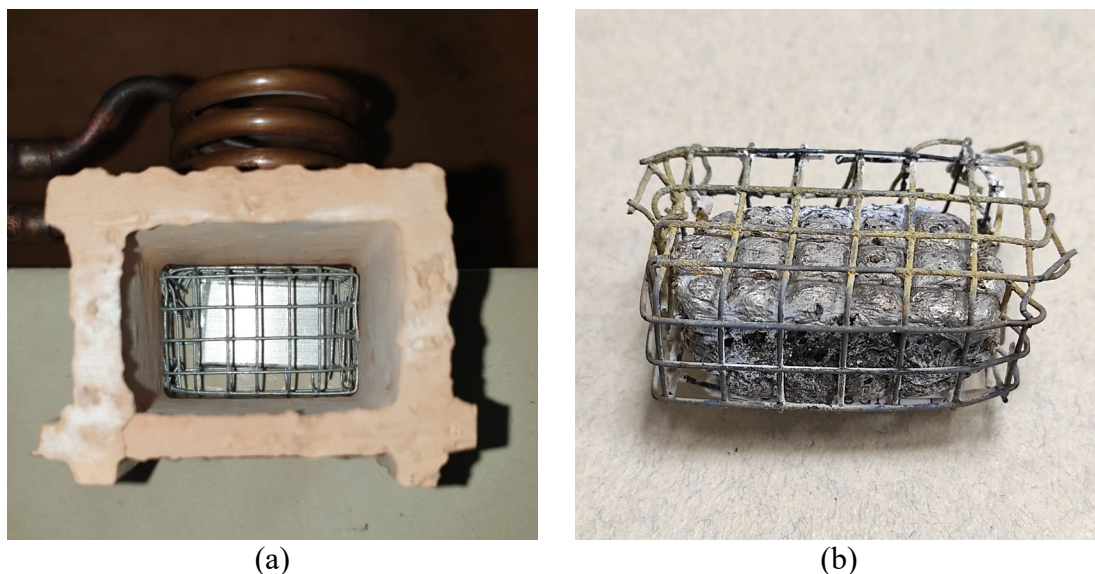


Fig. 6. Foaming test with the precursor locked in a box of mesh-grid: a) Setup; b) Foamed precursor.

Conclusions

The main goal of this preliminary work is to study a new, fast, and efficient heating technique to foam a metal precursor; more in detail, the induction heating is considered for an innovative one-step process, in order to manufacture plain and reinforced aluminum foam structures.

The results from an experimental campaign show that it is possible to reach the temperatures necessary for the precursor to foam in a few seconds, all using an easily automated system. In addition, various setups were analyzed to make heating more efficient. Finally, a steel wire mesh-grid can be used as foam reinforcement and, also, as a mold.

Future works will involve the optimization of the process setup: in detail, they can consider the control of the temperature and the cooling phase, the design of ad hoc induction coils, as a function of the applications, and the correct sizing and positioning of the samples; moreover, they can contemplate a mechanical and morphological characterization of the structures realized. Moreover, further subjects of investigation can be the heating frequencies, so as the propagation of the heat field as a function of the magnetic field, also by using finite element method analyses.

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