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USING AN OPTICAL FIBRE SENSOR TO MEASURE DISPLACEMENT OF ELECTRODYNAMICALLY FORMED SHEET METAL

The paper discusses the use of reflective fibre-optic sensor for the purposes of measuring motion parameters of sheet metal formed at high speed, subject to percussive Lorentz forces extorted in a pulsed magnetic field.

Keywords: Optical fibre sensors, photoelectric displacement measurements

1. INTRODUCTION

Electrodynamic processing (ED) is a new, unconventional plastic forming method, which makes use of volumetric Lorentz forces acting on metal elements placed in a pulsed magnetic field [1]. According to the concept shown in Fig. 1, a cylindrical or spiral electric coil 1 (called an inductor) is a working tool in this process, and it is being placed at short distance from semi-finished product 2. The inductor is connected to the terminals at the battery of capacitors 3, which discharge oscillatory current I in the inductor circuit after charging. Then a variable magnetic field with induction B, which is excited in the space surrounding the inductor, induces an eddy current i in the metallic semi-finished product. The flow of these currents generate a percussive Lorentz force which repulses a fragment of the semi-finished product from the coils of a mechanically reinforced inductor. In these conditions, pressure p of the force, which acts on the semi-finished product surface, is used in fitting operations and to form a fragment of the semi-finished product, e.g. tube or sheet, using a die or without a die [2].

During electrodynamic processing, the capacitor electric field energy is converted into the energy of the electromagnetic field generated in the inductor-semi-finished product arrangement. The latter in turn is converted into kinetic energy of the freely moving semi-finished product element and into mechanical work of its forming process effected by inertial forces. The forming process in the pulsed magnetic field is characterized by the fact that elements of semi-finished products subject to it reach instanta-

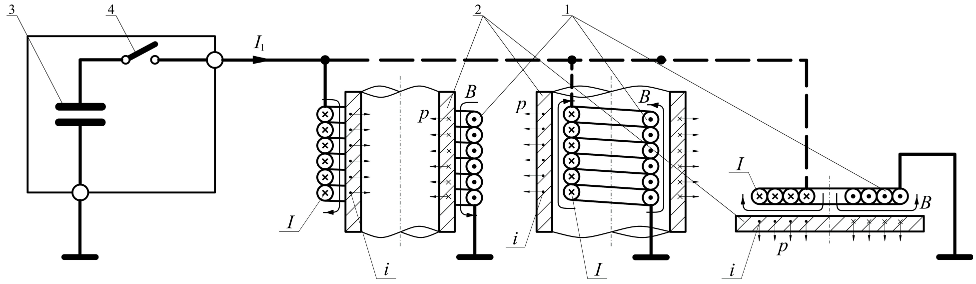

Fig. 1. The concept of electrodynamic metal processing: a) compression; b) expanding; c) pressing; I – current in inductor, i – eddy current in semi-finished product, B – magnetic field induction, p – pressure, 1 – inductor, 2 – semi-finished product, 3 – capacitor, 4 – commutator.

neous velocities of a few hundreds m/s within fractions of a second, whereas the level of the generated Lorentz force depends on the geometry of the inductor-semi-finished product arrangement, which changes during the process. In these conditions, it is a prerequisite to know the instantaneous values of quantities that characterize the movement of the semi-finished product subject to forming throughout the process to evaluate the possibilities to complete a certain forming operation using the ED method. For example, this allows to predict final shapes of freely formed material, or when a die is used, to position it at a sufficient distance from the semi-finished product's surface to ensure that kinetic energy of an accelerated element reaches its maximum level at the moment when it makes contact with the die surface.

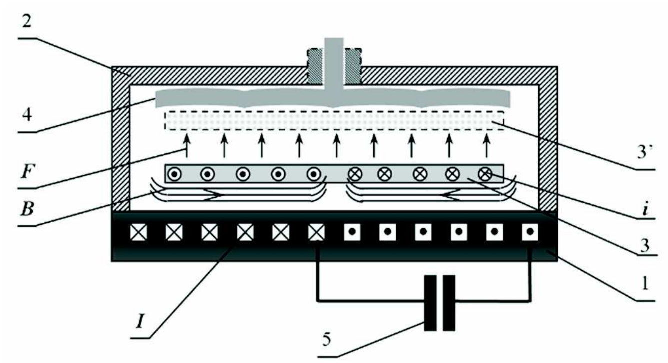

Fig. 2. Sheet forming system diagram: 1 – flat inductor; 2 – die block housing; 3, 3' – sheet metal subject to forming in its initial and final positions; 4 – die block; 5 – capacitor; I – current in inductor; i – eddy current in semi-finished product; B – magnetic field induction; F – Lorentz force.

The paper discusses the first stage of research on the method being developed by the Department of Process Control (DPC) at AGH UST and intended to measure instantaneous values of sheet element displacement, velocity and acceleration during the electrodynamic forming process. Figure 2 shows a diagram of an arrangement allowing to form sheet metal using a flat inductor.

2. MEASUREMENT PROCEDURE

2.1. Measuring sensor selection

The following variants were assumed for the purposes of the experiments carried out at the DPC: direct measurement of instantaneous position of sheet being moved during the electrodynamic processing, and planned determination of velocity and acceleration.

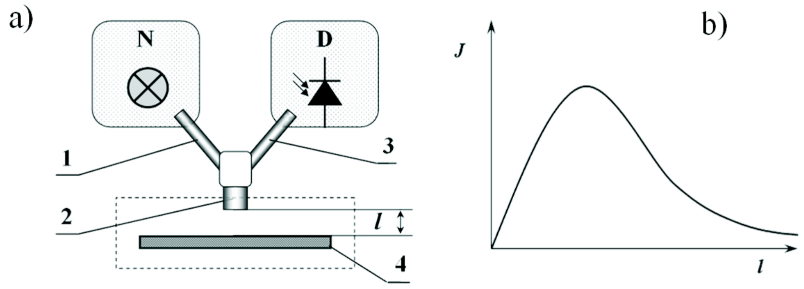

Fig. 3. Schematic diagram of a reflective fibre-optic sensor (a): 1 – transmitting optical fibre, 2 – sensor head, 3 – receiving optical fibre, 4 – sheet metal, l – sheet metal displacement, N – transmitter, D – detector; (b) the nature of relation between the intensity of reflected light radiation J and the distance l between sheet metal and sensor head.

In order to avoid measurement disturbances due to variable magnetic field characterized by considerable induction B, a reflective fibre-optic sensor was used to measure sheet metal displacement. This sensor is characterized by simple design and can be easily incorporated in the small space limited by inductor 1, processed sheet 3 and die block 4, which are positioned near each other (Fig. 2). Figure 3 shows the sensor principle of operation. The light wave emitted by transmitter N moves via fibre-optic cable 1 to sensor head 2. Light reflected from moving sheet 4 gets into the receiving fibre-optic cable 3 and goes further to detector D. The general character of the relation between light intensity J and displacement l of the reflecting surface is represented by the function graph shown in Fig. 3b, whereas the sensor measuring range may reach from one to more than ten millimetres, depending on the optical fibre system used [3–6].

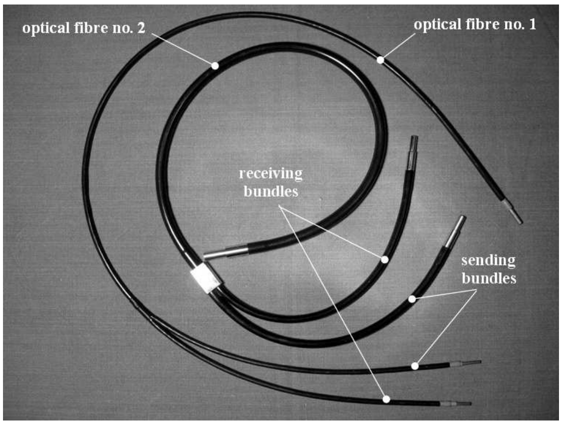

Fig. 4. Optical fibres used in an optical transducer.

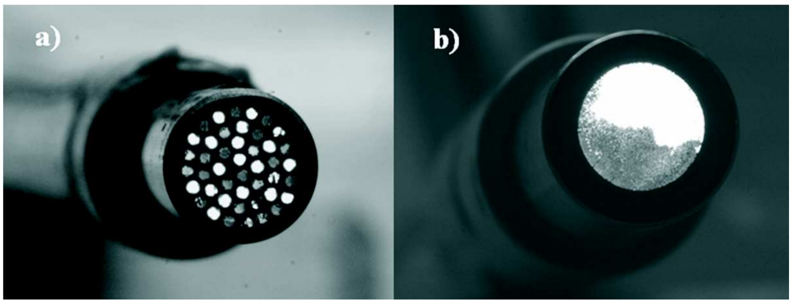

Fig. 5. View of the head front of fibre-optic sensor (a) no. 1, (b) no. 2 transmitting bundles – grey shade; receiving bundles – light shade.

Two types of manufactured sensors were put to tests, which differed in the type of employed fibre-optic cables (Fig. 4). Stranded optical fibres are in the form of a Y-shaped cable, in which it is possible to separate two bundles: transmitting and receiving, each more than ten centimetres in length. The bundles are combined in the head, and then run in a shared, less than a metre long cable section, to the grip holding the optical fibre tip over the sheet metal subject to measurement. Fibre-optic cable no. 1 (Fig. 4) was manufactured by the Institute of Electronic Materials Technologies (*Instytut Technologii Materiałów Elektronicznych*) in Warsaw. It consists of 44 PCS-type single optical fibres, which divide into two bundles (transmitting and receiving), 22 fibres in each bundle. Basic specifications for optical fibre no. 1: fibre diameter Φ_{w1} = 380 μm, core diameter Φ_{r1} = 200 μm, numerical aperture NA_1 = 0.9. The distribution of transmitting and receiving fibres in the shared section of the cable is quasi-random, that is they may form clusters of various sizes. Figure 5a shows a magnified view of the head front of optical fibre sensor no. 1.

Fibre-optic cable no. 2, (Fig. 4) was manufactured by the BIAGLASS Glass-Works in Białystok. The cable consists of 3000 single, loosely laid optical fibres characterized by abrupt changes of refractive index, divided into transmitting and receiving sections, the latter containing a larger number of fibres. Single fibres are of multi-mode type, their cores and coatings are made of multicomponent glass. Basic specifications for optical fibre no. 2: Φ_{w2} = 35 μm, Φ_{r2} = 30 μm, NA_2 = 0.54. Figure 5b shows a magnified view of the head front of optical fibre sensor no. 2. In the characterized fibre-optic cables, transmitting bundles shine with red light, and receiving bundles – with yellow. These colours are represented in Fig. 5 as grey and light shades.

2.2. Measurement setup

Figure 6 shows the schematic diagram of a setup for dislocation measurements. A semiconductor LED is used as a light source 4 in the photoelectric sensor system. The diode has increased brightness and light-wave length: λ = 630 nm. The diode light intensity J_V = 8000 mcd at rated current I_n = 20 mA is changeable owing to a current regulator used in the power supply circuit. Light emitted by the LED is brought via transmitting fibre-optic cable 5 to terminal 8 set in the housing of die block 2, which sends it towards sheet metal 3 lying on coils of inductor 1. Some light reflected from the sheet surface is sent via fibre-optic cable 6 to detector 9, an OPT 210 transducer from Texas Advanced Optoelectronic Solutions, [9]. The voltage output signal from the detector, proportional to the intensity of light incident onto its light-sensitive surface is brought via a measurement card 10 to the main memory of computer 11. The employed IOTech DaqBOARD 2000-type measurement card with a sampling frequency of 100 kHz and DasyLAB 8.0 software at the same time works as a conditioner bringing the supply voltage to the light source 4 and detector 9.

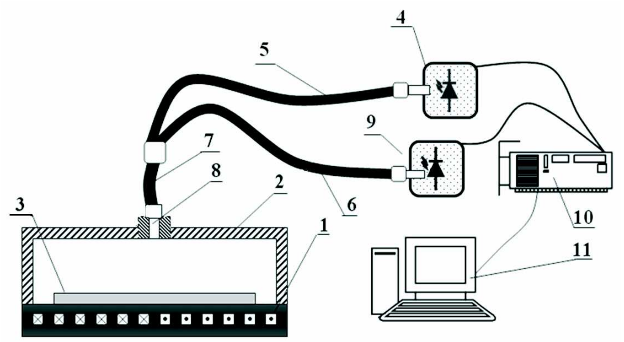

Fig. 6. Schematic diagram of a setup for measuring sheet motion parameters using a fibre-optic sensor: 1 – inductor, 2 – housing of die block, 3 – sheet metal, 4 – light source, 5, 6, 7 – fibre-optic cables, 8 – sensor head, 9 – detector, 10 – measurement card, 11 – computer.

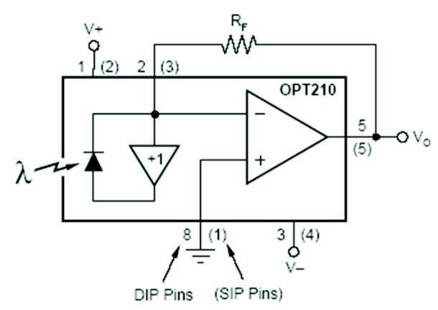

Fig. 7. Functional diagram of the OPT210 transducer internal structure.

The OPT210 system contains high-efficiency silicone photodiodes and an amplifier with high input impedance, (Fig. 7). The OPT 210 detector is built as a monolithic structure of integrated elements of a photodiode and an amplifier, which is provided with an external feedback resistor with resistance R_F = 1 MΩ. Its important advantages are: broad band of transmitted frequencies at low noise level obtained owing to reduced photodiode capacitive effects, and no deviations resulting from present leakage currents.

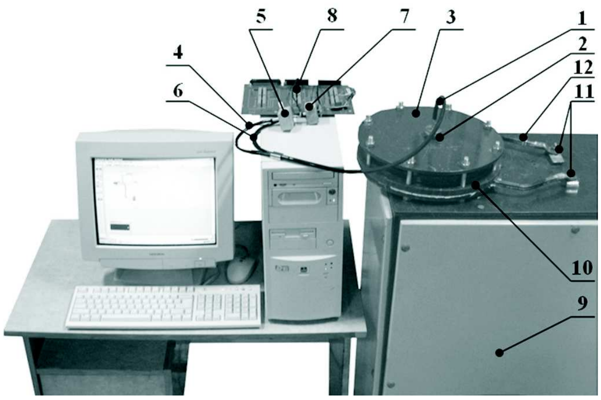

Fig. 8. Measurement setup, 1 – fibre-optic cable measurement end, 2 – nut, 3 – die block cover, 4 – transmitting bundle, 5 – block containing illuminator, 6 – receiving bundle, 7 – block containing detector, 8 – measurement card, 9 – generator, 10 – working head, 11 – generator output terminals, 12 – inductive probe.

The measurements were performed by the Department of Process Control Laboratory using the setup shown in Fig. 8, with controlled energy percussive generator 9 and head 10 for electrodynamic sheet-metal forming, fitted on top of the generator plate and connected to its output terminals 11 during the experiments [7, 8]. The main head element is a flat inductor, diameter 200 mm, (Fig. 9) wound so as to make an Archimedean spiral with eight double-laid coils, made of flat bar copper, cross-section

5×10 mm^2. The inductor coils were insulated with glass fibre tape impregnated with epoxy resin. In its initial position the sheet metal 2 (Fig.9) subject to forming was laid directly on the inductor working surface, while cover 3, (Fig. 8), with the die block fixed to it was positioned above sheet surface, at a distance adjusted using spacing rings 1. The generator allowed to select a certain output energy by means of a controller used to preset the capacitor battery charging voltage. Moreover, the station was used to carry out measurements of the capacitor discharge current flowing through inductor coils. A miniature inductive probe 12 was used for that purpose, attached to one of the cables connecting the inductor to the generator (Fig. 8).

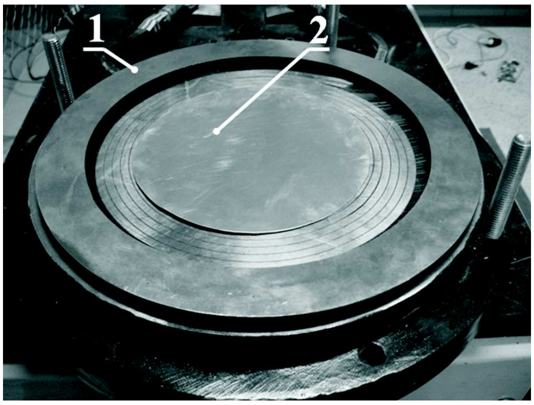

Fig. 9. Inductor head: 1– spacing ring, 2 – sheet metal subject to forming.

The measurement end 1 of fibre-optic cable, (Fig. 8), was placed centrally in the inductor axis. It was fixed by a nut 2 incorporated in die block cover 3. The provided nuts with different hole diameters allowed to use previously specified optical fibre sensors no. 1 and no. 2, with varying diameters. Standard ends of fibre-optic cable transmitting 4 and receiving 6 bundles made by the manufacturer were brought to connection blocks 5 and 7, containing the LED and OPT210 system. A PC provided with a measurement card connected via cables 8 with the illuminator and detector systems was the final measurement line element.

3. THE COURSE OF THE MEASURING EXPERIMENT

3.1. Determination of static characteristics

Static characteristics $U(l)$ of sensors used during the measurements were determined by way of measuring voltage U at the detector output, corresponding to the distance l between the fibre-optic cable head end and the sheet metal with a smooth surface. While determining the characteristics, different values of l were obtained by moving the sheet in parallel to the fibre-optic cable end. Pads of varying thickness were used for that purpose. Figure 10 shows example static characteristics for a sensor with fibre-optic cable no. 2, determined while the fibre-optic cable end was fixed in the die block housing so as to position its glass-covered photosensitive surface at the level of the die block working surface. Due to the fact that the fears regarding the optical fibre end being damaged when the electrodynamically displaced sheet metal would hit it were confirmed, the fibre end was put inside the die block and moved a few millimetres away from its working surface. This ensured direct contact between the optical fibre end and the sheet metal, impossible during the measurements. In these conditions, the static characteristics determined again for sheets made of various metals had only these sections which would correspond to with the dropping part of the static characteristic, Fig. 11.

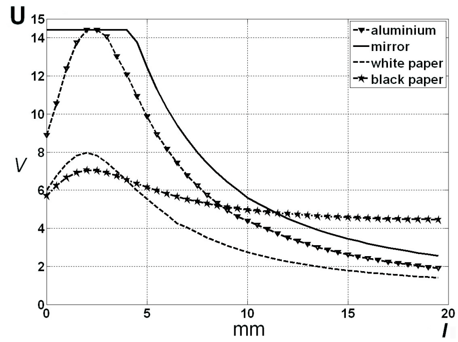

Fig. 10. Static characteristic for sensor with optical fibre no. 2, with indirect arrangement of fibres throughout change of distance l.

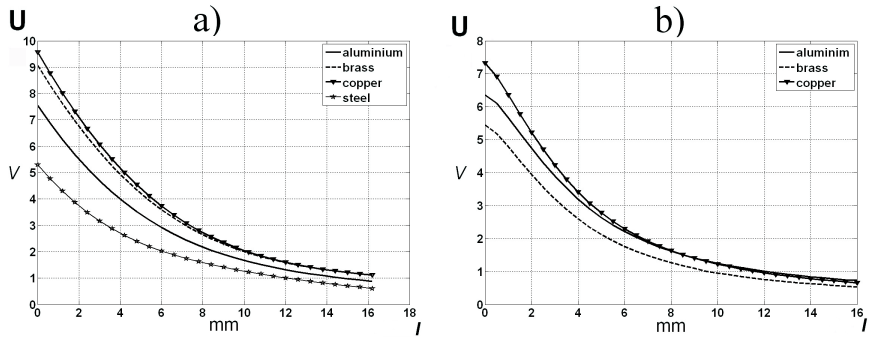

Fig. 11. Static characteristics for photoelectric sensors with optical fibres no. 1 (a) and no. 2 (b) used in the measurements.

Comparison of static characteristics shown in Fig. 11 a and b proves that sensor no. 2, used in further measurements, is characterized by lower sensitivity and higher measurement range as compared to sensor no. 1. Diagrams in Fig. 11 prove the unfavourable effect of the sheet metal reflection coefficient on the level of focal power brought into the receiving optical fibre in the sensor. As a result of this, it was necessary to determine the static characteristics for each type of sheet metal subject to forming. For computing purposes, the determined static characteristics were approximated with square functions.

3.2. Measurements of motion parameters for electrodynamically formed sheets

Measuring experiments carried out at the measurement setup characterized in the previous section allowed to register a function graph of capacitor discharge current flowing through inductor coils, which is the source of the Lorentz force acting on sheet metal, and to determine time function graphs for displacement, velocity and acceleration of the sheet metal subject to this force. Sheets made of various metals were used in the tests. The sheets were disk-shaped, varying in diameter and thickness. The measurements were carried out at small levels of energy delivered to the inductor head (no more than 1 kJ). During the measurements, die block housing 3 (Fig. 8) was fixed in a position in which the die block working surface was moved away from the inductor to a distance $l_o > l_{st}$, (l_{st} – maximum die block-inductor distance, set when determining the static characteristic, Fig. 11).

Displacement function graphs were obtained on the basis of the detector output voltage $U(t)$ function graphs registered in time t, taking into account previously determined static characteristics. Time function graphs for velocity and acceleration were determined in a planned way by single and double differentiation of the displacement function graph. Two differentiation methods were applied: one based on numerical differentiation using Newton interpolating polynomials , the other using a differentiating filter.

Figure 12 shows the following function graphs: displacement $l(t)$, velocity $v(t)$ and acceleration $a(t)$ of a sheet aluminium disk, obtained during its movement at the measurement setup. Sheet metal displacement towards the die block (rising graph section) is effected by the Lorentz force. The dropping section of the registered function graph corresponds to a free sheet falling onto the inductor surface. Measurement experiments, the results of which are discussed in this paper, covered only the analysis of sheet metal motion effected by a Lorentz force.

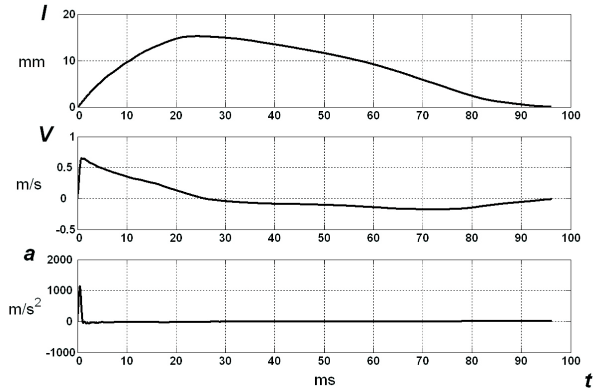

Fig. 12. Example function graphs for quantities that characterize sheet aluminium movement during electrodynamic forming.

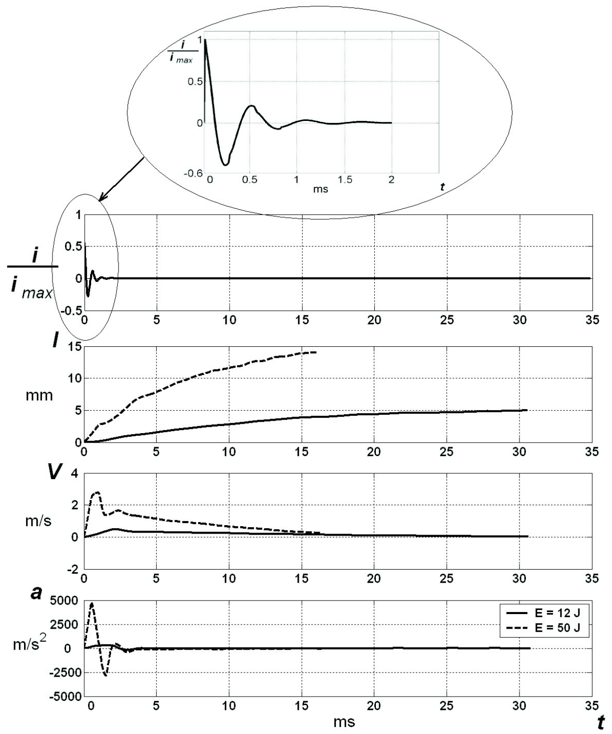

Fig. 13. Time function graphs for current in the inductor and motion parameters for a sheet aluminium disk sized as follows: thickness g = 0.8 mm, diameter d = 150 mm, at varying energy E values for the generator.

Oscillograms shown in Fig. 13 illustrate a model set of the l, v, a time function graphs obtained for one of the sheets at different generator energy levels. These function graphs were synchronized with the function graph registered at the same time for current flowing in inductor windings, shown in the Figure. Oscillograms in Figs. 14–18 were determined at various generator energy levels for sheet metal disks varying in size and type of metal they were made of. The presented function graphs let us draw a number of important conclusions allowing to evaluate the dynamics of processes involved in electrodynamic sheet metal forming.

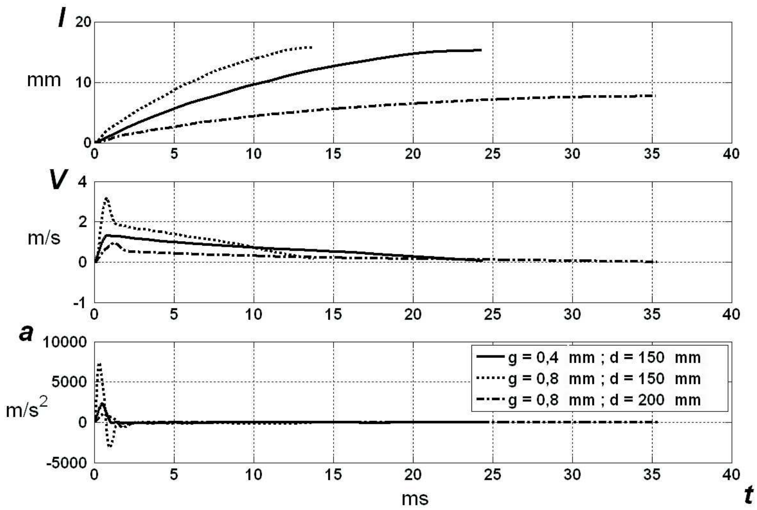

Fig. 14. Function graphs for quantities as in Fig. 14, for aluminium sheet disks varying in size; generator energy E = 12 J.

For example, if we take two sheet aluminium disks with the same diameter at a certain generator energy, then the disk with thickness g = 0.8 mm in a specified time interval is dislocated further away and reaches a higher velocity than the thinner disk with g = 0.4 mm, (Figs. 14, 15). This effect should be explained by more intense magnetic field density in the inductor-thicker sheet metal working gap, which contributes to the growth of the Lorentz force. The value of the Lorentz force is proportional to the square of the field induction. Function graphs shown in Fig. 16 indicate that it is a rule to obtain higher efficiency of Lorentz force generated in a magnetic field for sheet metal disks with determined sizes, made of the same metal. Function graphs for sheet metal disks made of annealed copper, (Fig. 16) and of brass in an unsoftened state, (Fig. 17), illustrate the effect of shape instability in case of soft sheet disk (changes in velocity and acceleration during sheet movement), contrary to the behaviour of a hard sheet disk which shows no change in geometry.

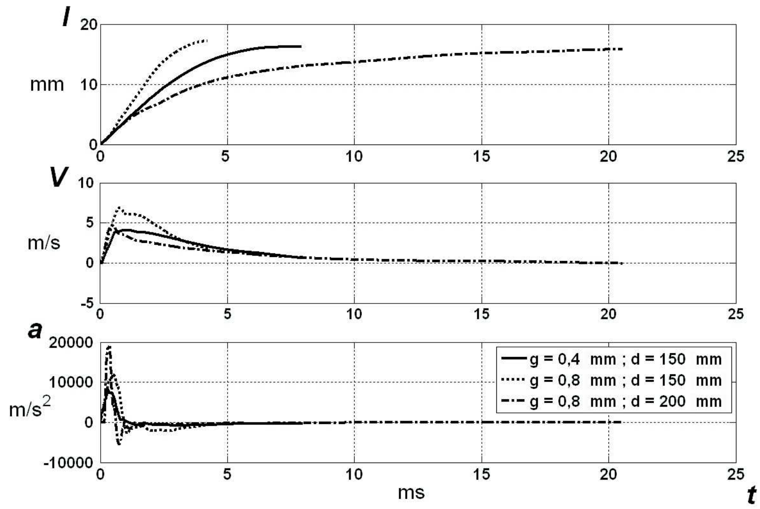

Fig. 15. Function graphs for sheet metal disks as in Fig. 14, at generator energy $E = 50$ J.

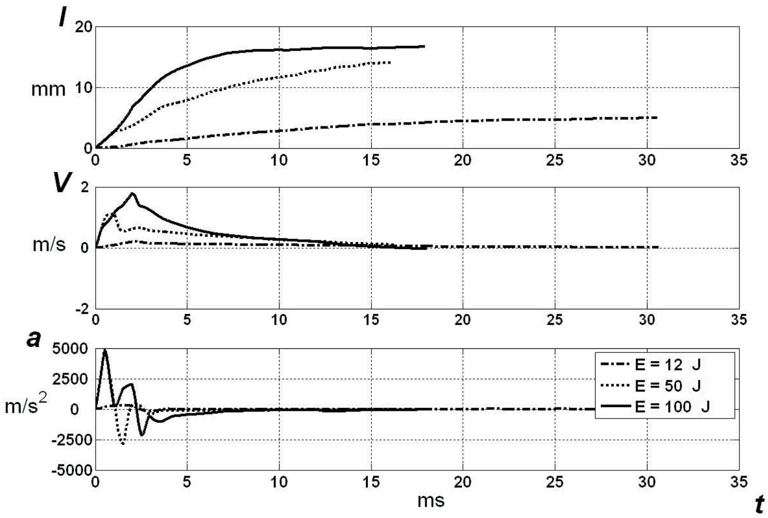

Fig. 16. Function graphs for quantities as in Fig. 14, for brass sheet disks – thickness $g = 0.2$ mm and diameter $d = 150$ mm, at varying energy E values for the generator.

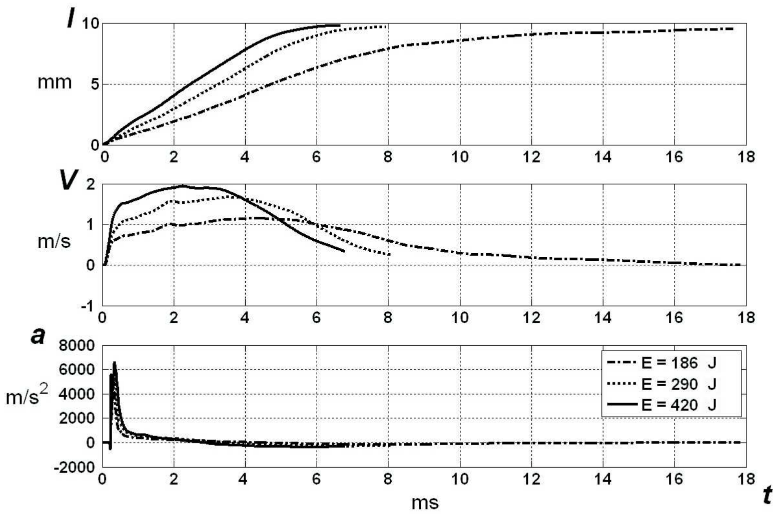

Fig. 17. Function graphs as in Fig. 14, at varying energy E values; copper sheet disks sized as in Fig. 16.

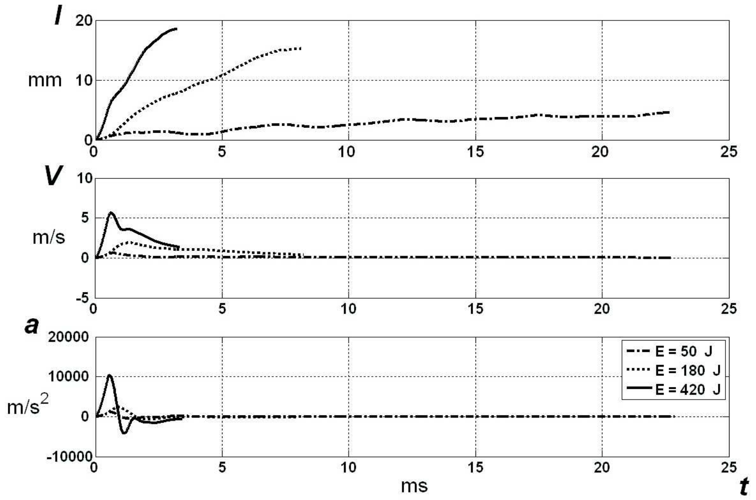

Fig. 18. Function graphs as in Fig. 14, at varying energy E values; steel sheet disks sized: g = 0.3 mm and diameter d = 150 mm.

It should be emphasized that the information presented in this paper concerns the initial stage of research carried out at the Department of Process Control on the construction of a reflective fibre-optic transducer. The completed experiments were introductory and proved high transducer usability to obtain broader knowledge on the specificity of the electrodynamic forming process. Time function graphs of formed sheet metal surface displacement obtained in the measurements can be used in free forming processes to determine the degree of possible semi-finished product deformation. Sheet movement velocity distributions are very useful in sheet forming operations involving the use of die blocks, which was stated in the introduction. Finally, known acceleration allows to determine maximum force values, which is important e.g. to evaluate the strength of inductors being used as forming tools. Function graphs shown in figures are presented synchronically as a function of time so as to illustrate the nature of changes in all measured quantities while the sheet metal moves towards the die block. Of course, for research purposes concerning a certain type of forming operation, it is possible to select any interesting quantity, e.g. velocity, and display its graph in a specified time interval, as shown in Fig. 19.

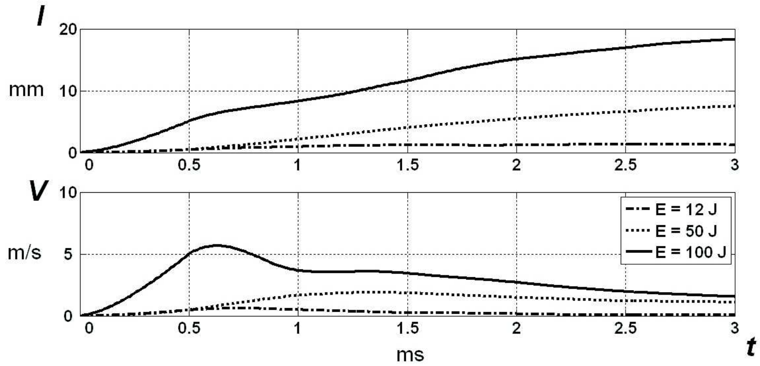

Fig. 19. Function graphs showing displacement and velocities of steel sheet disks with thickness $g = 0.2$ mm and diameter $d = 150$ mm, at varying generator energy values.

Moreover, it is important to apply constructional solutions allowing to obtain complete measurement information when designing a specified reflective sensor option. For example, it is useful to have a transducer with a broad measurement range for dislocation measurement, while it is advisable to use optical fibres with extended sensitivity at limited measurement range for velocity and acceleration measurements (option with the optical fibre shown in Fig. 5a).

The transducer measurement error consists of partial errors due to: the method applied to process measured quantity within the transducer itself, measurement signal processing, and the impact of external factors. In the discussed measurements, the global error largely depended on inaccuracies occurring when determining the static characteristic and its approximation with a monotone function, and signal processing errors in executive differentiating elements. Another important issue is the disturbance caused by external factors, revealed during calibration, which occurs due to a difficult-to-predict sheet metal colour change during the forming process. This unfavourable effect can be eliminated by using several sensors with suitably selected sensitivity characteristics. This will be included in further research aimed to improve the transducer. Unchanging sheet metal surface colour was maintained throughout the measurements. The largest error, within 6%, was estimated during the acceleration measurement.

The main purpose of research carried out during the first period was to develop and evaluate the usability of optical fibre transducers for the ED technology. No deepened error analysis was performed at that stage. No efforts were made to improve measurement accuracy, since this was planned for further stages of the research.

4. CONCLUSION

In order to learn about the specificity of percussive metal working in a pulsed magnetic field, it is extremely useful to know the motion parameters of elements formed using this method. It is not easy to determine them by way of analysis because of the complexity of electromechanical physical phenomena occurring during the process, which are described using mathematical models of varying simplification level. As a result of this, it becomes particularly important to be able to determine the discussed quantities by measurements, [7, 8]. The paper presents a prototype optical fibre transducer allowing to measure displacement time function graphs for sheet metal elements subject to forming in a pulsed magnetic field. The relatively wide transducer measuring range, which reaches a dozen or so millimeters, and the broad range of transmitted frequencies near 300 kHz decide about the transducer's full usability for measurements in conditions specific for processing in pulsed magnetic field, where in practice the die block is being set in relation to the sheet subject for forming at an initial distance of up to a few millimeters, and velocities obtained by sheet elements accelerated during the process may reach hundreds of meters per second. When comparing fibre-optic displacement sensors available on the market, e.g. manufactured by an American company, PHILTEC, INC., with a prototype transducer described in this paper, we should consider that marketed sensors are characterized by higher sensitivity, however they are designed primarily to measure displacements ranging from fractions to a few millimeters, whereas in their standard types the transmission band limit frequency does not exceed a dozen or so kilohertz. We should also point out that the prices of these sensors are considerably high and reach a few thousand US dollars. The specified sensor which was used in the measurements, allowed to avoid disturbances resulting from the occurrence of variable magnetic fields. Moreover, the researchers made use of easy fitting of its elements in a limited measurement space: inductor – semi-finished product – die block.

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