Electromechanical installation based on a powerful current pulse generator for materials treatment

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Abstract. The electromechanical device containing an electromagnetic solenoid with a piston operating in the reciprocating motion mode was developed. Technologies with similar operating modes are widely used in various industries. Economical generator of powerful unipolar current pulses with unique systems is used in the electromechanical device. It allows its main parameters to be regulated in a wide range and with high speed: pulse reproduction frequency and amplitude. The principle of generator operation is based on the periodic discharge of pre-charged capacitors to a low-resistance active-inductive load. The parameters of the mechanical and electrical parts of the electromechanical device are calculated: the initial coordinate of the piston, the magnetomotive force resulting from a change in the inductance L(x), the spring elasticity, the resistance force of the piston proportional to its speed, amplitude, duration and frequency of current pulses. A simulation model of the device in the environment of Matlab-Simulink was developed. Plots of transients during the device idling and under load were constructed. The analysis of the device operating modes was performed. The developed electromechanical installation allows the process parameters to be adjusted.

1. Introduction

Progress in the development of modern technology requires new structural materials with high technological and operational characteristics. Such materials and products from them cannot be obtained and processed by traditional methods. Therefore, one of the most important tasks of scientific and technical policy is the creation and implementation of qualitatively new technological processes, including the use of external energy effects on the strength and ductility of materials [1]. Experimental studies of high-density electric currents, high-energy electromagnetic fields, plasma currents, laser radiation and combined effects on electrically conductive materials have led to the creation of a new class of high-performance technological methods for materials treatment.

For the domestic and foreign metallurgical and machine-building industries, the technology using powerful pulsed electric currents in the processing of difficultly deformed metals and alloys has been disseminated [1]. These are the processes of forging and rolling [2, 3], drawing [4-7], metalworking [8-10], sintering [11-13], materials joining [14-16] and sheet forming [17-19] and others. The detailed review of these electrical technologies is given in [20, 21]. They are based on the electroplastic effect, discovered more than 60 years ago and consists in decreasing the resistance to deformation when current pulses are transmitted [22]. Its complex physical nature has not yet been clearly established,
since it consists of a number of interconnected ones – the thermal effect, electron-dislocation interaction, the ponderomotive effect, and others [1].

The basis of industrial electrical technologies is the use of powerful sources of electric current [22-25]. Generators of powerful (≈ 15 kA) current pulses created in recent years have been successfully used for electrically stimulated wire drawing [26]. Such installations can be implemented not only in the processing of metals by pressure, but also in the mining industry (crushing of ore, coal, rock), as well as mechatronics, robotics.

The aim of this work is to create, on the basis of a generator of powerful current pulses, an electromechanical device with a reciprocating piston for electrical stimulation of forging and stamping and to study its parameters.

2. Results and discussion

The main part of the device is an electromagnetic solenoid with a piston (figure 1). The device comprises the magnetic circuit with stacked steel on which a coil with a wire wound around is rigidly fixed. A piston is connected to the two springs in the steel casing of the magnetic circuit, as shown in the figure. The piston reciprocates along the vertical coordinate x. The first (pushing) spring with coordinates \( x = 0 \), and the second spring with a stiffness coefficient \( k = 20000 \) during the deformation process performs the function of a smooth stop of the piston at the extreme lower point of the coordinate \( x = x_1 \).

In the coordinate range from \( x = 1 \) to \( x = 0.7 \) (the working area of the piston), the piston experiences resistance from the load side (for example, coal seams), and depending on the force opposing the piston, an equilibrium state point appears at a distance of \( x = x_{\text{equil}} \). The transient motion of the piston under the action of electromagnetic forces occurs in accordance with the known equations [22].

\[
U = (R \cdot i + L(x) \frac{di}{dt} + i \cdot \frac{dL(x)}{dx} \cdot \frac{dx}{dt})
\]  

(1)

where: \( U \) – the voltage of the power source, \( V \); \( i \) – the current flowing through the winding of the electromagnet, \( A \); \( R \)– active equivalent resistance of busbar and coil winding, Ohm; \( L(x) \) – inductance as a function of the coordinate \( x \) of the piston.

**Figure 1.** Design of the electromechanical device. 1 – return spring, 2 – solenoid coil; 3 – a directing ring; 4 – steel casing with lined iron; 5 – a cylindrical steel piston; 6 – force impact on the piston, \( F_0 \).
The main variable component of the mechanical system is the coordinate of the piston \( x \). The equation of the mechanical part of the system is determined on the basis of Newton’s second law:

\[
F_{\text{sum}} = M \cdot a = M \frac{d^2 x}{dt^2} 
\]  

where: \( F_{\text{sum}} \) – the resultant of forces on the mechanical part of the system, N; \( M \) is the mass of the rod, kg; \( a \) – piston acceleration, m/s.

The equation for changing the variable \( x \) has the form:

\[
M \cdot \frac{d^2 x}{dt^2} = F_e - k(x - x_0) - b \frac{dx}{dt} - f_0 
\]

where: \( x_0 \) is the initial coordinate of the piston, m; \( k \) is the resistance coefficient, N/m; \( f_0 \) – external force on the piston, N.

Based on these equations, the model of the mechanical part of the electromechanical device is presented in the Matlab – Simulink environment (figure 2).

Figure 2. Model diagram of the electromechanical device.
The articles are known in which similar electromechanical devices are described using a battery as a power source [23, 24]. In this work, to implement such setup, a powerful current pulse generator was used [25, 26].

The principle of operation of the generator is based on a periodic discharge to a low-impedance load of pre-charged capacitors. The shape of the current pulse of such generator is close to sinusoidal, the pulse duration depending on the capacitance and inductance can be 100 – 10 000 μs, and the reproduction frequency up to 1000 Hz. The block diagram of the generator is shown in figure 3.

Figure 3. Structural diagram of a powerful current pulse generator.

The generator contains a charge unit with a reversible thyristor converter, consisting of counter-parallel connected thyristor bridges SV1, SV2, which is connected to the capacitors CB via series-connected equivalent resistance R1 and inductance L1, a capacitor discharge block for the load (CB capacitors, thyristor switch VS3, load Rn), recharge unit YP (transformer M, diode VD1, resistor R3, amplifier G 3, restriction unit S3), the principle of operation of which is described in [13], as well as the automatic regulation unit (system) ACS of generator parameters (BZU block voltage reference, RNZ regulators, RU, sensors of basic parameters DTZ, DU).

The automatic control systems formed in the generator allow the main parameters in a wide range to be adjusted: the pulse reproduction frequency and its amplitude. To create a reciprocating motion of the piston, device B2 (figure 2) generates a packet of pulses of adjustable duration, while the piston makes a working movement “forward” until it touches a solid body that needs to be destroyed or deformed. After the termination of the pulses, the return spring returns the piston to its original position.

Figure 4 shows the transient graphs of the electromechanical device model with a reciprocating piston.
Figure 4. Transient graphs of the electromechanical device.

The graphs show the following electromagnetic accelerator parameters:
1 – generator current pulses, A;
2 – distance traveled by the piston, m;
3 – counter-EMF formed by the inductance of the electromagnet coil, V;
4 – working force on the piston side and external load, kg.

3. Conclusion
The electromechanical device with a reciprocating piston and the influence of the latter on the load to deform it was developed. The model of the device in the Matlab – Simulink environment was implemented. The use of a powerful current pulse generator with an automatic parameter control system allows high-speed control of process parameters: force and piston distance.

References
[1] Gromov V E, Zuev L B et al 1996 Electrostimulated Plasticity of Metals and Alloys (Moscow: Nedra) p 293
[2] Salandro W, Jones J et al 2014 Electrically Assisted Forming: Modeling and Control (Basel, Switzerland: Springer) p 355
[3] Jones J J, Mears L and Roth J T 2012 ASME Journal of Manufacturing Science and Engineering 134(3) 034504
[4] Gromov V E, Erilova T V et al 1994 Izv. Vuzov. Ferrous Metallurgy 456–458
[5] Gromov V E, Kozlov E V et al 1994 Problems of Mech. Eng. and Machine Reliability 246–251
[6] Gromov V E, Zuev V I et al 1996 Izv. Vuzov. Physics 366–396
[7] Kozlov A, Mordyuk B and Chernyashevsky A 1995 Mater. Sci. Eng. A. 190(1) 75–79
[8] Hameed S, Rojas H A G et al 2016 Int. J. Adv. Manuf. Technol. 87(5-8) 1835–41
[9] Zhang D, To S et al 2012 Metall. Mater. Trans. A. 43(4) 1341–46
[10] Ji R, Liu Y et al 2011 J. Mech. Sci. Technol. 25(6) 1535–42
[11] Langer J, Hoffmann M J and Guillon O 2009 Acta Mater. 57(18) 5454–65
[12] Grasso S, Sakka Y and Maizza G 2009 Sci. Technol. Adv. Mater. 10(5) 053001
[13] Munir Z A, Quach D V and Ohyanagi M J. 2011 Am. Ceram. Soc. 94(1) 1–19
[14] Liu X, Lan S and Ni J 2015 *J. Mater. Process. Technol.* **219**112–123
[15] Santos T G, Miranda R and Vilaca P 2014 *J. Mater. Process. Technol.* **214(10)** 2127–33
[16] Santos T G, Lopes N et al 2015 *J. Mater. Process. Technol.* **216** 375–380
[17] Jeswiet J, Micari F et al 2005 *CIRP Ann. Manuf. Technol.* **54(2)** 88–114
[18] Fan G, Sun F, Meng X, Gao L and Tong G 2010 *Int. J. Adv. Manuf. Technol.* **49(9-12)** 941–947
[19] Fan G, Gao L, Hussain G and Wu Z 2008 *Int. J. Mach. Tools Manuf.* **48(15)** 1688–92
[20] Nguyen-Tran H, Oh H et al 2015 *Int. J. Precis. Eng. Manuf. Green Technol.* **2(4)** 365–376
[21] Guan L, Tang G and Chu P K 2010 *J. Mater. Res.* **25(7)** 1215–24
[22] Troitskii O A and Rozno A G 1970 *Solid State Physics* **12(1)** 203–210
[23] Zhmakin Yu D, Romanov DA et al 2011 *Industrial Energy* 622–26
[24] Zhmakin Yu D, Zagulyaev D V et al 2010 *Industrial Energy* 639–42
[25] Zhmakin Yu D, Zagulyaev D V et al 2011 *Industrial Energy* 128–32
[26] Kuznetsov V A, Gromov V E et al 2017 *Izv. Vuzov. Ferrous Metallurgy* **60(2)** 157–163