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Pulsed electromagnetic attraction of nonmagnetic sheet metals

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ABSTRACT

This paper is dedicated to a study of pulsed electromagnetic attraction based upon recently developed inductor design – "Inductor System with an Attracting Screen". The concept of attraction in this inductor system is based upon inducing currents flowing in the same directions in the screen and in the sheet metal blank, which, according to Ampere law, results in attraction forces between the screen and sheet metal blank. This system is capable of applying attraction forces to non-ferromagnetic sheet metal materials, for example, stainless steel or aluminum using low frequency discharges. An analytical model based upon solution of Maxwell equations was developed to estimate the attracting forces for low frequency discharges. In addition to the analytical model, the described concept is illustrated by the experimental results on attraction of sheet metal blanks of stainless steel employing a single turn inductor and a flat screen.

1. Introduction

Electromagnetic Forming (EMF) is an impulse or high speed forming technology which uses pulsed electromagnetic fields to apply forces to tubular or sheet metal work-pieces. A recent very detailed review by Psyk et al. (2011) provided a historical perspective of EMF processes development and highlighted the state of the art on modeling, coil design, sheet metal forming, tube forming, crimping, welding, cutting, calibration of parts and hybrid processes involving EMF. Detailed reviews of early experimental results and practical applications of electromagnetic forming technologies were provided by Bruno (1968) and Davies and Austin (1970). A lot of sources, for example Belyy et al. (1977), indicate that good specific conductivity for both work-piece material and inductor material is the major requirement for traditional EMF processes to be efficient.

All above mentioned applications are based upon repelling Lorentz forces between the EMF coil and conductive blank. In such a configuration, the coil and the tool (forming die, mandrel to which the blank is welded or crimped, shearing edge which is cutting the blank) are positioned from opposite sides of the blank. In addition to such repelling processes, another configuration of EMF processes is possible where the blank is attracted to the coil. The objective of this paper is to introduce a new manufacturing process of attraction of non-magnetic sheet material through the recently developed experimental system including single turn coil and attracting screen. This process is one of the few examples generating attracting forces with much higher capabilities than vacuum forming. The first application of this process is expected to be in automotive repair shops where an attracting one sided distributed force may enable low cost exterior panel damage correction.

2. Literature review on EMF attraction processes

An electromagnetic attraction of the designated areas of panels manufactured from sheet metal blanks is motivated by the restoration needs of exterior panels of aircrafts and ground vehicles. Analysis of real life examples indicates that a great number of damages are dents in the areas where access from the inside of the panel is very problematic if not impossible. These cases include aircraft wings and fuselage components as well as doors, hoods, roofs, fenders and bumpers of cars and trucks. From this perspective, there is a practical interest to devices allowing restoration of sheet metal parts by eliminating dents on the surface from the external side without disassembling of the components and avoiding damaging of existing paint and protective coating. A recent review by Batygin et al. (2013) described the concepts and technical devices in the field of the attraction EMF technologies mostly targeting restoration of the airplane body elements. These systems include interruption of slowly increasing fields and exciting currents as well as the natural effects of changing the force direction applied to a thin ferromagnetic sheet in low frequency electromagnetic processes. All mentioned concepts have certain disadvantages and limitations which complicate their practical

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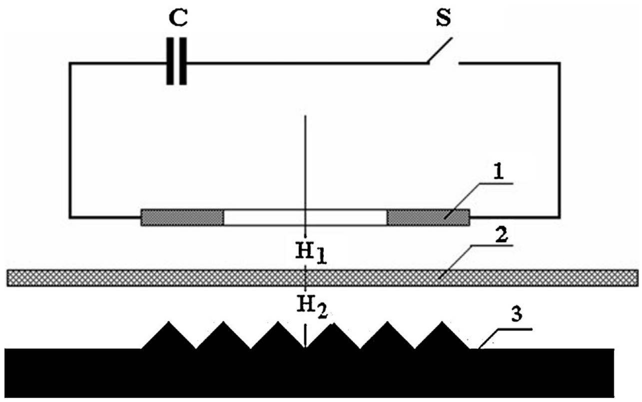

Fig. 1. Schematic of the traditional EMF process: 1 is a single turn inductor, 2 is a sheet metal blank, 3 is a one-sided die, *C* is the block of capacitors for electric energy storage and *S* is the switch of the discharge circuit, H_1 is electromagnetic field intensity in the clearance between the coil and the blank and H_2 is intensity of the electromagnetic field penetrated through the blank.

usage, such as employment of expensive switching components enabling interruption of high intensity currents or the requirement of the component material to be ferromagnetic.

For the first time, the initial concept of electromagnetic attraction based upon creating unidirectional currents in the blank and in the attracting screen was formulated by Batygin et al. (2006). The physical concept of the proposed coil design is based upon the Ampere law, described for example by Landau and Lifshitz (1984). In order to create unidirectional parallel currents, an additional conductive screen was added to a traditional single turn inductor design. A well-known single turn coil design is employed to create attraction forces in a new process: the inductor is positioned between parallel plates of the screen and sheet metal blank which requires treatment by attracting forces. Identically directed eddy currents are induced in the metal of the screen and the sheet metal blank by the current flowing through the single turn coil. The proposed design requires rather low frequency of discharge to accomplish intensive penetration of the electromagnetic field through the thickness of the blank and avoid repelling Lorentz forces, which are the natural result of interaction of magnetic field with a conducting environment. This research paper intends to formulate the methodology of defining the process parameters which provide sufficient attraction forces to deform a non-ferromagnetic sheet metal blank.

3. Concept of pulsed electromagnetic attraction of the non-magnetic metals

In order to make the new concept more clear, it needs to be discussed in comparison with the concept of traditional EMF processes. As it was indicated in a large number of publications on analysis and applications of traditional EMF processes reviewed by Psyk et al. (2011), traditional EMF technology schematically shown in Fig. 1 requires rather high frequency of discharge of capacitors through the coil in order to induce an electric current in the blank and contain the electromagnetic field within the skin layers of both the blank and the coil and the clearance between them.

Known methodologies of electromagnetic coil design and accepted design recommendations for EMF equipment typically intend to avoid penetration of the electromagnetic field through the thickness of the blank, as it was recommended for example by Belyy et al. (1977). The reason for that is that the pressure applied to the blank can be calculated as:

$$P = \frac{\mu_0}{2} \cdot (H_1^2 - H_2^2),$$

where H_1 is the electromagnetic field intensity in the clearance between the coil and the blank and H_2 is the intensity of the electromagnetic field penetrated through the blank. Based on this consideration, the number of turns of the coil, the capacitance and voltage of the equipment is usually selected in addition to the general intention to keep the connection between the equipment and the coil at minimum inductance level. In such configuration, the current induced in the blank has almost the same time form (but with phase difference $\sim\pi$) as the discharge current propagating through the coil. The slight shift in time phases of currents in the coil and in the blank caused by penetration processes could be observed in the experiments are usually not taken into account in practical calculations of EMF processes. In traditional EMF configuration, a strong repelling electromagnetic pressure is observed between the coil and the blank with good electrical conductivity and rather high frequency of the discharging current. Examples of experimental curves of exciting electric current running through the coil synchronized with the induced current running through the blank for the discharge frequency of 33 kHz and 1.33 kHz are shown in Fig. 2a and b, respectively. Comparison of these two cases indicates that for 33 kHz, currents in the coil and in the blank have a phase shift of $\sim\pi$ which means that currents run in opposite directions resulting in a strong repelling force. For 1.33 kHz, the currents in the coil and in the blank have $\sim\pi/2$ shift in phases leading to very weak interaction between the currents which periodically changes directions. This effect was discussed in the analytical model by Batygin et al. (2013) for two ultimate cases when the electrical conductivity $\gamma \to 0$ and when $\gamma \to \infty$. Technically, the EMF processes compete with traditional metal forming operations in two-sided dies, quasistatic hydroforming processes and superplastic forming processes based on hot gas forming, other pulsed forming processes such as explosive forming, electrohydraulic forming and laser forming. All these processes apply force directed outward from the tool to the blank.

The proposed process of electromagnetic attraction is among very few processes which can create force directed inward from the blank to the tool. A similar effect can be achieved by vacuum forming where pressure differential is limited to the atmospheric pressure naturally applied outside of the blank and deforming it due to the absence of pressure inside the blank. It can be also compared with quasistatic electromagnetic force for magnetic materials or the dynamic process recently described by Batygin et al. (2013) again appropriate only for magnetic materials.

According to the observed result, the concept of the process has some remote similarity to the vacuum forming, however, applied to electromagnetic forming. The idea is to create electromagnetic field from both sides of the blank and then eliminate it from one side by the opposite electromagnetic field generated by the screen. This process involves an additional piece of tooling – the electromagnetic screen which plays a critical role in creating the electromagnetic field of the opposite sign and force interaction of conductors with unidirectional currents for attraction of the non-magnetic sheet metals.

In order to eliminate the repelling force between the coil and the blank, the discharge frequency needs to be rather slow to accomplish very significant penetration of the electromagnetic field through the blank and also to increase the time shift in phases of current in the coil and in the blank: the induced current in the blank is now proportional to the derivative of the inducing current by time: for harmonic processes this shift in phases is $\sim\pi/2$. This second circumstance is ultimately important because it makes the dynamic interaction between the coil and the blank almost non-essential, while the screen starts playing the major role, since the phases of electric current induced in the blank and in the screen are identical. In this case, the coil is not subjected to any significant electrodynamic forces contrary to the traditional EMF processes.