THERMO-ULTRASONIC METAL PRINTING DEVICE

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ABSTRACT: The aim of the study was to design and construct the prototype of a device that can print metallic circuits on different types of materials including on the paper surfaces. The methodology to determine the optimum values for the processes that are used by the device it is represented and analyzed. This analyze is based on the finite element method (FEM) and consists in completion of the processes variables to which restriction conditions have been applied in order to achieve the device functionality. A recurrent FEM analysis using different parameters for the processes variables was applied in order to assess an optimum functionality of the device.

KEYWORDS: thermo-ultrasonic printing

1. INTRODUCTION

In the current paper, the authors simulate a system that could be used in printing industry. Due to current technological progress in the near future we can use in the printing industry, flexible displays with own memory and energy at very low cost. To produce displays it needs different technologically advanced systems. Therefore is simulated a device that is similar with the ordinary printing heads but with the ability to print on the synthetic paper the circuits of the display. The model contains a print head with a nozzle which is equipped with two types of devices. One of the integrated devices is the heating inductor and the other is the ultrasonic device. The integrated heating inductor has the ability to melt the metal micro wire and to form a droplet. The droplet will be released by the heating induction system immediately and because of the gravity force, the droplet will fall to the end of the nozzle channel. The end of the channel is equipped with an ultrasound device that has the ability to slow down the molten metal droplet and release it immediately in the desired shape, in order to obtain a precise display circuit diagram on the synthetic paper.

After setting the Thermo-Ultrasonic printing device dimensions according to the thickness of the deposited metallized layer and to the specific functionality parameters of the used materials, it is analyzed the functionality of the processes.

Optimized structural design for the structure parts of the Thermo-Ultrasonic device have to meet certain criteria regarding dimensional design and shape, material quality and functional compatibility.
Further is described the principle of operation.

2. PRINCIPLE OF OPERATION

The parts of the device that generates the metal steam from metal powder are composed by copper coils and an integrated ultrasonic transducer. A source of high frequency electricity is used to drive a large alternating current through the induction coils. These induction heating coils are known as the work coils. The passage of current through these work coils generates a very intense and rapidly changing magnetic field in the space within the work coils. The metal powder is directed within this intense alternating magnetic field. The alternating magnetic field induces a current flow in the conductive metal powder. The arrangement of the work coils and the metal powder is thought of as an electrical transformer. The work coils are like the primary where electrical energy is fed in, and the metal powder is like a single turn secondary that is short-circuited. This causes tremendous currents to flow through the metal powder. These are known as eddy currents. The high frequency used in induction heating applications gives rise to a phenomenon called skin effect. This skin effect forces the alternating current to flow in a thin layer towards the surface of the metal powder. The skin effect increases the effective resistance of the metal to the passage of the large current. Therefore it greatly increases the induction heating effect of the induction heater caused by the current induced in the metal powder.

The metal powder is transformed into a metal steam. The steam is directed to the end of the nozzle orifice by the pressure that ultrasonic waves give.

Figure 1. The thermo-ultrasonic metallization device.

Figure 2. The thermo-ultrasonic metallization device principle of operation.

Figure 3. The metal steam temperature radiation into the nozzle.

3. COMPUTATIONAL ALGORITHM

The micro induction heating system consists of copper induction coils with a diameter of 4 µm and metal particles with a diameter of 4 µm and height of 60 µm. The distance between the inductor and the metal particles is 2 µm. The driving frequency of the system is 7 MHz and the current intensity is 80 A. At the start of heating induction radiation, air temperature in the nozzle is 19°C. The induced current flows through the conductor of the metal powder forming a spiral cage on the surface of the cone and have $4\pi$ length and $60\delta$ section. Therefore the electrical resistance of the conductor is

$$ R = \rho \frac{4\pi}{60\delta} $$

where $\delta$ is the surface thickness of the metal powder where the whole energy of heating induction is transmitted.

Power losses in the metal powder occur through Joule-Lenz

$$ P = \rho \frac{4\pi}{60\delta} (NI)^2 $$

where $N$ is the number of coils and $I$ the current intensity.
The equation for current intensity flowing through the depth of penetration is

\[ I = J \delta \left( 1 - \frac{1}{e} \right) \]

where \( J \) is the current density at the surface.

Power dissipation can be increased by increasing the intensity of magnetic field in other words by increasing the number of ampere-turns in it. Increasing the number of turns can be limited by the space available and the size of the metal powder dissipation surface.

The steam is directed to the end of the nozzle orifice by the pressure that ultrasonic waves give resulted by an alternating current electric potential of 100 V that is applied to the top of the nozzle transducer.

In the area of air and solid boundary condition for the acoustic structure is that the pressure is equal to the normal acceleration of the solid, thereby:

\[ n \cdot \left( \frac{1}{\rho_0} \nabla p \right) = a_n \]

where \( a_n \) is the normal acceleration.

Due to the current applied in the piezo plate resulting vibration that produces air pressure. The nozzle is subjected to acoustic pressure changes in the air.

4. MODELING

Following mathematical calculations the induction heating modeling was done between the interior wall of the nozzle.

The system to be solved is given by

\[ j \omega a(T) A + \nabla \times (\mu^{-1} \nabla \times A) = 0 \]

\[ \rho C_p \frac{\partial T}{\partial t} - \nabla \cdot k \nabla T = Q(T, A) \]

where \( \rho \) is the density, \( C_p \) is the specific heat capacity, \( k \) is the thermal conductivity, and \( Q \) is the inductive heating.

The electrical conductivity of micro wire, \( \sigma \), is given by the expression

\[ \sigma = \frac{1}{[\rho_0(1 + \alpha(T - T_0))]^2} \]

where \( \rho_0 \) is the resistivity at temperature \( T_0 \), and is the temperature coefficient of the resistivity. \( T_0 \) is the temperature 19°C, and \( T \) is the actual temperature in the domain.

The time average of the inductive heating over one period, is given by

\[ Q = \frac{1}{2} \sigma |E|^2 \]

The mathematical calculations for the ultrasonic pressure out to the nozzle, are:

\[ \nabla \cdot \left( -\frac{1}{\rho_0} \nabla p - q \right) - \frac{\omega^2 p}{\rho_0 c_s^2} = Q \]

5. RESULTS AND DISCUSSIONS

This model have been analyzed in frequency of 7 Mhz and current intensity at 80 A.

The time radiation of the metal powder with induced currents is between 0 and 0.00005 seconds. During this time the temperature of the metal powder will increase from 19°C to 249.7°C.

In figure 4 is represented the last time of the irradiation with induced currents. After melting the metal powder that was irradiated, the metal steam formed will fall along the canal because of the gravity.

![Figure 4. Schematic set-up and magnetic field distribution.](image)

The steam is directed out to the nozzle by the ultrasonic pressure. In the integrated ultrasonic transducer originally frequency was set to a value of 1800 Hz in order to see the flaws nozzle operation at lower frequencies, resulting in an uneven vibration over the entire nozzle (fig. 5). Set the frequency of 28 kHz was found to be optimal due vibration propagation direction nozzle orifice (fig. 6).

The direction of the metal steam particles are represented on the figure 6. The particles are broken and redirected out to the work piece surface.

Piezoelectric transducer is made of PZT 4 crystal, which is a common material in piezoelectric
transducers. Structural analysis is harmonic in time and represents analysis of the frequency response.

**Figure 5.** The application of the electric potential at a frequency of 1800 Hz inside the piezoceramic plates.

**Figure 6.** The application of the electric potential at a frequency of 28000 Hz inside the piezoceramic plates.

6. **CONCLUSIONS**

The benefit is that the currents that heat the metal powder and melts it are induced by means of electromagnetic induction. This means that no physical contact is required between metal powder and induction coils. This method can also improve efficiency by avoiding heat losses from the irradiated surfaces and it does not affect other systems inside the nozzle channel.

On the reached saturation, despite increasing magnetic field, magnetic flux density in the material will remain limited and so, although there is an increase in power density transferred from the inductor, the system performance will decrease.

Growth rate of the frequency does not lead to a significant increase in power dissipation and, in addition, brings a downside where increasing the inductance of the inductor and thus might be a limitation of power.

Propagation of the acoustic energy density around the metal steam leads to thousands of drops deformation by balancing the gravitation and capillary forces of the steam drops. With increasing ultrasonic frequency into the integrated transducer the drops will be deformed and with a continuous growth of the horizontal diameter and broken. Beyond a certain critical value, the shape of the drops may change into a toroid shape. The center of the toroid shape flattens more and more with further increased acoustic power. Larger samples or drops with small surface tension show a typical self-inflation or buckling until they finally explode. The drops with high surface tension remain almost spherical.

Due to sound absorption, a radial and axial temperature profile exists, similar to the energy density profile in the standing wave field. The sound absorption increases with lower ultrasonic frequencies.

The energy density distribution in the standing wave field induces an acoustic convection flow. This streaming effect slightly enhances heat and mass transfer phenomena, characterized by an increased Sherwood and Nusselt number. Sherwood number and Nusselt number are describing the resulting convective enhancement of heat and mass transfer between a drops and its environment, compared to the non-convective transfer based on conduction and diffusion, respectively.

The effective acoustic convection flow velocity can be used to define a corresponding Reynolds number.

Slight asymmetries in the acoustically induced convective flow field might result in mostly undesired and uncontrolled drops rotations.

The drifting drops represent, together with the radial and axial dispersion force profile, a system which is able to perform damped oscillations. Such oscillations might be self-induced or externally activated by reducing frequency amplitude modulation of the ultrasonic carrier wave and are in general characterized by certain resonance frequencies.

When the mass of the drifted drop changes the frequency of the resonant oscillation will also change. This provides a means to determine diffusion constants by measuring the mass variation of a droplet as a function of time.

Externally applied amplitude modulation of the ultrasonic wave can also be performed in a way that self-oscillations of the oscillating drop deformations are induced.

Due to the possibility of melting metal by induction heating, metal steam becomes possible activating the ultrasounds.

With this printing device can be obtained thin layers of metal on different types of materials.
7. REFERENCES

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