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PRODUCTION OF FLAT PARTS FROM FOAM ALUMINUM IN ALTERNATING MAGNETIC FIELD

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The electromagnetic technology for production of ultralight panels of materials based on foam aluminum is investigated. The theory of the interaction of the electromagnetic field with matter in the solid-liquid state and the formation of its corresponding distribution in space and time for the implementation of new technologies and equipment are considered.

The suggested technology for the production of ultralight panels of materials based on foam aluminum include the following main stages: loading of powdered raw materials; preparation of the blank and the formation of the container; compacting (consolidation) by hot rolling; foaming of the preform precursor; production of a marketable product. The most difficult task is the process of heating the precursor to the temperature of foaming. In the course of the research, two possible modes of blank heating – static and periodic with reciprocating motion – were considered.

The requirements for ensuring the temperature field of heated blanks for the production of foam aluminum are presented. The determining factor in the selection of the heating mode is the criterion for the quality of the blank heating. The main parameters that provide the required temperature field are the selection of the blank heating mode; speed of workpiece movement, and frequency selection. The displacement amplitude for reciprocating motion was chosen based on the available theoretical and practical experience of heating in this mode. The choice of frequency was influenced by several parameters, such as efficiency, voltage and current of the inductor, and its reactive power.

The optimization of the process of electromagnetic processing of flat products on the basis of foam aluminum according to the results of numerical simulation makes it possible to develop an electromagnetic system for influencing metals in the solid-liquid state.

***Key words*:** foam aluminum production technology, electromagnetic field, electromagnetic processing of materials, induction heating, solid-liquid state of metal

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Introduction. Because of a complex of unique physico-mechanical and chemical properties the aluminum alloys are now being increasingly used in modern technology [4, 5, 9]. Today, the use of aluminum alloys in the aerospace, shipbuilding, chemical and other industries can be considered traditional, but the scope and conditions for their use are constantly expanding (for example, cryogenic products, hydro and electrometallurgy, energy, etc.). In connection with the increase in requirements for quality, reliability and safety of machinery and equipment, the requirements for materials used in its production also increase [2, 3]. To provide the required physical and mechanical properties of materials from aluminum alloys, certain requirements are imposed on the processing of such products, including heat treatment [1, 5, 12].

In this paper, we investigate the electromagnetic technology for producing ultralight panels out of materials based on foam aluminum. The production line makes it possible to obtain at the first stage a compacted intermediate product (precursor) having the thickness of 2.5 to 15 mm with a cladding thickness of 0.5 to 5 mm (Fig.1, *a*). The horizontal dimensions of the precursor are: width × length – up to 900 × 2200 mm.

The panel (sandwich) made of foam aluminum based materials (Fig.1, *b*) has the following dimensions: width × length – up to 900 × 2200 mm, thickness is 6-30 mm with cladding layers out of aluminum or titanium with thickness from 0.5 to 5 mm (usually 1 mm). The density of the foam aluminum layer is 300-1000 kg/m^3, the foam is with closed pores of average diameter of 0.8-4 mm.

a *b*

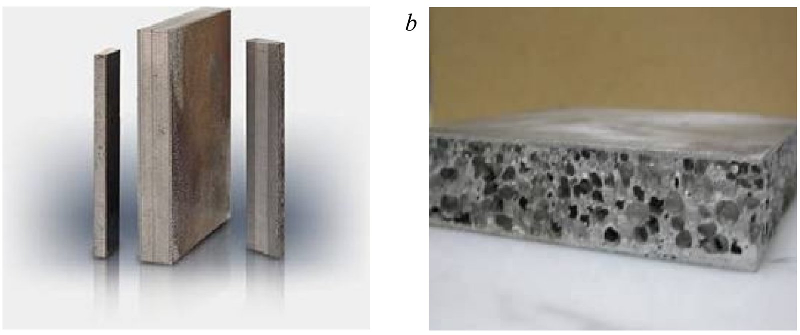

Fig.1. Precursors of different thickness (*a*) and composite panel (*b*)

The precursor is a cladding metal sheets layers of aluminum or titanium having the usual thickness from 1 to 5 mm made from pressed aluminum alloyed powder with 1 % of frothing material. The density of the precursor is at least 97 % of the compact metal (aluminum alloy). Thus, the properties of the precursor are almost similar to those of the compact aluminum alloy from which it was made. The precursor has specific effects due to the presence of cladding surface layers (titanium, aluminum). All properties of the foam metal layer directly depend on its density, which can be from 300 to 1000 kg/m^3.

The suggested technology for production of ultralight panels made of foam-aluminum based materials for further development in a project consists of the following main stages: loading of powder-like raw materials; batch preparation and container formation; compacting (consolidation) by hot rolling; foaming of the blank-precursor; production of the finished goods.

The raw materials include powders of various aluminum alloys, titanium hydride, as well as aluminum and titanium rolling [5]. In the production process, aluminum alloy powders [8], after mixing with a small amount of foaming material (titanium hydride), are poured into a flat steel or aluminum container ensuring the formation of predetermined geometric dimensions of the precursor and the final sandwich panel. The mixing process must be taken into account when designing an induction furnace used for heating in a periodic or continuous mode of a container of powdered aluminum alloys to 400-550 °C for subsequent hot rolling and obtaining a compacted intermediate flat product (precursor).

The container for powder filling is made of steel or aluminum rolled products and has horizontal dimensions corresponding to the dimensions of the precursor. Taking into account the closed edges, the width of the container exceeds the width of the precursor by about 4-5 cm. The thickness of the rolled metal from which the container is made is 1 mm. The finished container is placed on the loading device.

The container is loaded with a powder mixture with dosing and weighing. The powder mixture is fed into the loading device, where cladding layers of aluminum or titanium sheet are also added to the container. After loading, the mixture is pre-compacted.

The furnace is designed to heat the container up to 400-550 °C [10]. The conveyor of the furnace moves at the speed of the rolling mill (about 10 cm/s). After leaving the furnace, the container is immediately sent to a rolling mill for hot compaction. Depending on the design peculiarities, there is a possibility to provide intermediate heating to maintain the temperature of the container on the path to the rolling mill.

As soon as the container is heated to a predetermined temperature, it is subjected to rolling. The rolling mill compacts the container and its contents with a predetermined rolling thickness corresponding to the thickness of the precursor. The rolling mill operates at a speed of about 10 cm/s but there is a possibility to regulate it. Compacting makes it possible to obtain a precursor material with a density of at least 97 % of the density of the metal. At the exit of the rolling mill, the temperature of the container is within the range of 350-400 °C.

After rolling, the container with the inside precursor is fed to cutting or preliminary cooling. The container is cooled to a temperature suitable for being handled by operators. The container and precursor are cut at the edges along the entire perimeter. The size of the trimming can vary depending on the way the container is closed before it is compacted. After trimming, the container and precursor are separated. The precursor is placed in a closed ceramic mold and sent to the foaming oven.

Foaming is achieved by decomposing titanium hydride with the emission of hydrogen gas. The process of foaming passes at 700-750 °C with a change in the vertical size of the precursor by 3-5 times. The duration of the operation depends on the size of the panel and the power of the heater. During foaming, the precursor is packaged in a closed ceramic mold to ensure the preservation of geometric dimensions. When foaming, it is necessary to have a top and bottom restriction that forms an even surface.

Research methods. The research was carried out using computer simulation methods of mathematical physics and computational mathematics. As a basic method of research induction systems, a numerical method was adopted with the development and modeling of various computer systems. In particular, the simulation was carried out in the UNIVERSAL software environment [6] by computation of spatially three-dimensional temperature and electromagnetic fields [7].

Requirements for ensuring the temperature field of blanks. Modern metallurgical machine building is an extensive and multidisciplinary branch of industry, the characteristic feature of which is a huge variety of machines and mechanisms, different in design, types of operational loads, working environments, temperature conditions, etc. In accordance with this, the range of metallic materials used in machine building is very wide: engineering, stainless, acid-resistant, heat-resistant steel, steel for cryogenic temperatures and with special physical properties, alloys on copper, aluminum, nickel, titanium and other bases. However, the high rates of development of modern technology in various production fields place even greater demands on the development and working out of new metals that combine the properties of different metallic materials [13, 14, 17, 18].

The main requirements for the quality of heating of large-sized flat products based on aluminum alloys are: the formation of an extremely uniform temperature field along the length and section of the blank, and minimized heating time.

The first requirement is dictated by the feature of the technological process for the production of foam aluminum. It is necessary to ensure heating throughout the entire blank to a strictly pre-defined temperature with an error of about 20-40 °C. The underheating does not allow the alloy to achieve the necessary plasticity to form a porous structure due to the gas emission during heating process, and overheating results in complete melting of the entire blank. The second requirement is due to the fact that the increase in the duration time of heating significantly reduces the density of the material of the workpiece, which leads to a decrease in its physical and mechanical properties.

When choosing the best way to heat products based on aluminum alloys to the specified temperature, we should carefully consider the features of all possible heating modes.

Optimization of the process of electromagnetic processing. The process of heating the precursor to the foaming temperature is the most difficult task [11, 15, 19], therefore, to select the parameters of the induction heater, we will predominantly be guided by the data obtained during the simulation of the process of heating the precursor to the foaming temperature [6].

In the course of the research, there have been analyzed two possible modes of blank heating – static and periodic with reciprocating motion. Continuous mode was not considered due to the fact that it is requires simultaneous heating of the blank to the pre-defined temperature values all over its entire length.

Each mode has its own advantages and disadvantages. Thus, the static mode has a higher efficiency and, as a result, a shorter heating time, but it has a very significant drawback – poor-quality heating of the ends of the blank. A zone with a temperature that is outside the required range can make up almost a third of the loading length (Fig. 2), which makes this method extremely unprofitable for use in production. It should also be noted that for a good uniformity of the temperature field in the central part of the blank, the inductors should be placed close to each other, which complicates the process of loading and unloading of the blank.

Heating in a periodic mode with reciprocating motion is a bit worse than the static mode of heating in terms of operating efficiency coefficient and heating time, but allows to reduce the zone of non-qualitative heating at the ends of the blank (Fig. 3) by several times. In addition, with the same level of uneven temperature of the central part of the blank, the inductors can be located at a certain distance from each other, which facilitates the process of creating a system for loading and unloading the workpiece.

Thus, the determining factor in the selection of the heating mode was the criterion for the quality of the blank heating, i.e. the best uniformity of temperature along the length of the blank. The research shows that for heating of a blank, a periodic heating mode with reciprocating motion is preferred [17].

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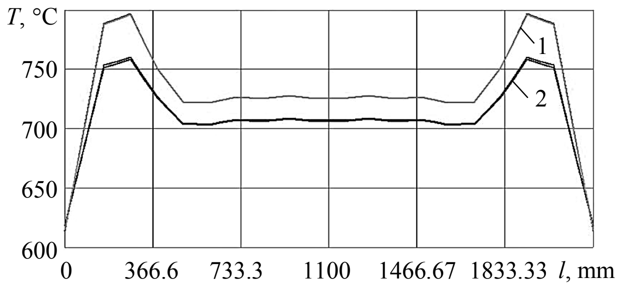

Fig.2. Distribution of temperature along the precursor length in a static heating mode
1 – blank surface temperature; 2 – blank central point temperature

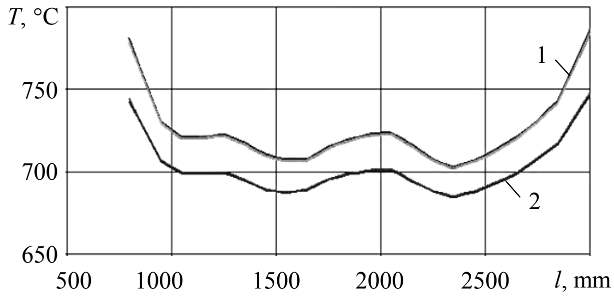

Fig.3. Distribution of temperature along the precursor length in periodic heating mode
1 – blank surface temperature; 2 – blank central point temperature

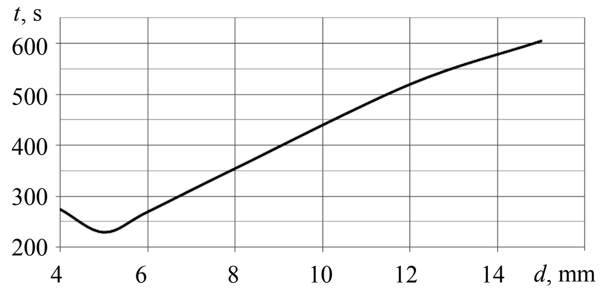

Fig.4. Dependency of heating time up to a foaming temperature and precursor thickness

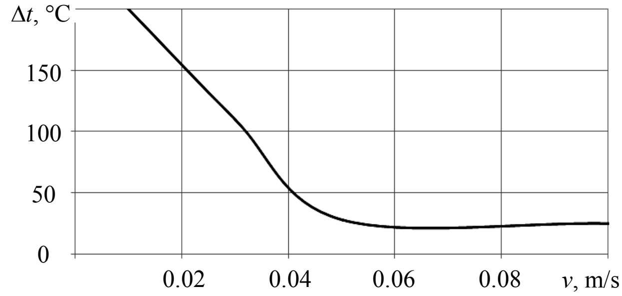

Fig.5. Dependency of temperature difference along the blank of a precursor having thickness of 5 mm and its movement speed

Further, the dependence of the heating time on the thickness of the precursor was determined (Fig.4). It can be seen that at a given power of 400 kW, it is possible to quickly heat the precursor only at a thickness of 4 to 7 mm. In case of thicker blanks there is no enough time to be warmed up, and thinner blanks become transparent to the electromagnetic field and are not heated up to the required temperature.

The amplitude of movement during reciprocating motion was chosen on the basis of the available theoretical and practical experience of heating in this mode [16]. It is established that the movement amplitude should be a multiple of the sum of the length of the inductor and the width of the gap between the inductors, in our case this is 750 mm.

The choice of frequency was influenced by several parameters, such as coefficient of efficiency, voltage and current of the inductor, and reactive power. The optimal variant is the use of a frequency of 8-10 kHz, since it allows obtaining values of current and voltage acceptable for production of the required voltage at the inductor. At lower frequency values, the efficiency of the installation decreases and the inductor current rises. At frequencies of 30-100 kHz, the voltage on the inductor increases significantly, cosφ decreases and the inductor current slightly decreases too.

The speed of the workpiece movement directly affects the temperature difference along the length of the blank. At low speeds, the non-uniformity of heating is very high. Thus, at a velocity of 0.03 m/s it is 100-120 °C, with an increase in speed, the unevenness decreases: at 0.05 m/s it is equal to 22-28 °C. With a further increase in speed, there are no longer significant changes in the temperature difference along the length of the workpiece. It should also be taken into account that an increase in speed can lead to slippage of the blank at the time of changing its direction of motion, so it is necessary to choose the slowest possible speed (Fig.5).

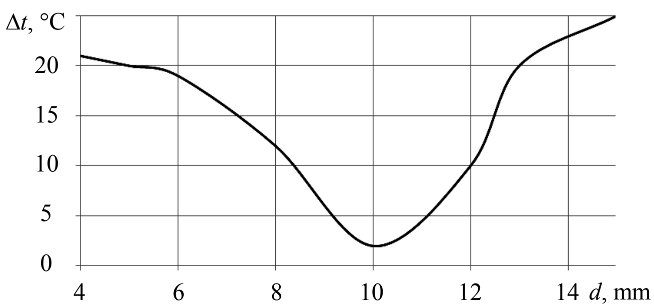

Fig.6. Diagram of temperature differences along the width of the blank depending on precursor thickness

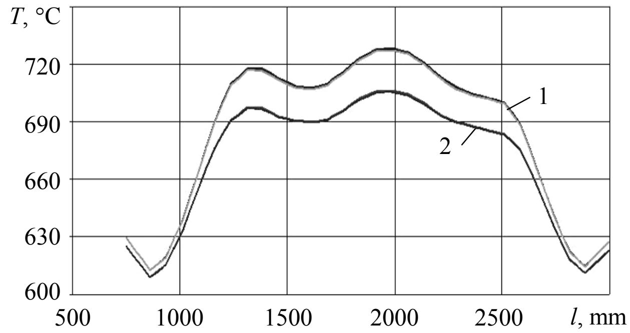

Fig.7. Distribution of temperature along the length of the precursor during increase of windings at the edge inductors

1 – blank surface temperature; 2 – blank central point temperature

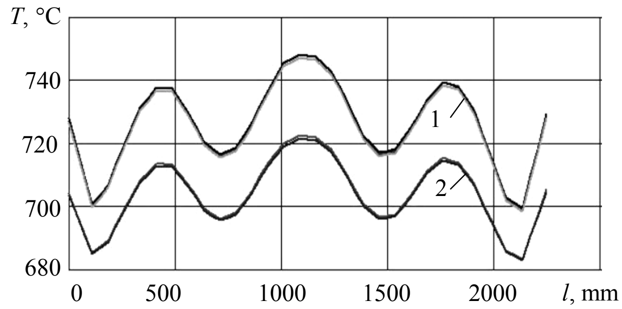

Fig.8. Distribution of temperature along the precursor length during increase of height of windings at the edge inductors

1 – blank surface temperature; 2 – blank central point temperature

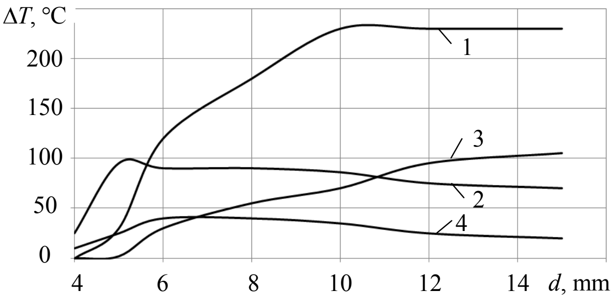

Fig.9. Diagram of dependency of maximum temperature difference from precursor thickness

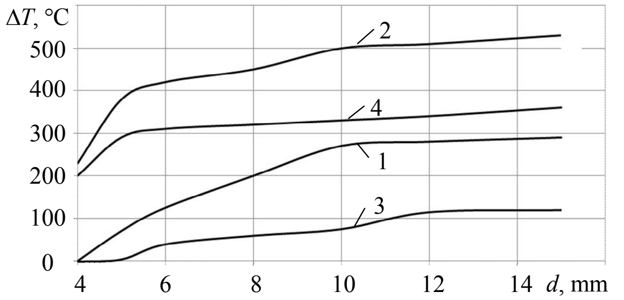

Fig.10. Diagram of dependency of edge zone length with temperature difference from precursor thickness

As it was said before, uneven heating of the blank is observed (see Fig.3). In this case, several types of uneven heating can be distinguished, as a result of which there are temperature differences: along the length in the regular part of the workpiece, along the width, and at the ends.

In the central part of the workpiece, the temperature gradient can be adjusted by changing the speed of the blank movement. As can be seen from Fig.3, according to the width of the workpiece, the temperature difference repeats the profile of the temperature drop along the length in the regular part of the workpiece and depends on the thickness of the heated blank (Fig.6). In this case, when the thickness of the workpiece is less than 10 mm, the side edges of the workpiece are underheated, and if there is a larger thickness, the over-heating is observed.

The temperature difference at the ends of the workpiece is a consequence of the edge effect during induction heating. This temperature difference has the greatest value and goes beyond the permissible temperature range. To control the temperature drop, a change in the power of the end inductors is required. Therefore, all eight inductors are connected in parallel to one source. The change in the power released on the inductor is possible due to the change in the number of windings.

Let us further consider the temperature distribution along the length of the blank in the case when the inductors have one more winding (Fig.7) and when the inductors have a higher height: 95 and 100 mm, i.e. they are allocated less power (Fig.8).

The diagrams in Figs.9 and 10 show the dependence of the maximum temperature difference from the specified range and the length of the end zone with this difference of temperature from the thickness of the pre-cursor for cases when the number of windings of all inductors is the same (curve 1), when the end inductors have six windings (curve 2) and when the inductors have a height of 95 mm (curve 3) and 100 mm (curve 4).

As it can be seen from the diagram 9 and 10, in our case the regulation of the quality of heating by changing the number of windings is very rough because of the small number of windings. The change in the height of the end inductors gives much more precise control, which makes it possible to reduce both the temperature difference from the specified range and the width of the end zone with a temperature difference, but still cannot provide the required quality of heating of the whole range of blanks. In the case of the same number of windings in the inductors and when the inductors have a higher height, the end zones are overheated, and when the end inductors have one more winding, the end zone is not enough warmed up.

The power supply has its own closed two-circuit cooling system, so it is necessary to separately cool only the inductors and the capacitor bank. From the results of numerical simulation, it was found out that the total power dissipated on inductors is 185-200 kW. At a given power for heat removal, a cooling water flow of at least 5.4 m^3/h is required. According to the technical characteristics of the capacitors, to cool the condenser battery, the minimum flow of cooling water must be at least 3.6 m^3/h. Water consumption for cooling bus wire is 2 m^3/h. The total cooling station must provide a cooling water flow of at least 11 m^3/h.

On the basis of the conducted research the induction equipment for high-temperature electromagnetic processing of large-sized flat products on the basis of aluminum alloys in an induction furnace has been developed.

Conclusions

1. The electromagnetic systems of influencing metals in a solid-liquid state have been investigated. The analysis of the results of numerical simulation with subsequent optimizations of the technological process and the parameters of the induction heater has been conducted.
2. Induction equipment for high-temperature electromagnetic processing of large-sized flat products based on aluminum alloys in an induction furnace has been developed.
3. The technology of induction production of large-sized products from foam aluminum has been developed.

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