The impact of local current density increase on conductor destruction

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Abstract. A numerical simulation and experimental study of the impact of inhomogeneities at the edges of flat busbars on the distribution of magnetic pressure generated during the flow of a current with a density of 100 kA/mm$^2$ and more were carried out. It is shown that the disturbance of the homogeneity of the spatial distribution of the pressure parameters is affected on the size scale of the defect. The formation of defects of type of crack on the edge of flat tires with current can be described using the magnetohydrodynamic approach, typical for describing the destruction of solenoids in strong pulsed magnetic fields.

1. Introduction
At present, strong pulsed magnetic fields are widely used in solving technological and research problems. Due to the high energy density characteristic of strong pulsed magnetic fields and the specificity of their interaction with conductive materials, the tasks of pulse forming, see, e.g., the works presented at International Conferences on High Speed Forming [1], welding of dissimilar alloys and metals [2] and etc are being solved.

Generation of magnetic field with induction up to 50–70 T (technological level) is carried out with the use of thick-walled single-turn solenoids of materials which mechanical strength exceeds the effective magnetic pressure. In this case, the effects characteristic for fields with induction of more than 100 T and associated with nonlinear diffusion [3, 4], the electric explosion of the surface layer [5], and the formation of the shock-wave flow [6, 7] are not observed. For a single generation of the fields of the technological level, the magnetic system usually is not destroyed and can be used repeatedly. Restricting factor for the resource of such systems is the formation of local defects that develop across the streamlines due to thermal stresses and the accumulation of plastic deformations near the surface layer—the saw effect [8]. As it is mentioned in [9], thermal stresses arising in the surface layer lead to the formation of defects of type of microcrack in the material even after the first generation of a field with an induction of 40 T. The appearance of these defects in subsequent impacts leads to an accelerated growth of these defects, caused by an increase in the local current density in the defect zone and, as a result, an increase in the local heating and growth of thermal stresses. However, at current densities smaller than that are used for the magnetic fields generation, an opposite effect is possible: melting of the metal near the crack tops and their “healing” [8, 10], which leads to a decrease in stress concentration and increase in the strength of the material.
Also, magnetic systems in the form of thin-walled solenoids [11] or of flat busbars [12, 13] can be used to solve certain technological problems, while the requirements for these magnetic systems are related not so much to the resource as to the uniqueness of the distribution of the magnetic field and magnetic pressure. Typical for such systems is the appearance of a defect on the edge of the system and its further growth even in the process of pulse generation [14–16] under the influence of a millisecond current pulse. In some works, the possibility of using the magnetic saw effect [17] for cutting sheet metals is considered.

In this paper an experimental study of impact of initial defect length on the character of failure and magnetic pressure distribution in flat busbars in microsecond-duration modes was carried out.

2. The impact of defect size on magnetic pressure distribution, generated with the use of flat busbars system

Conducting studies of the material behavior of under conditions of high-speed loading with the use of the magnetic-pulsed method requires the implementation of loading schemes with a stress state of the sample determined in the process of action. The fulfillment of this requirement is possible when the sample is loaded with a uniformly distributed pressure, which can be realized by using a system of flat busbars transferring the magnetic pressure directly to the sample [12]. In this case, it is possible to implement loading schemes that provide fast deformation modes without a preliminary stage of sample compression [18]. The homogeneity of the pressure distribution acting on the sample is an important factor for describing the results and requires a special study.

Experiments on the formation of pulsed magnetic pressures in the range up to several GPa of microsecond duration are carried out in magnetic fields with inductions up to 30–35 T and are provided by forming in the system of flat busbars impulse currents with density of 200 kA/mm² and more. The amplification of the current density at inhomogeneities can lead to a local increase of the action integral and the destruction of the conductor with loss of controllability of the pressure pulse.

The experimental current pulse can be described by expression

$$I(t) = I_m \sin(2\pi t/T) \exp(-t/\tau),$$

(1)

where $I_m = 195$ kA, $T = 11.9$ µs, $\tau = 14.9$ µs.

The distribution of magnetic pressure generated by flat busbars system with the current of (1) is shown in figure 1.

The magnetic system is made in the form of flat busbars with a width of 25 mm and a thickness of 0.25 mm with defects at the edges in the form of artificially made notches with a width of 170 µm of various lengths. Maximal current density does not exceed 26 kA/mm², the value of action integral

$$J = \int_0^t j^2 dt,$$

(2)

is substantially less than critical value for the used material (CuSn6), which is enough for complete melting of the busbar: $3.72 \times 10^{15} < J_{sm} = 4.75 \times 10^{16}$ [A² s m⁻⁴].

In this case, the use of analytical expressions to calculate the current density at the tip of the defect, obtained in [19] in the quasistatic approximation, can not be used, since there is heating and nonlinear diffusion of the current at the tip of the defect, where the value of the magnetic field induction reaches a significantly larger value (2–5 times more depending on the defect length) than in the flat defect-free part of the system. The induction of the magnetic field, according to the results of three-dimensional (3D) simulation, reaches 15–35 T at the tip of the defect.
Figure 1. 3D simulation of flat busbars system with the defect of type of crack: (a) simulation scheme and magnetic field structure at the peak current value; (b, c) spatial distribution of relative magnetic pressure for different defect lengths along the axes $x$ (b) and $z$ (c).

The results of 3D simulation performed in the Comsol multiphysics environment show that in the considered current exposure mode the presence of micro-inhomogeneity at the busbar edge leads to disruption of the homogeneity of the magnetic pressure distribution both in the direction along the flowing current [see figure 1(b)] and the direction across the flowing current [see figure 1(c)] reduced to pressure in the defect-free region of the system. The tip of the defect is accepted for a starting point. Herewith, the scale of the impact of the defect is determined by its size, and this impact can be neglected at a distance from the defect of the order of its two dimensions.

The simulation was carried out at the supercomputer centre “Polytechnic” with heterogeneous cluster high power computer Tornado, which consists of one node of the cluster RSC Tornado—2 central processing units with 14 cores each ($2 \times$ Xeon E5-2697v3, 2.6 GHz, 64 GB random access memory).

3. Defect of type of a crack fracture features

Local amplification of the current at the tip of the defect leads to the destruction of this zone. Destruction is typical and manifests itself in the form of a circular crater with traces of flow or ejection of molten metal. In a number of works it is mentioned that the action integral (2) is the determining factor in the development of failure at relatively slow (hundreds of microseconds) current actions [14, 15].

In the microsecond impact interval, the development of defects was studied by passing a pulsed current of the form of (1), the amplitude and duration of the pulse varied, and the
Figure 2. The images of the defect tips and their size for loading modes: red circles—mode 1; blue triangles—mode 2; solid lines 1 and 2—calculated dependencies according to the “slow” explosion model for modes 1 and 2, respectively.

action integral over the average section of the busbars remained the same and reached the value 0.087 from the critical value. The current pulse parameters for mode 1 had the next values: $I_m = 195$ kA, $T = 11.9$ $\mu$s, $\tau = 14.9$ $\mu$s; and for mode 2: $I_m = 353$ kA, $T = 6.25$ $\mu$s, $\tau = 4.35$ $\mu$s.

As one can see in figure 2, the size of destruction in mode 1 is significantly higher than that one in mode 2, in which the pulse current is shorter but with a larger amplitude. Consequently, the action integral can not be considered as the only acting factor determining the process of crater formation.

Simulation shows that on the surface of a defect during the current flow, it is possible to generate magnetic fields which induction amplitude can reach 15–25 T in the studied parameter range. A simple model describing the destruction of a single-turn solenoid as a result of plastic flow can be used in the description of processes in such fields [7, 20].

We assume that a magnetic pressure acts on the inner surface of the solenoid and exceeds the plasticity limit of the material. As a result of such pressure, a flow is formed, at which the material is carried along the lines of force, moving away from the field—the “slow” explosion model. The rate of boundary displacement is determined by the following expression:

$$V = V_a \sqrt{1 - \frac{B_s^2}{B_m^2}},$$

where $V_a = B_m/\sqrt{\gamma_0\mu_0}$, $B_s$ to be induction, at which the magnetic pressure exceeds the limit of plasticity for material, $\gamma_0$ to be density of medium, $\mu_0$ to be magnetic permeability of vacuum.

Integrating (3) within the limits when $B_m > B_s$ it is possible to obtain the field-conductor displacement offsets for both loading modes, the form of which is shown in figure 2 by curves 1
and 2. Calculated dependences demonstrate a qualitative correlation with experimental points, while these dependences pass somewhat lower than the experimental ones. The difference can be connected with the fact that in the process of destruction, especially at large crack lengths (for large induction values), other mechanisms of material destruction, leading to the growth of the crater, for example a “rapid” explosion [7], are also possible.

4. Conclusion
Analysis of the results of experimental and numerical simulation of the interaction between high-density currents and defects of type of cracks on the edge of current-carrying busbars showed that defect impact on the process of generation of magnetic pressure by a system of flat busbars is manifested in violations of the homogeneity of the distribution of magnetic pressure on a scale of 1.5–2 the size of the defect. It should be is taken into account (or defects should be excluded) during testing the properties of materials using the magnetic-pulse method.

The model of the plastic flow of material in strong pulsed fields can be used to estimate the residual fracture of a micro defect of type of crack on the edge of a current-carrying busbar under the influence of a current of microsecond duration.

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