On the impact of the elastic-plastic flow upon the process of destruction of the solenoid in a super strong pulsed magnetic field

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Abstract. At interaction of super strong magnetic fields with a solenoid material, a specific mode of the material flow forms. To describe this process, magnetohydrodynamic approximation is traditionally used. The formation of plastic shock-waves in material in a rapidly increasing pressure of 100 GPa/µs, can significantly alter the distribution of the physical parameters in the medium and affect the flow modes. In this paper, an analysis of supporting results of numerical simulations in comparison with available experimental data is presented.

1. Introduction

An especially non-stationary character of forming of energy release zone, which is close to or even exceeds material sublimation energy, obtained during numerous experiments is characteristic for generation of super strong magnetic fields. Achieving high energy density is provided by high speed of current rise, which leads to its uneven distribution across the thickness of the conductor. Magnetic induction in the zone of current flow during the generation of strong and super strong pulse magnetic fields in single-turn coil by the direct discharge of the capacitor bank does not change along radius from the conductor in the direction of the field [1–3]. Penetration of the diffusion layer and the material transfer is determined by the processes in the wall of the coil and its extension in terms of high energy impact on the inner side. In other words, there are no spatial constraints to increase the area occupied by the magnetic field in single-turn coils—an open system. Z-pinch configuration of the electromagnetic field implemented with an electrical explosion of a wire is characterized by the decline of the magnetic induction at the distance from the conductor in the area occupied by the current and the field and the possibility of movement of the material and the diffusion field to the wire axis which is limited with conductor size—a closed system. The propagation of a zone of high density of electromagnetic energy deep into the conductor significantly affects the energy release processes in that zone, despite the type of system. In that case, the limit values of specific energy input for the material are determined not only by the rate of energy input, but also by various mechanisms of energy loss, one of which is related to the speed of change in the size of the energy release zone.

Traditionally, the analysis of the occurring processes during the electric explosion of conductors and generation of strong and super strong pulse magnetic fields is carried out within the framework of magnetohydrodynamic (MHD) equations with corresponding equations of state.
for material and conductivity models. Study of the interaction process between strong and super-strong magnetic fields and a conductor in closed systems revealed some patterns of electrical explosion process of conductor [4–9] and demonstrated the complexity and multifactorial nature of mentioned phenomenon. However, the issues, related to the influence of the geometry and spatial structure of the magnetic field on the diffusion processes and parameters of skin layer explosion, continue to be the subject of the study. In this connection, the paper [10] should be mentioned, in which a significant influence of geometry on electrical explosion modes of the wire in the basis of the MHD simulation is shown. The transition to the use of the MHD approximation for open systems with the wall thickness greater than the depth of the magnetic field penetration may be limited to the process of elastic-plastic material flow, which is not affected by the energy release in the current flow area, but subjected to the action of magnetic and gas-kinetic pressure. Plasticity wave velocity is significantly lower than the speed of sound and the shock wave velocity in the material [11, 12], so the elastic-plastic material flow process is possible to impact strongly on the results of the MHD calculations. In this paper, an analysis of supporting results of numerical simulations in comparison with available experimental studies of strong and super strong pulse magnetic fields generation by direct discharge in miniature single-turn copper coils was provided to make it possible to estimate the impact of plasticity flow on the deformation process of the thick-walled single-turn coil in such magnetic fields.

2. Possible flow mechanisms

Experimental data on generation of magnetic field with the induction of 360 T with rise time of 0.55 µs in a single-turn coil represented in [13] show, that visible solenoid motion is absent until the maximum induction, and a sharp change in its dimensions begins after exceeding maximum magnetic field (figure 1). Detailed description of experimental methods and results of applying are also given in [13]. Figure 1 shows the typical behavior of an open magnetic system—a single-turn coil, the expansion of which is constrained by the material properties and characteristics of the formation of high-intensity flows of medium. Within the two-dimensional simulation of the hydrodynamic flow the experimentally observed delay in the start of movement of the internal radius of the coil was explained and the picture of nonlinear field diffusion processes was substantially clarified.

Experiments presented in [13] were provided with the use of single-turn coils following characteristic dimensions, inner radius $R_0 = 1$ mm, wall thickness $h = 2$ mm, length $l = 2$ mm. For such correlation among dimensions the structure of processes definitely has a three-dimensional character. However for a qualitative understanding of influence of main factors one-dimensional approach will be sufficient.

Numerical simulation of the interaction process of magnetic field and a conductor with the use of the conductivity model [14,15] and the three-term equation of state of the single-turn coil material in a two-dimensional MHD approach was provided. Here, according to the findings of the simulation, the mechanical characteristics of the material, which are formed in the process of magnetic field generation of with pressure amplitude of about 50 GPa, do not affect the solenoid expansion.

2.1. Nonlinear diffusion

Nonlinear magnetic field diffusion in material with energy up to material sublimation energy is a complicated process [1,16–18]. The description of this process requires adequate equations of state for material and appropriate conductivity model. Analytical estimation of the diffusion rate for linearly increasing magnetic field is presented in [19] and is clarified in experimental research [20], by additional dimensionless parameter $\xi$ of order unity. The penetration depth of the field in the nonlinear diffusion mode is associated with the characteristics of medium and
Figure 1. Typical oscillogram of current $I$, the induction of the magnetic field in the center of the coil $B$ and evolution of coil during generation of strong and super strong pulse magnetic field according to [1,13]. The location of the x-ray picture of the coil corresponds to the time of registration.

magnetic field parameters in the following relation:

$$\Delta_j = \frac{B(t)}{B_0} \sqrt{\frac{t}{\mu_0 \sigma_0}} = \frac{B(t)}{B_0} \Delta$$

(1)

where $B(t)$ is a relation between the induction of magnetic field on the conductor surface and time, $\Delta$ is the depth of the skin layer for linear diffusion, $B_0$ is the characteristic induction of magnetic field (for copper $B_0 \approx 42–45$ T [1,19,20]), $\sigma_0$ and $\mu_0$ are the electrical conductivity and the magnetic permeability in the initial phase.

2.2. Some typical modes of shock wave propagation

It is known [21] that in the field with the induction $B$ of 1000 T the medium speed $u_f$ behind the shock-wave front can be described using the approximation:

$$u_f = a_0 B^{3/2},$$

(2)

for copper $a_0 = 0.15 \text{ m s}^{-1} \text{T}^{-3/2}$.

The Rankine–Hugoniot relations [22] and equation (2) used in [19] allowed to show that the distance traveled by the shock wave is determined by the following equation:

$$\Delta_f = \int_0^t D dt = \frac{1}{2a_0 \mu_0 \rho_0} \int_0^t B(t) dt,$$

(3)

where $D$ is the shock velocity, $\rho_0$ is the material density.

Shock velocity significantly exceeds magnetic field diffusion rate in magnetic fields up to 240 T. However, the implementation of mode when the forming of shock wave is slower than current diffusion is possible as shown in [19].

Further propagation of the wave front occurs in conjunction with the captured current forming a specific course of flow. Here, an additional energy release in the shock front due to joule heating of the material takes place. Analysis of experimental data [23] shows that shock velocity with additional energy inlet can exceed usual shock velocity, initiated by appropriate magnetic field pressure. Relation which demonstrates shock-wave propagation with external energy inlet is
Figure 2. The induction of the magnetic field and movement trajectories: 1—the induction of the magnetic field; 2—the distance passed by the shock-wave front; 3—front of shock-wave with external energy inlet; 4—plastic wave front; 5—the wave front of the current diffusion; 6—a sound wave.

Presented in figure 2, curve 3. Energy release area forming is determined by the combined action on single-turn coil material of magnetic pressure, Joule heating, field diffusion. An additional factor, which may influence on evolution of energy release area, is transitional character of flow mode forming. It is mentioned in the number of papers [24] that process of shock-wave forming in relation with its amplitude may have the duration from 20 to 100 ns.

Results of experimental shock-wave loading reveal that shock-wave does not have time to form at a distance of 2 mm in copper at pressure amplitudes of up to 20 GPa. Flow mode, in which the velocity of the compression wave propagation is significantly below the speed of sound, is observed in a large number of papers. Since the material in these modes is in a state of deep plastic deformation, this flow mode is classified as elastic-plastic wave mode.

Aligned velocity profiles of inner and outer walls of 2-mm single-turn coil loaded by pressure corresponding to magnetic field (see figure 1) are represented in figure 3.

The simulation results are qualitatively the same as those features of the formation of elastic-plastic waves observed in [25, 26]. In this case, as shown in figure 3 the shock wave does not have time to form completely during the advancement of the coil wall. The velocity profile of the outer wall has the structure, which is characteristic for an elastic-plastic wave. The relation
Figure 3. Velocities of inner (curve 1) and outer (curve 2) walls of the copper coil under the influence of pulse pressure of 51.6 GPa duration of 1.1 µs. Curve 2 is shifted to 0.386 µs.

of the distance traveled by a plastic shock-wave, defined according to [25], is shown in figure 2, curve 4.

In figure 3, we can observe the two times decrease of pressure front duration when comparing the wave at the output moment to the outer wall (curve 2) with the impact on the inner wall (curve 1).

The elastic precursor wave duration is about 0.2 µs, and time for achieving the maximum of pressure starts to decrease. Thus, the flow structure has an elastic-plastic transition zone. For this flow mode the achievable speed of transition zone propagation is less than the sound and the stationary shock wave speed.

It is obvious that for an adequate analysis of nonlinear diffusion of superstrong magnetic fields process in the conductor and the skin layer explosion the feature of elastic-plastic material properties which can affect the flow structure should be considered.

3. Analysis of the simulation results
Possible trajectories of advancement of wave fronts and front of nonlinear current diffusion into the copper coil wall with thickness 2 mm, during generation of a magnetic field with induction amplitude 360 T are shown in figure 2.

As shown in figure 2, the depth of plastic wave front propagation is substantially less than the distance traveled by the shock-wave and the shock-wave with external energy inlet. The output of this wave to the outer wall of the coil occurs at the moment of maximum current and is not contrary to the behavior of the coil outer wall, observed in the experiment, the movement of which starts in the moment of time 0.65–0.7 µs.

From the side of the magnetic field the slow rate of plastic shock-wave propagation limits the growth of the area occupied by the flowing current, in which energy of source is released. The modification of parameters in this area is slower than in case of shock-wave and shock-wave with
external energy inlet. It may lead to energy density increase. This energy releases in current flow area, limited by propagation of plastic shock-wave.

Simulation of flow process can be provided in the framework of the Johnson–Cook model [27], which describes the material deformation curve behavior in wide range of loading rates. The applicability of mentioned model for the description of fast processes is confirmed in several papers, e.g. [28]. Results of numerical simulation in ANSYS environment [29] allow to determine release moment of the plastic shock-wave front (point JC in figure 2), which almost coincides with release moment of the plastic shock-wave, calculation is based on the experimental data [25]. Further advancement of outer wall according to this model is similar to the experimentally observed. However the results obtained using the JC model are preliminary since the observed strain rates significantly higher than the verified application range of this model, while this results do not contradict the physics of the process.

Dependences of changes in the inner radius of the 2-mm single-turn coil presented in figure 4 show that addition of determining parameters of elastic-plastic material properties to the system leads to a slower evolution of the flow and, as a consequence, to a less rapid growth of the inner radius of the coil in comparison with MHD calculation.

The simulation of flow process of shock impact in the hydrodynamic and elastic-plastic formulation is provided in a number of papers [30,31]. Results presented in [31] demonstrate the need to consider elastic-plastic material properties in the simulation of shock-wave processes. It should be noted the hydrodynamic approach seem to be justified at pressures typical for process of generation of strong and super strong pulse magnetic fields, because it allows determining the basic patterns of non-linear diffusion and material flow process [17,32].

4. Conclusion

In cases where the depth of magnetic field penetration into the conductor as a result of non-linear diffusion (nonlinear skin layer) is smaller than the characteristic size of the conductor in both closed and open systems, one can expect a significant modifications of flow characteristics, caused by the existence of elastic-plastic material properties.

Decrease of the rate of propagation zone occupied by the magnetic field should lead to a change in the energy density distribution and the conditions of the surface layer explosion especially in the initial phase of the process.

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