Prospective methods of investigation of the functioning of cumulative charges

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Abstract. As a result of the analysis of the application of numerical modeling in modern studies of the cumulation process, it is proposed to isolate the estimated parameters at the time of the formation of a shaped jet as an effective way to reduce the resource intensity of calculations. The numerical method is used to study the influence of the microstructure of the cumulative lining material on the efficiency of jet formation. The following parameters are proposed: the angle between the reduced velocity vector of the jet head and the charge axis $\gamma$, reflecting the efficiency of the deformation of the cumulative jet material, and the collapse angle of the cumulative lining $\gamma'$, reflecting the efficiency of the deformation of the cumulative jet material. The results of the calculation correlate with the known data obtained by other methods, and this confirms the prospects of the chosen direction of the research.

1. Introduction

The term "cumulation" comes from Latin ‘cumulate – accumulation’ or "cumulo" - accumulating and literally means an increase of any effect due to the addition or accumulation of several effects similar to it. The characteristic feature of the current research of the cumulation process is the use of numerical modeling, which expands the capabilities of the research both by increasing the range of variable parameters, and, consequently, the results obtained, as well as due to the fact that when conducting numerical experiments, there is a decrease in material costs in comparison with those carried out by physical experiments.

As it is often the case in numerical studies of the shaped charges functioning, the estimated parameter is the depth of penetration of the target by the shaped charge jet. A relationship is established between the investigated (optimized) parameter of the shaped charge, obstacle or environment and the resulting penetration depth, and on the basis of this relationship, the studied patterns are identified (the optimal value of the investigated parameter is determined).

This approach has significant drawbacks. First of all, it limits the researcher within the framework of a specific task: the results obtained directly depend on such specificities of the formulation of the problem as the features of describing the mathematical model of the environment, obstacles and shaped charge elements, the correct selection of the focal length of the shaped charge (moreover, there are a number of problems where keeping the focal length is impossible), etc. Secondly, this approach implies the choice of computational domains of large length (the cumulative jet is capable of stretching more than 10 times). Since the step of the computational grid in the simulation of cumulation is usually about 100–250 $\mu$m, the need to simulate the process on large computational domains entails huge
computational costs. However, when imposing such requirements, it is important to assess the current level of technological developments, their capabilities and prospects. Let us consider some of the well-known ones.

The most common way to manufacture shaped linings is rotary spinning and its derivatives. Traditional rotary spinning is relatively economical, but finished products are characterized by inhomogeneous deformations in the material, which leads to energy dissipation during jet formation. In order to avoid the described effect, it is possible to use the method for manufacturing cumulative linings, which is based on a phased bi-directional deformation of the workpiece, alternating with recrystallization annealing. The use of this technology makes it possible to obtain workpieces with plastic properties similar to those before processing, and ensures the absence of shear distortions in the material, because phased bi-directional extraction ensures their full mutual compensation. This method provides a microcrystalline structure with a fine and uniform grain, and its use allows, depending on the distance to the obstacle determined by the application conditions, to increase the breakdown effect of shaped charges by 15-30% [1].

Blasting technologies are among the most advanced in modern metalworking. There is a way to use them in order to increase the penetrating power of shaped charges. While manufacturing the shaped linings, a layer of high-density powder material - tungsten and denser - is applied to their inner part using a detonation gun, thereby the operation of micro-welding of projected particles with the substrate material is carried out, i.e. a jet-forming metal layer with new characteristics is formed. As a result of tests on the penetration of a package of steel plates with perforating shaped charges equipped with modified shaped linings made according to the proposed technology (deposition thickness 0.1-0.5 mm), the researchers noted an increase in the penetration depth by 15% in comparison with standard samples [2].

One of the newest is the idea of using a cumulative lining with anisotropic mechanical properties. A variant of the cumulative facing is proposed, in which all crystals are oriented in the direction of the material flow. In the similar way, the maximum plasticity of the material is achieved, on which, in fact, the length of the cumulative jet and, accordingly, the depth of the punched hole depend. The blank of the shaped lining is made by the method of directional freezing of the metal onto the mold, and in order to use low-grade copper as the material of the cumulative lining, a layer of pure electrolytic copper with a thickness of 200-300 microns, necessary for jet formation. The technology makes it possible to obtain cumulative linings with a dense radially directed columnar structure, while the amount of penetration according to the results of experiments increased by 23% -29% in comparison with liners made by turning [3].

Due to the physical and mechanical properties of the material and as a result of processing in the workpiece, technological heredity manifests itself in the form of inhomogeneity of deformations, stresses in the metal, altered crystallographic structure, which ultimately determines the macrocharacteristics of the finished product [4]. Stress inhomogeneity and metal microstructure are closely related. For example, metals obtained by the methods of severe plastic deformation are characterized by instability of the microstructure upon heating as well as during annealing aimed at relieving internal stresses in the workpiece.

The aim of the work is to create a universal technique for evaluating the results of numerical modeling of the functioning of shaped charges. This goal provides for solving a number of problems: patent-information review of scientific and technical literature, highlighting the optimal parameters for assessing the efficiency of the cumulation process, conducting a numerical experiment on the functioning of the shaped charge and analyzing the results of numerical modeling by using the proposed method.

In the second section, the Theory, theoretical aspects of the influence of the metal grain size on the efficiency of the formation of a cumulative jet are highlighted, as well as a patent information review on this issue. The third section, the Materials and Methods, highlights the materials and designs under study, as well as research methods. In the fourth section, the Calculation results and evaluation, the data obtained in the course of the numerical study are highlighted and analyzed.
2. Theory

The capabilities of modern modeling environments allow you to apply other approaches to research. For example, the selection of the estimated parameters at the time of the formation of the cumulative jet allows one to minimize the disadvantages noted above. Usually, when assessing the efficiency of jet formation, the parameters of the length of the formed jet and the speed of movement of its head are distinguished. However, in the first case, the problem of the resource intensity of the calculation remains, and in the second, the results obtained by themselves do not allow making clear conclusions.

Developments to improve shaped charges are carried out by the scientific and technical community in the following areas: optimization of the size and shape of the shaped charge, shape, geometry and material of shaped lining; improving the quality, energy content, density and detonation speed of the explosive; installation of the lens assembly; appropriate choice of the focal length for the charge and improving the accuracy of manufacturing charge parts and their assembly [5]. Let us consider the possibilities of using modern modeling environments in research in one of the above areas - improving the material of the shaped lining.

Metals have a crystalline structure - they consist of many crystals of irregular shape, called crystallites (grains). There are three main critical grain sizes, in the vicinity of which significant changes in the properties of a polycrystalline metal occur. When grinding a grain with a diameter less than 10 nm, the sign of the Hall–Petch coefficient changes – grain-boundary hardening is replaced by grain-boundary softening; 100 nm - displacement of dislocations to grain boundaries, i.e. the formation of dislocation-free grains. With an average crystallite diameter of more than 1000 nm, the number of statically stored dislocations is greater than the geometrically necessary dislocations [6, 7]. These regularities explain the nature of the differences between the plastic flow of fine-grained alloys and the behavior of similar coarse-grained alloys.

Another important aspect in assessing the microstructure of a metal is the strength of the grain boundaries. At the grain boundaries – two-dimensional specific regions separating various homogeneous parts of the crystal - there is a transition layer in which the regularity of the arrangement of atoms is sharply violated. It should be noted that during the formation of a fine-grained metal structure, the thickness of the intergranular layer decreases due to the total increase in the number of grains, therefore, the dispersion of mechanical properties in this layer decreases, and the mechanical properties of the grain and the transition layer are leveled. The boundary layers of grains differ from the inner layers by their physicochemical properties. The lack of the correct structure of the metal in the boundary intergranular layers leads to the fact that the atoms in these layers are not in positions corresponding to the minimum potential energy. Hence, it follows that their mobility can be greater than in the inner layers of grains, and their relative movement can require somewhat lower shear stresses. Consequently, the process of jet formation and formation of a cumulative jet occurs in the case of sufficiently strong grain boundaries, when intercrystalline displacements are insignificant, without causing additional energy consumption during jet formation.

If we consider the cumulation process as a technological process for obtaining holes of a given diameter and depth, then in this case the cumulative jet is a tool that forms a hole with specified parameters in an obstacle (part). Therefore, it is advisable to consider an approach for providing and forming these geometric parameters, in which the different microstructure of the shell material itself is considered as types of structures that set the parameters and dimensions of the cumulative jet. Then, in order to achieve the greatest penetration depth of the cumulative jet, the following requirements are imposed on the material microstructure: the average metal grain diameter does not exceed 10 nm; grains are uniform in shape, size and orientation; grain boundaries are strong.

In recent years, great success has been achieved in the production and study of a new class of metallic materials - materials with nano- and microcrystalline structure, having unique properties - increased strength, cold brittleness, resistance to radiation, etc. - and used in many fields of science and technology [8]. Such materials are obtained by the methods of severe plastic deformation [9, 10]. For example, the technology of equal-channel angular pressing allows you to control the grain size during processing, which, in turn, opens up wide opportunities for experimental research. For example, in the
existing experimental studies of changes in the penetration depth of shaped charges, depending on the average grain size and inhomogeneity of the material of the shaped linings, it is noted that a decrease in the grain size from a point No. 6 to No. 14 leads to an increase in the stability of the action of shaped charges by 2-3 times, and with the appearance of inhomogeneity (an increase in the number of grains in the metal from one to four), the effectiveness of the shaped charges with an average grain number 6 (0.044 mm) decreases by 28% [11].

The technologies described above have their own advantages and disadvantages, however, the technology of equal channel angular pressing is the most suitable for the given requirements, developed and allowing to obtain the most stable result.

The performance enhancement of fine grain shaped linings can be interpreted in a different way. Let us assume that when the grain is refined to such a size, the shape of the crystallites has little effect on the course of high-speed plastic processes. That is, when the grain is refined to a size of 10 nanometers and finer, the intercrystalline interactions are so small that it can be assumed that the material in this case behaves like a monolith: the movement of crystals is not chaotic, due to different orientations, different shapes of grains, but ordered, leading to the least loss of energy process on plastic deformation and, consequently, increasing the length of the jet - the amount of penetration of the barrier.

3. Materials and methods

Investigations of the relationship between the microstructure and the behavior of the metal of shaped linings are usually carried out experimentally, and only their results are processed using computer software systems, since a rigorous and complete description of the behavior of real metals during deformation causes certain difficulties.

In the physics of plasticity and strength of metals, the phenomenon of grain boundary sliding is well known - the displacement of one crystallite relative to another along a common boundary [12]. Physical mesomechanics [13] considers grain-boundary sliding and intragranular dislocation deformation at various structural-scale levels: grain boundaries in polycrystals are classified not as a micro-scale defect, but as an independent 2D subsystem of the mesoscale level [14]. Using this assumption, in the environment of modeling high-speed nonlinear dynamic processes Ansys Autodyn (2-D Euler solver), it is possible to conduct a numerical experiment on the functioning of an axisymmetric shaped charge shown in Figure 1, with a cone-type facing for three variants of assigned steps of the computational grids - three sizes of cell-grains - to reveal the assumed relationship between the average grain size of the metal and the ordering of its plastic flow - the kinematics of the jet formation process [15].

![Shaped charge](image)

Figure 1. Shaped charge.

The problem is posed in 2D space, symmetry is axial, upper and lateral boundaries are open. The basic equations are solved by the Euler method. The step of the computational grid is set in 125, 250
and 500 μm, based on reasonable calculation accuracy and computational costs. There are two criteria that indicate that the process of jet formation proceeds with minimal losses.

First, the efficiency of plastic deformation: the direction of motion of most of the cells-grains that form the jet at a given moment must correspond to the direction parallel to the main axis of symmetry of the charge: the angle between the reduced velocity vector of the head of the jet and the charge axis γ must be close to 0. Second, the efficiency of plastic straining: the value of the angle of collapse of the shaped liner γ’: it is obvious that at large γ’, the already formed part of the cumulative jet is blurred. The scheme for evaluating the effectiveness of the process is shown in Figure 2:

![Figure 2](image)

**Figure 2.** Scheme for evaluating the process’s effectiveness.

4. Calculation results and evaluation

The convergence of the grid was checked during test calculations based on the pressure distribution on the axis of symmetry. As a result, the selected steps of the calculation grid are recognized as giving adequate results. The result of calculating the operation of an axisymmetric shaped charge with a conical shaped lining in a caliber of 50 mm for a calculated grain cell with a side of 500 μm, 250 μm and 125 μm at t = 9 μs is shown in Figure 3:

![Figure 3](image)

**Figure 3** Calculation of the initial stage of jet formation for an axisymmetric shaped charge with a conical shaped lining: (a), (b) enlarged fragments for a calculated grain cell with a side of 500 μm, (c), (d) enlarged fragments for a calculated grain cell with a side of 250 μm, (e), (f) enlarged fragments for a calculated grain cell with a side of 125 μm.

For the proposed design, the time of the beginning of jet formation corresponds to t = 9 μs. The direction of the vectors of the copper grains should ideally coincide with the direction of the symmetry
axis. Figure 3 (a) clearly shows that not all velocity vectors are parallel to the axis, i.e., the process of jet formation is disordered, with energy losses for the chaotic movement of metal grains. The angle between the reduced velocity vector shown in figure 3 (b) and the charge axis was $\gamma = 0.8^\circ$. In contrast to the results of the previous calculation, the velocity vectors of the copper cells in figure 3 (c) are practically parallel to the jetting symmetry axis. There are local areas of deviation of the direction of the vectors from the main axis, but these deviations are minimal. The angle between the reduced velocity vector shown in figure 3 (d) and the charge axis was $\gamma = 0.2^\circ$. The calculated pattern shown in figure 3 (e), in comparison with the calculated patterns presented in figure 3 a) (500 $\mu$m) and figure 3 (c) (250 $\mu$m), indicates the greatest stability of the process: localization of deviations of the velocity vectors of the cells - grains are minimal and in general visually directed in the direction of material flow. That is, with a decrease in the size of the cell of the computational grid - metal grains - the movement of the metal flow is actually ordered, from which it follows that the energy imparted to the shaped lining by the detonation products is spent most efficiently - without losses for the chaotic movement of crystallites. The reduced velocity vector shown in figure 3 (f) and the charge axis are parallel ($\gamma = 0^\circ$).

Also, one should pay attention to the shape of the jet head. If in figure 3 (a) the head of the forming jet is "flattened", then in the design pictures of figure 3 (c) and figure 3 (e) the head is elongated, thin, which corresponds to the existing concept of the relationship between the grain size of the cumulative lining metal and the process efficiency jet formation: according to the known experimental data, it is known for certain that when the grain is refined, the length of the cumulative jet increases and, accordingly, the depth of penetration of the obstacle [11].

5. Conclusion

Indeed, the selection of the estimated parameters at the moment of the formation of a cumulative jet - reflecting the efficiency of plastic deformation of the angle between the reduced velocity vector of the jet head and the charge axis $\gamma$ and reflecting the efficiency of plastic deformation of the collapse angle of the cumulative lining $\gamma^\prime$ when studying the effect of the microstructure of the cumulative lining material - the average grain size of copper - on the efficiency of jet formation made it possible to significantly reduce computational costs due to the absence of the need to calculate the problem on large computational domains.

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