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## Concept of Smart Electrohydraulic Press for Impulse Sheet Forming

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Electrohydraulic impulse sheet forming (EHF) method proved its high efficiency at pilot, small-batch, and middle-scale production conditions. As the latest achievement, multielectrode discharge blocks provide effective forming of the middle and large size sheet parts. However, wide application of EHF technology in industry is limited mainly by two problems: instability of impulse pressure fields and lack of literature as well as skilled EHF specialists. Now the problem of instability is solved by a qualified EHF specialist with intermediate disclosing of tooling, inspection of intermediate shapes of blank, making corrections in loading diagram (electrodes' connections), and setting of new level of discharge energies. New approach to this problem includes solutions based on intellectual computer numerical control of EHF equipment: monitoring of intermediate shape of sheet blank after each discharge and making corrections of loading parameters for the next discharge till the final shape of part. Intermediate shape can be determined by measurements with special sensors built in a die in characteristic places (points). Another subsystem should analyse position of several principal segments of blank, compare them with total strategy of forming procedure for a definite type of sheet part, reveal those places, which need higher pressure to harmonise forming process, and give this information to the subsystem controlling a multicircuit current generator for optimised configuration of activated

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electrodes and energy level, thus, determining new pressure loading diagram for the next discharge. Now, the tests for blank shape measuring system are planned to solve this principal problem for realisation of the submitted concept. In addition, principal design solutions for multicircuit current generator with special unit for reconnections of electrodes are in work.

**Key words:** press, computer numerical control, electrohydraulic impulse forming.

Спосіб електрогідравлічного імпульсного листового штампування (ЕГШ) довів високу ефективність в умовах пробного, дрібносерійного і середньосерійного виробництва. Новітнє досягнення, — багатоелектродні розрядні блоки, — забезпечує ефективне штампування листових деталей середніх і великих розмірів. Однак широке застосування технології ЕГШ у промисловості обмежується в основному двома проблемами: нестабільністю імпульсних полів тиску і недостатчею літератури та кваліфікованих спеціалістів у галузі ЕГШ. У теперішній час проблема нестабільності розв'язується кваліфікованим спеціалістом ЕГШ шляхом розкриття оснащення, оглядом проміжних форм заготовки, внесенням корекцій у схему навантаження (схеми підключення електрод) і встановленням нових рівнів енергії розрядів. Новий підхід до розв'язання цієї проблеми передбачає рішення, які ґрунтуються на використанні інтелектуальної комп'ютерної числової системи керування обладнанням ЕГШ: виявлення проміжної форми листової заготовки після кожного розряду і внесення корекцій у параметри навантаження для кожного наступного розряду до одержання кінцевої форми деталі. Проміжну форму можна визначити шляхом міряння спеціальними давачами, яких вбудовано в штамп у характерних місцях (точках). Друга підсистема має аналізувати положення декількох принципових ділянок заготовки, порівнювати їх із загальною стратегією процесу штампування для певного типу деталей, виявляти ті ділянки, які потребують більш високий тиск для гармонізації процесу формоутворення, і надавати цю інформацію в підсистемі, які керують багатоконтурним генератором струмів для утворення оптимізованої конфігурації підключених електрод і рівня енергії, таким чином, визначаючи нову схему навантаження для наступного розряду. У теперішній час заплановано дослідити по системі міряння форми заготовки для розв'язання цієї принципової проблеми в реалізації запропонованої концепції. Також опрацьовуються принципові конструкторські рішення для багатоконтурного генератора імпульсних струмів зі спеціальним пристроєм для перемикання електрод.

**Ключові слова:** прес, числове програмне керування, електрогідравлічне імпульсне штампування.

Способ электрогидравлической импульсной листовой штамповки (ЭГШ) доказал высокую эффективность в условиях пробного, мелкосерийного и среднесерийного производства. Новейшее достижение, — многоэлектродные разрядные блоки, — обеспечивает эффективную штамповку листовых деталей средних и больших размеров. Однако широкое применение технологии ЭГШ в промышленности ограничивается в основном двумя проблемами: нестабильностью импульсных полей давления и недо-

статком литературы и квалифицированных специалистов в области ЭГШ. В настоящее время проблема нестабильности решается квалифицированным специалистом ЭГШ путём раскрытия оснастки, осмотром промежуточных форм заготовки, внесением коррекций в схему нагружения (схемы подсоединения электродов) и установлением новых уровней энергии разрядов. Новый подход к решению этой проблемы предусматривает решения, основанные на применении интеллектуальной компьютерной числовой системы управления оборудованием ЭГШ: определение промежуточной формы листовой заготовки после каждого разряда и внесение коррекций в параметры нагружения для каждого последующего разряда до получения окончательной формы детали. Промежуточную форму можно определить путём измерения специальными датчиками, встроенными в штамп в характерных местах (точках). Вторая подсистема должна анализировать положение нескольких принципиальных участков заготовки, сравнивать их с общей стратегией процесса штамповки для определённого типа деталей, выявлять те участки, которые нуждаются в более высоком давлении для гармонизации процесса формообразования, и подавать эту информацию в подсистемы, которые управляют многоконтурным генератором токов для создания оптимизированной конфигурации подключённых электродов и уровня энергии, таким образом, определяя новую схему нагружения для следующего разряда. В настоящее время запланированы опыты по системе измерения формы заготовки для решения этой принципиальной проблемы в реализации предлагаемой концепции. Также прорабатываются принципиальные конструкторские решения для многоконтурного генератора импульсных токов со специальным устройством для переключения электродов.

**Ключевые слова:** пресс, числовое программное управление, электрогидравлическая импульсная штамповка.

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## 1. INTRODUCTION

Variety of sheet metal parts in terms of geometry complexity and overall dimensions, materials used, required quality parameters and production rate accounts for wide range of sheet metal forming processes available at the market. Among them, well-known and widely used methods like roll forming or stamping as well as novel techniques like incremental sheet forming (ISF), ford freeform fabrication technology (F3T), which are developed to overcome the limitations of long-term used well-known processes.

Focusing on complex 3D-shape structures, the most widely used forming methods are stamping, hydroforming, rubber-pad forming and superplastic forming. These conventional industrial sheet metal forming processes have already reached high level of their maturity and have clear application domains and limitations.

For example, cold or hot stamping, being economically efficient processes for large batch manufacturing, lose their advantages if the low production volume or short-term order fulfilment are required. The reasons are expensiveness of two-side tooling (*i.e.* punch and die set) and long duration of tooling design, manufacturing and try-out. Moreover, in case of complex parts, forming more than one two-side tooling set is commonly required due to the forming process realisation in several stages.

Hydroforming requires single rigid tool (die or punch), while another one is fluid that forms metal into a die inside the pressurised chamber. However, its wide application is limited due to complexity and expensiveness of the respective machinery. Hydroforming presses require thick-walled chambers able to withstand high static pressure of up to 2000 bars with pressure-tight covers. High pressure is created by complicated and energy intensive hydraulic system with pressure amplifiers. In addition, this method is characterised by the uniform pressure distribution along the workpiece surface that makes its application non-efficient for complex 3D-shaped sheet parts with local elements.

Rubber-pad forming process having the same advantage of one-side metal tooling uses elastic material (rubber or polyurethane) for shape generation. This method is applicable for small- and middle-size sheet parts under small- and middle-scale production, but its capabilities are limited to shallow 3D shapes. Another drawback of rubber-pad forming is an increased springback of the formed parts caused by the relatively low pressure to the part and decreased pressure in local elements due to high viscosity of rubber. Manufacturing of middle and large-size sheet parts has low efficiency due to the necessity of large hydraulic presses with high energy consumption.

Another alternative method for 3D-shapes' manufacturing is a superplastic forming by an inert gas (typically argon) under the high temperature (500–600°C). This process allows obtaining of super elongations of sheet metal (up to 600–1000%), but it is characterised by extremely high energy consumption and is applicable for limited range of materials. Only ultrafine grain structures (1–2 µm) has superplastic capability, thus sheet materials have to be preliminary treated which significantly increases process cost-efficiency. One more limitation is caused by the uniform pressure field resulting in excessive thinning in local 3D elements that reduces total part strength.

In comparison with the above-reviewed forming methods, the electrohydraulic impulse sheet forming (EHF) method has advantages of one-side die, improved formability and small springback due to high speed of deformations, low material intensiveness of equipment, low electric energy consumption per an item produced.

EHF method proved its high efficiency at pilot, small-batch and middle-scale production conditions. The latest achievement—

multielectrode discharge blocks—provide effective forming of middle and large size sheet parts due to improved controllability of pressure fields generated by large number of electrodes [1–3]. However, wide application of EHF technology in industry is limited mainly by two problems: instability of impulse pressure fields and lack of specialised literature and skilled EHF specialists.

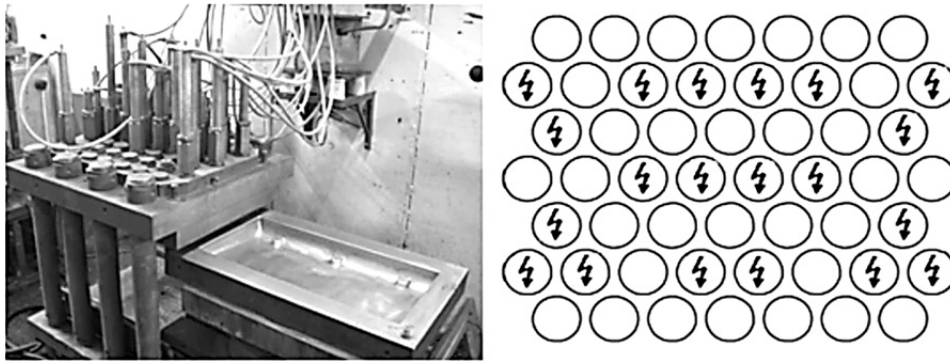
Instability is realized in two aspects: instability of pressure distribution along sheet blank surface and low repeatability of pressure field from one discharge to another. Long-term experience in EHF presses usage allowed to reveal and analyse factors that cause instability of sheet parts forming: instability of discharge electric parameters initiated by high-voltage breakdown in a liquid, position instability of discharge channel in a spark gap, shadow effects of electrodes, wear of current rods and insulators of electrodes, changes in a sheet blank shape during forming process, increases of work volume and distance between spark gap and sheet blank with a blank shape progress, *etc.*

Now, the EHF problems are solved by a qualified EHF specialist with intermediate disclosing of tooling, inspection of intermediate shapes of blank, making corrections in loading diagram (electrodes connections) and setting of new level of discharged energies (by changing a charged voltage and capacitance). Thus, pressure field and energy for the next discharges are determined on the basis of experience and skill of EHF specialist.

The purpose of this work is to develop new principal concept of EHF press based on previous publications [4, 5] on intellectual control system to overcome current limitations of EHF method for wide industrial application.

## 2. UP-TO-DATE REALISATION OF MULTIELECTRODE EHF TECHNOLOGY

An idea of multielectrode discharge block (MEDB) application for electrohydraulic forming was generated and patented by Prof. Yuri Chebanov in 1983 in the National Aerospace University ‘KhAI’. Unlike traditionally used single electrode pair in a dome-shaped discharge chamber, MEDB includes great number of closely positioned insulated electrodes fixed in one solid plate. Another plate (called ‘discharge plate’) with holes serves as common opposite-charged electrode for all insulated electrodes. At the same time, holes serve as guiding nozzles for pressure impulses (shockwaves), because each electrode is surrounded by the wall of hole in discharge plate with opening directed to a sheet workpiece. This small discharge volume for each electrode forms pressure impulse directed to sheet workpiece and the wall protects insulated electrode from action of other pressure impulses. Each electrode in this case has to be served with individual high-voltage capacitors (discharge cir-



**Fig. 1.** General view of MEDB of UEHF-2 experimental installation and representative scheme of possible electrode pairs arrangement [6] (positions marked with ‘⚡’ symbol are active on the MEDB photo).

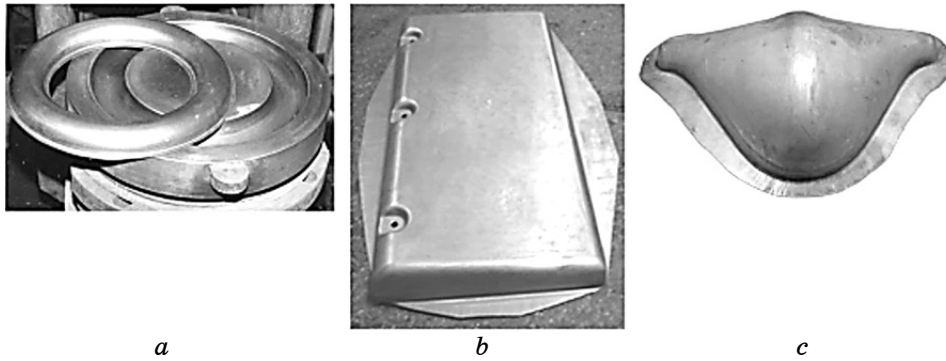
cuit).

It was a revolutionary solution for improvement of EHF capabilities by means of efficient control of generated impulse pressure field. This efficient control is realised by means of activation of not all electrodes available in MEDB, but only several of them. Simultaneous discharges of optimally selected electrodes enable generation of non-uniform impulse pressure field of optimal configuration that corresponds to the specific geometry of the part to be produced. It means that impulse pressure is concentrated in those areas of workpiece where maximum deformation is required. Moreover, non-linear effects of several shockwaves interaction significantly amplify pressure field intensity and overall MEDB-based forming process efficiency.

MEDB concept feasibility was validated in the ‘KhAI’ Laboratory of Electrohydraulic Forming. Demonstrated in the Figure 1 proof-of-concept prototype UEHF-2 provides a possibility to use up to 22 active electrodes that could be placed in 52 different positions. Maximum number of active electrodes is defined by the number of discharge circuits of multicircuit pulse current generator available for connections.

During UEHF-2 prototype application, an optimal arrangement of active electrodes either is determined experimentally or is based on the previous experience accumulated, while electrodes positioning and connection/activation are realised manually. Even at this low technology readiness level, great potential of MEDB application was demonstrated by successful production of complex 3D-sheet parts of middle and large size made of different materials that are shown in the Fig. 2.

Experience in application of EHF presses based on MEDB design revealed two problems that prevent wide usage of EHF technology in industry: instability of impulse pressure fields and lack of specialised literature and skilled EHF specialists.



**Fig. 2.** Examples of complex sheet metal parts produced in UEHF-2 installation: torus-type semi-product made of 08kp steel (thickness 1.5 mm) in the die made of the same steel [2] (a); box-type semi-product made of AMg6 high-strength aluminium alloy (thickness — 2.0 mm) produced in the die presented in Fig. 1 [6] (b); ‘pan’ semi-product made of 12Cr18Ni10Ti stainless steel (thickness 0.8 mm) produced in Al–Zn die [7] (c).

Instability is realised in two aspects: instability of pressure distribution along sheet blank surface and low repeatability of pressure field from one discharge to another. Long-term experience in MEDB design usage allowed to reveal and analyse factors that cause instability of sheet parts forming: instability of discharge electric parameters initiated by high-voltage breakdown in a liquid, position instability of discharge channel in a spark volume between two opposite electrodes, shadow effects of electrodes, wear of current rods and insulators of electrodes, changes in a sheet blank shape during forming process, increases of work volume and distance between spark gap and sheet blank with a blank shape progress, etc. All these factors result in unstable formed shapes though configuration of activated electrodes is optimal.

Now, this problem is solved by high-skilled EHF specialist. He makes periodical inspections of semi-formed sheet part after one or several discharges in order to estimate rightness of forming process and to do corrections in activated electrodes configuration and discharge energy level for each activated electrode for the next forming step. In order to perform inspections, EHF press operator should pour out ware from discharge block, unclamp die, and move it to auxiliary position, *i.e.*, each time for inspection the disclosing of die is needed. Of course, these actions do take long periods of time that significantly reduce EHF efficiency.

After inspections, the solutions for the next discharges are made on basis of accumulated experience in MEDB application for manufacture of complicated 3D shapes during several years. In addition, these solutions are made at each of three stages of forming process: generation of general shape, forming of smaller local elements and calibration. Un-

fortunately, this experience is not formalised and not described in specialised literature in sufficient volume yet.

Therefore, further implementation of novel EHF MEDB equipment and processes should include solutions of these problems by modern means with application computer-based technologies [8].

Demonstrated efficiency of MEDB-based EHF process in combination with extensive capabilities of advanced simulation methods, sensing techniques and control systems create a positive ground for renewal of EHF process industrial application. Being developed at the new level, the EHF process will be able to cope with current trends in mechanical products design and stricter economic and ecological requirements.

### 3. CONCEPT OF SMART MULTIELECTRODE EHF PRESS

The purpose of new concept is to overcome current technical state-of-the-art of EHF processes in terms of process automation and reliability in parallel with achievement of high level of material and energy efficiency for customised and small batch production of complex 3D sheet metal parts. To reach these ambition targets, the overall concept consists in the synergy of three innovative approaches:

- application of adaptive MEDB system instead of one pair of electrodes; system adaptivity will ensure activation of optimal set of electrodes that are pre-selected by the control system to generate optimal multielectrode discharge and create shape-generating pressure field that fits to the part geometry; it will increase EHF process efficiency and reduce energy consumptions; innovative architecture of adaptive MEDB system will make possible to realise sheet metal part forming process in automated mode;
- integration of sensing capabilities into the one-side die to create an innovative sensing die and realise continuous in-process monitoring of workpiece shape, thus contributing to EHF process reliability and supporting real-time process control and optimisation by the intellectual control system;
- automation and real-time optimisation of sheet metal part forming by smart control system to ensure EHF process efficiency, high quality of sheet metal parts and minimum use of energy; control system operation will be based on application of advanced simulation models and optimisation algorithm to define optimal multielectrode discharge to be realised by adaptive MEDB system [9].

The listed principal solutions are depicted in a graphic form in the Fig. 3. It is obvious that principal element of the proposed solution is a sensing die, *i.e.*, die equipped with sensors indicating positions of various segments of a formed sheet blank. Coordinates of the sensors ( $x_i, y_i, z_i$ ) along the die cavity will give data for plotting 3D models for intermediate shapes after each multielectrode discharge and indicate com-



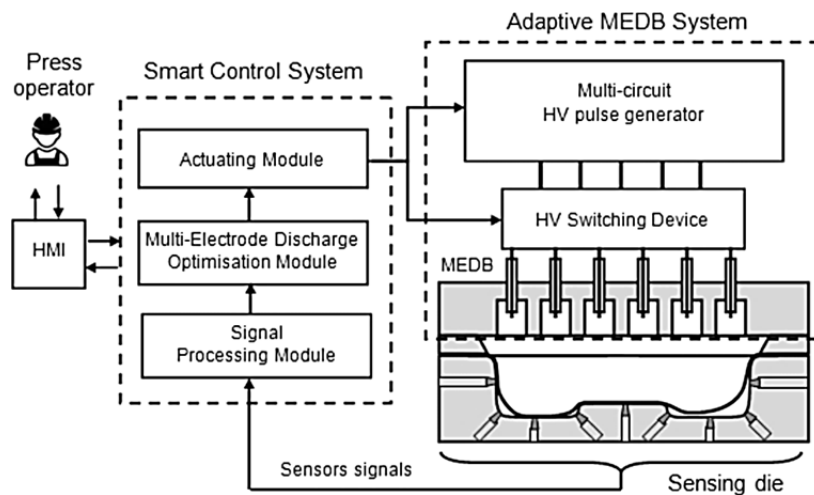


Fig. 3. General diagram of smart EHF press.

pleteness of final shape formed (Fig. 3, signal processing module). This is so-called feedback system giving information about actual shape of a formed blank without opening of tooling and so making possible to do reconnections in MEDB for activation of those electrodes needed for improved pressure field at the next discharge. Correctness of 3D models depends on coordinates and quantity of sensors. The latter can be estimated as 5 for simpler shapes and 30 and more for complicated shapes with big number of small local elements characterised by small radii. It should be noticed here that accuracy of detection of intermediate shapes at the first general forming stage will not be so high, because of small-area contact of sheet blank and die surface, but it is enough to plot 3D model and do prediction for the discharge. Accuracy of 3D models at the second (local forming) and the third (calibration) stages will be high due to definite position of most blank elements contacting with the die surface having exact geometric configuration. Using Human Machine Interface (HMI, Fig. 3), a press operator can observe progress of blank shapes from one discharge to another and check correctness of forming procedure without opening of tooling, in comparison with present situation, when forming process should be stopped, tooling should be opened in order to inspect intermediate or final shape of blank.

Decisions on improvements in pressure field for the next discharge are made in automatic mode by multielectrode discharge optimisation module (Fig. 3) by generating commands for setting new configuration of activated (connected) electrodes and new levels of charged voltage and capacitance for each electrode connected to multicircuit high-voltage (HV) pulse generator, thus determining a new level of energy

discharged over a definite segment of sheet blank. The decisions are made in such a manner to keep general forming strategy for a definite type of shape (dome round, box, semi-torus, steeply curved half-pipe, fairing, *etc.*) taking into account positions and dimensions of local elements. Therefore, the optimisation module should include database of forming strategies for representative parts as well as for unusual intricate shapes (Fig. 4). Optimisation module can include different parameters for optimisation: realisation of deep-drawing procedure, stress distribution to avoid wrinkling, sheet thickness distribution to ensure the same strength parameter, improvements of accuracy and springback, *etc.*

Configurations of activated electrodes and levels of energy elec-

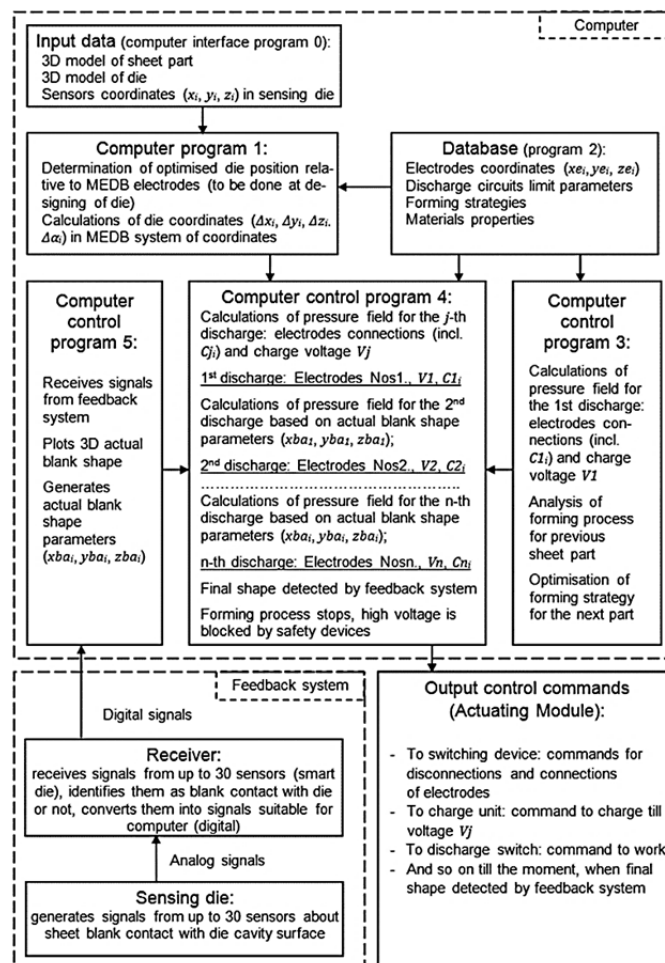


Fig. 4. Architecture of smart control system.

trodes' levels for the first discharge are initially determined from the general forming strategy for a representative part. The next discharges parameters are based on comparison of forming strategy steps (assigned intermediate shapes) and actual intermediate shapes. After the forming of first part of definite geometry and material, its forming procedure can be considered and remembered as a new optimised forming strategy for this definite part. Further improvements in the strategy are determined by wear of electrodes, variations in sheet material properties and thickness, deviations of initial blank configuration and its initial position relative to the die cavity, *etc.*

Development of forming strategies for database (Fig. 4) is based on experience accumulated during long years of experimental EHF of 3D shapes of representative types of parts and described in publications and scientific reports. In addition, computer simulations of multielectrode EHF processes for typical and unusual shapes will be useful for compiling the forming strategies for materials with different physical and mechanical properties.

Output commands of smart control system are realised by adaptive MEDB system before each multielectrode discharge. The control system should also generate control commands for usual functions of EHF press (not shown in Fig. 4): motions of die to work position and back, filling of MEDB with water and pouring it out, air evacuation, *etc.*

#### 4. CONCLUSIONS

Suggested concept of smart electrohydraulic press is presented in short description with principal solutions for three constituent components: sensing die, adaptive MEDB system and smart control system.

Practical realisation of this concept needs performance of large volume of design, manufacturing and investigation works.

Realisation of this concept will allow solving the problems of instability of impulse pressure fields, lack of specialised literature and skilled EHF specialists as the conditions for wide industrial implementation of EHF technology that finally will bring big economical effect.

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