Application of a systems engineering and SysML in the development of a universal die set for hydraulic presses

Oleksandr Tarasov[1], Dmytro Pavlenko[2], Liudmyla Vasylieva[1,3], Victor Kotsyuba[4] and Vadym Shkarupylo[3,6]

[1] Donbas State Engineering Academy, Kramatorsk, 84313, Ukraine
[2] National University Zaporizhzhia Polytechnic, Zaporizhzhia, 69063, Ukraine
[3] Kyiv National Economic University named after Vadym Hetman, Kyiv, 03680, Ukraine
[4] Joint Stock Company Motor Sich, Zaporizhzhia, 69061, Ukraine
[5] National University of Life and Environmental Sciences of Ukraine, Kyiv, 03041, Ukraine
[6] G.E. Pukhov Institute for Modelling in Energy Engineering of the NAS of Ukraine, Kyiv, 03164, Ukraine

Abstract

This article is devoted to developing a methodology for describing models of technical systems, based on the methodology of system design and system modeling language (SysML). Using the "press-die" system as an example, the specific design steps used to form the structure of a universal die set (UDS) with advanced technological characteristics used on hydraulic presses are presented. Provides examples of activity diagrams that describe the sequence of technological operations and the kinematics of movement of die set elements during the implementation of typical forging technological cycles. An algorithm for selecting design solutions for a UDS is proposed. The analysis of the requirements for the design of hydraulic presses and die sets for the implementation of a number of metal forming processes with complex kinematics of tool movement in the forging technological cycle was carried out to demonstrate the technique. Particular, such processes as extrusion with counterpressure, some processes of severe plastic deformation (SPD), pressing blanks from powder materials, etc., need complex kinematics of tool movement. The generalization of the requirements for the design of a universal die set for the implementation of a number of metal forming processes with different sequences and operations kinematics was performed.

Keywords

Systems engineering, system modeling language (SysML), universal die set, "press-die" system

1. Introduction

Systems engineering technologies recently developed to create new technical objects based on models and design languages such as SysML allow us to generalize approaches to product design and comprehensively and accurately document their models. This ensures the high quality of the technical solutions used. In addition, justification for the choice of technical solutions for the design or the creation of new ones is more reliably provided.

One of the important tasks in the development of new designs is the application of a systematic approach to design [1, 2]. It defines the general principles of analysis and synthesis of technical systems, the use of model-based design technologies, selecting the aspects of considering objects to simplify their analysis and design solutions [3, 4]. As an example, consider the process of creating universal stamping equipment for hydraulic presses, which ensures the implementation of a number of technological processes. Obtaining forged products by forging and extrusion, from powders, and additional forging of pre-sintered powder blanks in mass production, as a rule, is carried out on specialized equipment. This is due to a decrease in the cost of the process of obtaining a large number of semi-finished products in the conditions of serial and mass types of production. In small-scale metal forming production, universal equipment and die sets are most often used. Similarly, studies are carried out to obtain semi-finished products from new materials, as well as to develop new technological processes (TP). Actively developing in recent years, new metal forming methods, in particular, severe plastic deformation, in some cases require more complex kinematics of operating

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alexandrtar50@gmail.com (O. Tarasov); dvp1977dvp@gmail.com (D. Pavlenko); vasileva.dgma@gmail.com (L. Vasylieva); ktu@motorsich.com (V. Kotsyuba); shkarupylo.vadym@gmail.com (V. Shkarupylo)

0000-0002-0493-1529 (O. Tarasov); 0000-0001-6376-2879 (D. Pavlenko); 0000-0002-9277-1560 (L. Vasylieva); 0000-0003-0234-1768 (V. Kotsyuba); 0000-0002-0523-8910 (V. Shkarupylo)

tools movement [5, 6]. Such processes can also include extrusion with counterpressure and pressing with active friction forces. Research of this kind is becoming increasingly widespread due to the emergence of new materials and methods of their processing to obtain products with unique properties [5, 7]. For example, it is known that counterpressure deformation increases the plasticity of materials by creating a high level of hydrostatic pressure on the blank [8].

Therefore, to implement a number of technological processes and complex sequences of operations on universal hydraulic presses, a technique for creating universal die sets with advanced technological capabilities is required.

2. Literature Review

For the effective creation of new technical solutions, a model of the environment is needed in which the object functions to form requirements, as well as to describe its structure and behavior [9, 10]. As a result of the analysis, functional requirements for the design object are formulated, which are implemented in the process of its creation [11, 12].

Formation of a conceptual model of a design object, technical solutions for elements and structures as a whole do not currently have fully developed automation systems. In this regard, the interest in methods for solving creative engineering problems, the issues of choosing technical solutions from a number of options has recently grown significantly [13]. In particular, the process of selecting technical solutions is being formalized and automated [13, 14].

After the automatic generation of a number of technical solutions, the issues of their validation and selection from the proposed alternatives are considered [11, 15]. Researchers, in particular, suggest using artificial intelligence methods in the form of knowledge bases [16], Semantic Technologies, heuristic algorithms for generating and selecting optimal designs in the process of component engineering design [9, 13]. In this regard, improving the quality of automated search for necessary technical information on the Internet is of particular importance [17]. Modern products usually include several heterogeneous subsystems based on different physical principles [18, 19]. These subsystems together provide the necessary functionality of Mechatronic Systems [20]. In particular, the technological equipment that is considered in this work is part of the "press-die" system. In particular, UDS for research may include means of automating auxiliary operations, a system for monitoring strain-stress state parameters, which is integrated into a press control system.

The selection of design aspects allows the decomposing of the designed object according to the physical principles within which the subsystems operate, as well as performing the design separately for each aspect [12]. Control of the completeness of solving problem in each aspect can be carried out on the basis of various algorithms, which are usually presented in the form of block diagrams [16]. To display the structure of the designed object, graphs and the corresponding adjacency or incidence matrices are used, which show the system structural elements and their relationships [21, 22]. The behavior of the object can be represented as a finite state machine [13, 23], in which the operating conditions of the system act as restrictions on the technical decisions made. To establish these connections and assess their significance, the accumulated data and expert assessments can be used.

An important addition to UML is the SysML parametric diagram [18]. It allows for establishing the interrelations and limitations of the parameters of a technical system. The use of mathematical models simplifies the development of algorithms for calculating the interrelated parameters of a product. Thus, parametric diagrams together with requirement diagrams allow significant refining of the tasks of creating a new system. In particular, when creating new technical objects, it is mandatory to construct a geometric model.

Some stages of designing technical objects before building a geometric model can be automated. The most important process is the selection of technical solutions. It can be based on an analysis of the properties and evaluations of technical solutions accumulated in databases. Information from databases is used to implement the functions selected at the previous stage. The choice of options is also carried out based on an analysis of the possible values of the system elements indicators and an assessment of the system as a whole based on various models [14, 24].

After evaluating and selecting a layout option for the object, ideographic models of the structure are built from the selected parts. UML deployment component diagrams [22] or SysML block diagrams [20, 25] can be used as analogs. As a system modeling language, SysML provides visual tools for documenting projects at the conceptual level and the possibility of a versatile representation of the designed object as a system [26, 27].

Thus, it can be argued that it is rational to carry out the design of UDS structures in combination with an analysis of the kinematic and power capabilities of the press. To describe the "press-die" system, it is necessary to formulate a set of requirements and restrictions, to characterize the functions, sequence of operations, and structural elements. Complex systems are characterized by synergetic interaction between their components. Therefore, there is a need for new multidisciplinary approaches to design [19].

Taking into consideration that the hydraulic press and the die set form a single "press-die" system, a number of requirements are imposed on its design to ensure its long-term and reliable operation. The hydraulic press plant has a number of standard units to ensure the working tool movement, and it also has a number of features associated with the plastic deformation mode and the ejection of products from the die. The die set is installed on the universal hydraulic press, which should provide not only the pressing force, but also the necessary kinematics of the process. In most cases, partial automation of the technological process steps is also required. Automation of the hydraulic press control is considered, in particular, in [28], and automation of the flexible manufacturing systems is described in [29]. Special conditions for the implementation of extrusion processes with counterpressure, especially for hard-to-cut alloys, predetermine a number of specific requirements for pressing equipment on which they can be implemented.

Thus, for the research and implementation of a number of metal forming processes, it is necessary to expand the technological capabilities of universal presses. This can be achieved by creating universal die sets that allow modifying the design, provide various options for the tool kinematics, the possibility of changing the connections among the UDS elements and the slave cylinders of hydraulic presses.

Changing connection will make it possible to implement the required kinematics of the working tool in conditions where the number of active movements of the cylinder rods is less than it is required for the TP.

To improve the quality of designing technical objects, the authors of [11, 18] proposed a modification of the method for formalizing information about the composition and structure of a product at the stage of conceptual design. Its essence is in the application of technical solutions for the simultaneous implementation of several functions, which provides increased opportunities for design changes or the creation of a new product.

The use of the modified conceptual design method makes it possible to formalize the design description for the possibility of high-quality decomposition and subsequent application of optimization methods [30], for example, a genetic algorithm [31].

An analysis of the literature has shown that today the use of domain-specific languages for modeling systems in the metal forming field is limited. This does not allow using a systematic approach in the design of the die set for hydraulic presses, which is intended for the implementation of existing and promising methods of metal forming. Increasing the UDS design efficiency is necessary for a more active introduction of technologies based, in particular, on SPD methods.

At the same time, the task of providing the necessary kinematics of the moving parts and expanding the technological capabilities of the hydraulic presses based on the use of additional elements of the universal sets, which change the structure of the connections between the set elements and the press hydraulic cylinders, was solved in the process of implementing the technological metal forming cycle.

The purpose of this paper was to develop an algorithm for selecting design solutions for the universal die set of hydraulic presses concerning many metal forming processes, based on the methodology of system engineering. The main tasks of the work were: development of an algorithm and methodology for a formal description of the structure, behavior of the "press-die" system and the process of choosing design solutions for several metal forming technological processes; creation of the UDS project for pilot testing or implementation of metal forming processes for blanks on the hydraulic presses in the conditions of small-scale production of semi-finished products.

The proposed algorithm for the development of the UDS design includes several stages that coincide with the system engineering methodology [32]. The improvement of this approach in this work is connected with the need to generalize the functionality in the UDS design and improve the information support of the design based on the systematization and formalization of the experience accumulated in the metal forming.

3. Results and discussion

3.1. Analysis of the requirements for the design of the universal "press-die" system

Let us consider the successive stages of design and development of models concerning the "press-die" system during forging on the hydraulic presses. At the first stage, based on the features of the materials being processed, the TP type, power, kinematic, speed and thermal deformation modes, the requirements for the functionality of the designed UDS system are determined. It should provide a forging cycle. At the same time, if a universal die set is created, it is necessary to consider and provide functionality for the entire range of TP for which it will be used.

At the first stage of the study, an analysis of the requirements for the die set design was carried out for a number of blank deformation processes with intensification of shear deformations. The scheme, power parameters, kinematics and temperature-speed mode of the technological process are the basis for choosing the design of the main elements of the die set for metal forming.

Based on the analysis of the features of some blank deformation processes, die set designs for their implementation, the results of modelling the metal forming processes and the behavior of blanks during the deformation process, a number of requirements for the design of the UDS for universal hydraulic presses have been established.

First of all, design solutions should provide a full cycle of execution of technological process at one working position. The set design must be universal and allow the performing of various technological operations, using tools of different configurations. Also, the set design should exclude the formation of burrs between all UDS working elements: between the parts of the matrix, the container, punches and the matrix.

When extruding blanks, special attention is paid to the design and use of the receiving container in the course of counterpressure deformation. The receiving container must provide not only counterpressure when the blank is deformed but also removal of the forgings from the container by the lower punch after the end of the process. In this case, the movement of the receiving container and the lower punch must be coordinated kinematically. In addition, the UDS design should provide a given thermomechanical mode of forging to ensure the stability of the process results.

The installation for deformation, in addition to the direct technological tool, should include several subsystems that ensure its efficient operation. Firstly, it is a UDS, which ensures the operation of the "press-die" system as a whole. The universal die set is installed in the working space of the press and is attached to the table (the lower plate of the die set) and the press slider (the upper plate of the die set), as well as to the press ejector subsystem. The die set has many functions to ensure the installation operation, fixation and centring of the working tool elements: the punch, the matrix, the lower punch, the receiving container, etc. In particular, it is equipped with columns that provide centring of the UDS plates and the working tool, regardless of the press. The subsystem for fixing the working tool gives not only reliable fixation but also a quick replacement for maintenance and repair. It eliminates the metal runout into the gaps of the die set during the deformation process.

Taking into account the economic conditions necessary for the successful implementation of the process in the conditions of small-scale production or experimental research of new technologies of metal forming, the installation design should ensure the minimum cost and labour intensity of operation. In this regard, a number of requirements ensuring the long-term, reliable and convenient operation of a UDS are also imposed on its design.

When designing a die set, as a rule, a model of a particular process or operation is considered. This allows simplifying the set and reducing the cost of the research process or experimental development of technology. However, such an approach leads to additional spending at the stage of industrial development of the research results. One of the ways to solve this problem lies in the field of creating the UDS for several technological processes. When designing such structures, a generalization of the approach to the formation of functional requirements for the UDS is required. They include requirements for the power and thermal regime of loading the blank, UDS elements, and the requirements for the kinematics of structural elements. After determining the set of functions, the possibility of their limitations for the group of selected technologies should be considered to reduce the redundancy of technical solutions and, accordingly, the UDS cost.

Based on the description of the requirements for the "press-die" system, a reasonable transition to the choice of design solutions for structural elements and their connections is necessary. To ensure the universality of technical solutions, the structure of the system, if necessary, must change in the process of replacing technology or even within the deformation cycle. The desire to provide promising options for UDS use leads to redundancy of design solutions at the design stage. This increases the cost of the structure. In this regard, a methodology for evaluating the effectiveness of the adopted design solutions is needed. The coefficient of unification of design solutions (K_u) calculated by the formula (1) can be taken as such an assessment:

$$K_u = N_u/(N_1 + N_2), \quad (1)$$

where N_u is the number of unified elements; N_1, N_2 are the number of additional structural elements for each of the two TP types, which are the working tool and elements for installing and fixing the working tool in the UDS.

The additional complication of the design can be estimated using the formula:

$$K_d = N_d/N_u, \quad (2)$$

where N_d is the number of additional structural elements in the UDS design for installing and fixing the working tool in the UDS and ensuring the operating cycle.

The rational value of the coefficient of unification for the die set can be considered as Ku > 0.6. For a more accurate assessment, it is necessary to apply the calculations of the cost of manufacturing or modifying a die set for the accepted technical specifications. In any case, the solutions incorporated in the design at the stage of conceptual design must allow the necessary UDS modification. This requires the analysis and development of its model in the design process using the SysML language tools.

3.2. Specification of requirements for the "press-die" system

At the second design stage, the requirements for the sequence of operations, the kinematics of movement of hydraulic press moving parts. The technological efforts and limitations of the process or group of processes for which development is being carried out are also determined. The results of the analysis of requirements for the UDS are presented in Figure 1 in the form of a requirements diagram. Thus, the analysis of system requirements and their specification in the form of a requirements diagram practically determines the composition of the product subsystems. Then the requirements diagram is decomposed to find an effective solution for each subsystem at the following design stages. UDS is designed to perform several technological operations, so in this case the requirements can be divided into two related groups: the universal part and the working tool.

To determine the UDS composition, an analysis of the external subsystems that form the environment of the technological equipment in the “press-die” system (Figure 2) has been made.

The hydraulic press must provide the power and kinematic operation of the UDS. In particular, the value of the generated forces, and the movements of the press working elements must be no less than required for the implementation of the process using the UDS. The die set must be installed in the working space of the hydraulic press and integrated with external subsystems, for example, with the control system of the press in an automated operation mode.

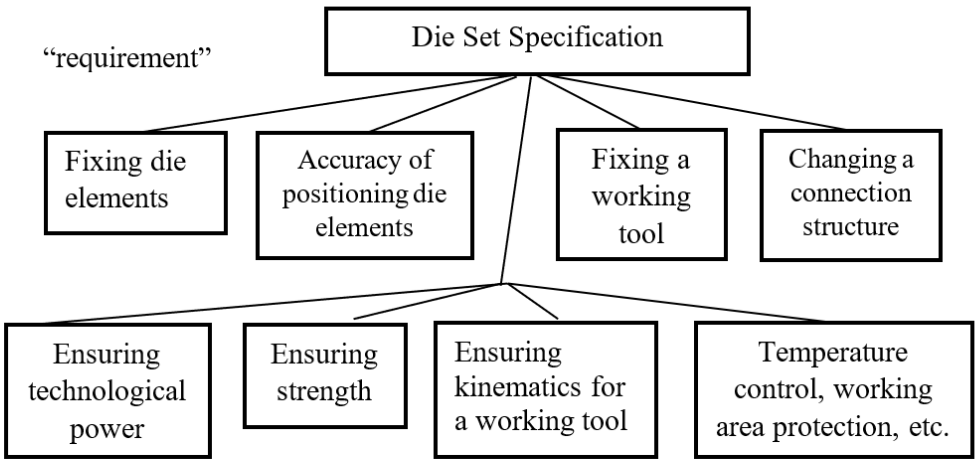

Figure 1: Requirements for UDS for the implementation of metal forming processes and the expansion of the technological capabilities of universal hydraulic presses

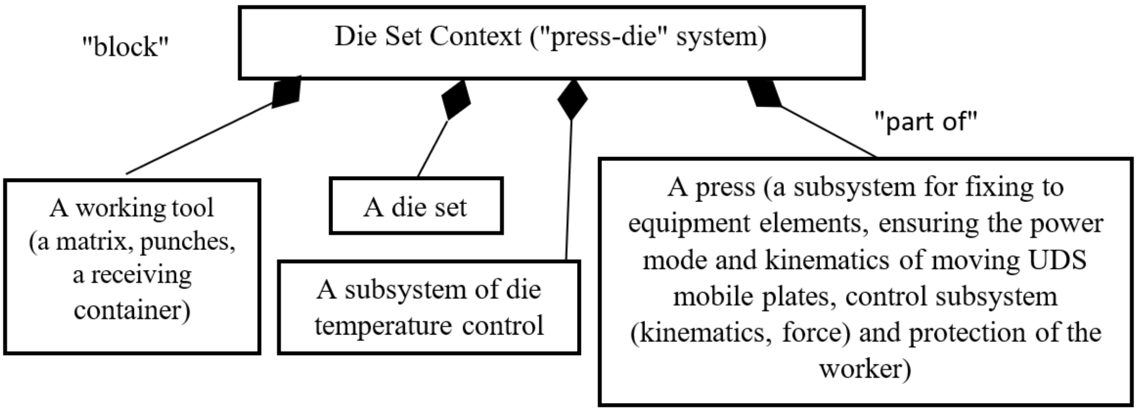

Figure 2: Block definition diagram for determining the UDS composition and external subsystems of the "press-die" system

An analysis of the operation cycle of the installation during SPD, extrusion with counterpressure and pressing with active friction forces has shown that the number of operations in these cases exceeds the capabilities of their performance by the power cylinders of universal hydraulic presses. In this regard, it is necessary to switch the operation of the drive cylinders based on a change in the connections between the "press-die" system elements in order to change the kinematics and perform a given sequence of operations.

In the next step, the behavior of the designed UDS in the metal forming process is simulated. At this stage, information about the system behavior can be formalized in the form of activity or state diagrams for further development of design solutions.

Let's consider formalizing the sequence of technological operations for forging on a hydraulic press. A finite non-empty set of basic activity states (3) is introduced. When performing a typical forging process, three successive stages are implemented, including a cycle of equipment and tooling operation.

$$BaseActivities = \{A, B, C\}, \tag{3}$$

where A is the initial state (preparation for forging), B is the execution of a technological operation (forging), C is the ejection of the finished part from the die, restoration of the initial state.

The results of the analysis of the "press-die" system behavior for a typical UDS design during forging are presented in the form of an activity diagram (Figure 3).

This cycle is repeated for each part. However, the implementation of each TP operation depends on the technology features, the shape of the part, the material and a number of other factors.

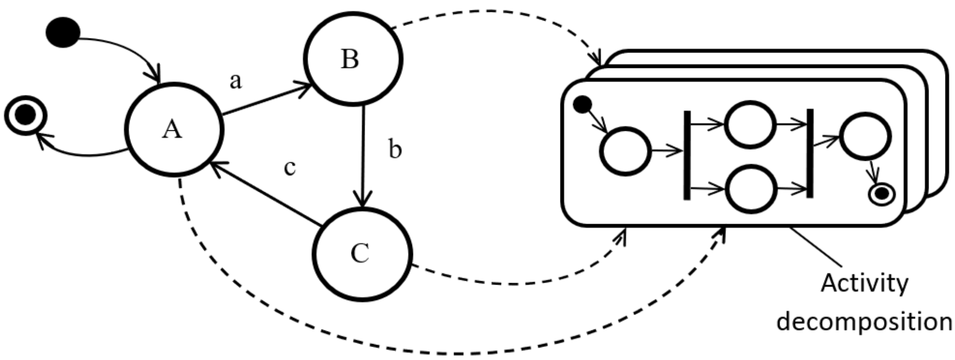

Figure 3: General diagram of activities for forging TP and decomposition of basic states: A - preparation of the cycle (tool lubrication, fixing the blank, etc.); B - working stroke (forging) with the return of the slider to its starting position; C - extraction of the forged product with the return of the ejector to its starting position; a, b, c - events that initiate transitions between activity states

For a detailed consideration of the stages, the decomposition of the system behavior is performed. In the initial state, the stage of preparation of the forging process, maintenance of the UDS, and installation of a new blank (state A) are implemented. Then the forging technological operation is performed (event a, state B), where the blank shape is changed. The deformation force during forging is generated by the press master cylinder.

In the third operation (event b, state C), a forging is removed from the die, and the press slider returns to its initial state of waiting and preparing for the next cycle (event c). In this case, the forged product is ejected by a slave cylinder or an ejector cylinder.

3.3. Model of the "press-die" system behavior

The behavior model of the "press-die" system forms the requirements for the elements that implement the forging cycle. In addition to the requirements for processes and the die block, the possibilities of a press drive are also considered. The purpose of the analysis is to conclude whether the functionality of this press is sufficient to perform this TP. At this stage, problems are identified in the implementation of TP, taking into account the capabilities of the press selected. The basic capabilities of the hydraulic press, on which the UDS is installed, for clarity, can be represented in the form of a forging cyclogram with an ejector cylinder, displaying typical operations (Figure 4).

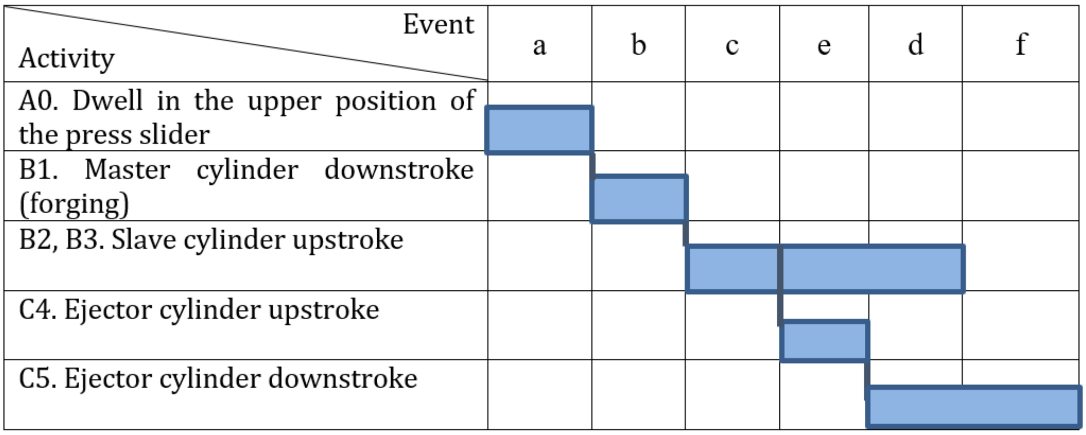

Figure 4: Cyclogram of forging on a hydraulic press with an ejector cylinder; performing various operations when events a…f occur

The system presented in the cyclogram contains non-empty finite sets of activities:

$$Activities = \{Master\ cylinder\ downstroke, Slave\ cylinder\ upstroke,\\ Ejector\ cylinder\ upstroke, Ejector\ cylinder\ downstroke\}, \quad (4)$$

and many events:

$$Events = \{a, b, c, d, e, f\}, \quad (5)$$

where *a* – event (command) to start the working downstroke of the slider, forging;
b – the beginning of upstroke of the slider until the start of the ejection of a forged product;
c – the beginning of the ejector cylinder upstroke (ejection of a forged product);
d – the slider in the upper starting position;
e – the start of the ejector cylinder downstroke (return);
f – the ejector in the lower position;
f and *d* – completion of the forging cycle, dwell for the preparation of the next cycle.
The diagram of the activity for this process is shown in Figure 5.
The base activities set (4) is a set of sets:

$$A = \{A0\}, B = \{B1, B2, B3\}, C = \{C4, C5\}, \quad (6)$$

where *A0* – dwell in the upper position of the press slider;
B1 – master cylinder downstroke (forging);
B2 – upstroke of the slave cylinder until the die is opened;
B3 – accelerated upstroke of the slave cylinder;
C4 – upstroke of the ejector cylinder;
C5 – downstroke of the ejector cylinder.

In the starting position, the press slider is at its highest point, and the ejector cylinder is at its lowest point (activity state *A0* - preparation of the forging cycle). After fixing the blank (event *a* - start of the forging cycle, transition to activity *B1*), the master cylinder moves down with the slider and the UDS upper plate; then the forging is formed with the working tool. After the tool stops in its lower position, the press slider with the upper tool starts moving upwards (event *b*, transition to state *B2*). The die opens, the punch leaves the matrix and makes space for the forged product to be ejected (event *c*).

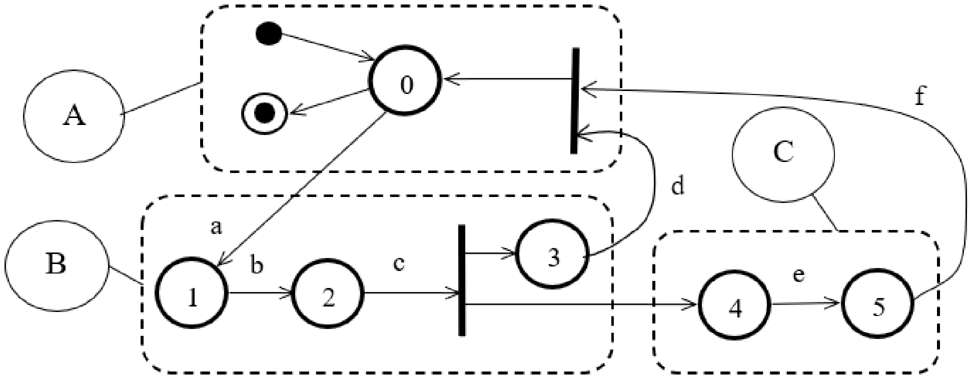

Figure 5: An activity diagram with a decomposition of the basic states for forging TP using an ejector cylinder to eject the forged product: A - cycle preparation; B - working stroke; C - ejection (pushing out) of the part; a...f – events that initiate transitions between activity states

Then the ejection of the forged product from the die begins (state *C4*). At the same time, regardless of the ejector cylinder, the press slider returns to its starting upper position (event *d*, state *B3*). After removing the forged product, the ejector cylinder returns to its lower position (event *e*, state *C5*). When the ejector cylinder (event f) and the press slider (event *d*) return to their places, the moving parts come back to their starting positions and the cycle is completed (state *A0*). The system continues to prepare for the upcoming cycle.

3.4. The choice of design solutions for the UDS

At the next design stage, design solutions for the elements of the die set and tool are determined, which allows the implementation of the transitions of the technological cycle. They represent the system composition, in this case, the UDS, which should include a number of subsystems that ensure its commercial operation (Figure 6). Design solutions are determined based on the analysis of the requirements diagram and the constructed model of the "press-die" system behavior.

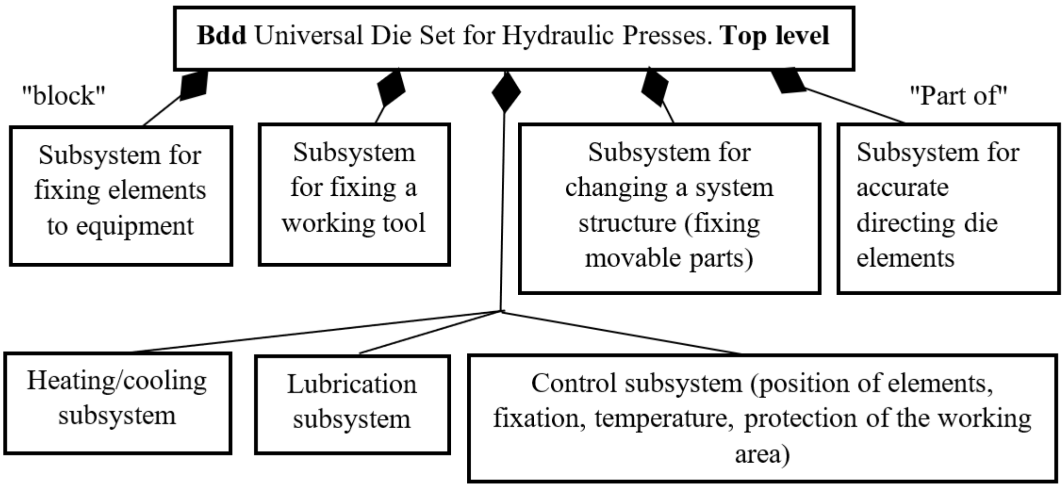

Figure 6: Block definition diagram, including UDS elements for typical metal forming processes on hydraulic presses

4. Conclusions

Thus, based on the system engineering methodology using the domain-specific system modeling language SysML, an algorithm and methodology for creating a model of behavior and structure of technical systems as an example of the "press-die" system have been developed. The requirements for the implementation of power and kinematic modes of operation of a universal die set for the number of blank forging technologies are determined.

The basis of the formulation of the requirements for the UDS is the generalization of the behavior of the "press-die" system during the implementation of a number of TP for blanks deformation on the hydraulic presses.

The proposed sequence of stages and the methodology for creating a model of the designed UDS made it possible to purposefully search for rational technical solutions for its general layout scheme, as well as its individual components and parts.

In general, the application of systems engineering and SysML to the creation of a new universal die set for hydraulic presses allowed us to formalize and document the process of creating this device with advanced technological capabilities. As a result, a design of UDS was developed based on the generalization of the requirements for a number of technological processes. At the same time, the use of SysML allows us to provide information on the structure and behavior of the elements of this system.

This technique of graphical representation of information ensured the selection of parameters for the UDS both when setting the problem and when creating a mathematical model for its design. SysML enables you to store a project at a conceptual level for future use, which is crucial. For example, this project can be used for discussion, further modification, transfer to customers, etc.

The use of various types of mathematical models in this case allowed to substantiate technical solutions. To expand the kinematic capabilities of hydraulic presses and the technological capabilities of die sets, it is proposed to change the structure of connections between the UDS elements. Activity diagrams and forging cyclograms were used as a model in this case.

The UDS includes a universal part and a working tool. The formula for assessing the universality of the technical solution made it possible to obtain an assessment of technical solutions for various processes.

The emphasis in this work is on the presentation of kinematics and the possibility of changing the structure of universal die set. For a more complete design of tooling for a specific hydraulic press, it is necessary to build a geometric model and a strength model. These problems are solved already at the stage of using CAD/CAE systems.

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