Implementation of plasma ions in pistons as a cause of nanosatellite hull defects

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Abstract. The article deals with estimating strength losses during the pulse launch of a nanosatellite in the railgun barrel and their allocation in the process of hydrogen plasma ions irradiation. The authors take into account that the plasma piston consists of charged and non-charged particles, so there will be both bosons and fermions. That is why we use modified quantum statistics. As a first estimate we use the Kinchin and Pease theory of radiation defects and our assumption of the defects even distribution in the nanosatellite hull crystal. The article describes estimations of strength losses time variation.

1. Introduction
The strength losses of a nanosatellite hull result from the implementation of plasma ions in pistons. This problem appears during the nanosatellite pulse launch [1-6]. The pulse launch looks to be more effective for the launch of different numbers of nanosatellites compared to the rocket launch which has a number of problems. Different systems of a pulse launch are proposed. The authors consider the electromagnetic railgun system using a plasma piston. As the load upon the nanosatellite reaches the yield point it can cause the appearance of defects and extending cracks.

The interaction between the materials that the plasma piston and the nanosatellite hull are made of is complicated and multi-parametrical. It is possible to make decomposition on the following tasks:
1. The definition of plasma formation micro-parameters and macro-parameters;
2. The modification of quantum distribution taking into account additional conditions and the degree of ionization;
3. The number of defects in nanosatellite hull materials and the strength losses calculation;

The authors estimate that the plasma piston consists of the hydrogen plasma, the material of the nanosatellite hull is structural steel, the temperature (T) of ions rises from 300 K up to 3000 K during the process of acceleration.

2. Determining relations and parameters
The plasma piston particles energy distribution is equal to the quantum statistics from the article [7]

\[
\frac{(n_b + 1)(n_f - 1)}{n_b n_f} = C, C = e^{\frac{E_{b-f} - \mu}{kT(t)}},
\]

where \(n_b\) is the energy distribution of bosons, \(n_f\) is the energy distribution of fermions, \(\mu\) is the chemical potential, \(t\) – time, \(r\) – radius of plasma formation particles, \(P\) – pressure, \(k\) – the Boltzmann constant.

According to [7] it is necessary to obtain the relation between bosons and fermions. The Saha ionization equation (Saha-Langmuir equation) is used as this relation:
where \( n \) is the volume concentration of all particles of plasma piston, \( n_i \) — volume concentration of ions, \( V \) — volume of system, \( m_e \) — mass of electron, \( E_a \) — energy of ionization, \( \hbar \) — Planck constant over two pi.

The formula for density of states (Z):

\[
Z = \pi \sqrt{2} \left( \frac{m_e}{\pi^2 \hbar^2} \right)^{3/2} \sqrt{E}
\]  

The number of defects \( N_{\text{def}} \) in the material of a nanosatellite hull is calculated according to Kinchin and Pease theory [9]:

\[
N_{\text{def}} = \frac{1}{2} \frac{N_{\text{im}} E}{E_d}
\]  

where \( N_{\text{im}} \) — the number of implemented ions, \( E_d \) — formation of dislocation energy.

The estimation of strength losses is equal to the variation of yield point \( (\sigma) \) by changing the averaged square of atoms layer (S):

\[
\sigma_{\text{def}} = \frac{\sigma_0 S_{\text{def}}}{S_0}
\]  

The function of temperature rise is equal to [10]

\[
T = T_{\text{max}} \left( 1 - e^{-\frac{t}{\tau}} \right) + 300
\]  

where \( \tau_{\text{max}} \) — the maximum temperature in the process, \( \tau \) — the discharge time of capacitors and 300 K — the initial temperature.

3. Energy distribution and calculations

Because

\[
\frac{n_i}{n} = \frac{n_f}{n_f + n_b} \quad \text{as} \quad n_e = n_f + n_b = \frac{N_f + N_b}{Z} = \frac{N}{Z} \quad \text{and} \quad n_i = \frac{N_i}{V}, N_i = N_f
\]

the Saha ionization equation is expressed as

\[
\frac{n_f}{n_e} = A, A = \frac{1}{2} \frac{2^{3/4} (m_e kT(t))^{3/4}}{\sqrt{N/V}} e^{\frac{1}{2} \frac{E_a}{2kT(t)}}
\]  

After substituting (7) with (1) and solving the square equation

\[
n_e = \frac{1}{2} \frac{2A - 1 - \sqrt{-4A^2C + 4AC + 1}}{A(AC + A - C - 1)}
\]
the second root of this equation has no physical sense because it is negative. For calculating the number of particles with energy we have to integrate the distribution function (8) plotted on Figure 1 and DOS over energy and time:

\[ N_{in} = V \left( \int_{t_{max}}^{t} \int_{E_{d}}^{E_{max}} n(E,t)Z(E) \, dE \, dt \right) \]  

(9)

Figure 1. Distribution of particles with energy in time

The calculations are made for the following parameters:

\( E_d = 13.6 \, eV \)

\( t_{max} = \frac{1}{10000} \, s \)

\( E_d = 50 \, eV \)

\( \tau = 10 \mu s \)

\( P = 250 \, MPa \)

\( r = 5.29 \cdot 10^{-11} \, m \)

For these parameters the numerical calculation gives

\[ N_{in} = 5.192610^{99} \]  

(10)

So, according to (4) \( N_{def} = 5.4523 \cdot 10^{20} \)
the new yield point is \( \sigma = 0.9998 \sigma_0 \). On the one hand, cumulative strength losses within the bounds 0.02\% are truly low and may not cause a failure. On the other hand, when 2 defects from \( 5.4523 \times 10^{20} \) are close enough to make a line the defect (micro crack) can occur. In this case the formation of extending crack is possible. While the shockwave passes through the material with the intensity up to the values from the articles [11-13] the failure is also possible.

To estimate the strength losses with other times Figure 2 was plotted based on the results of the numeric modeling.

![Figure 2. Strength losses in time](image)

4. Mechanism of the material destruction

Previously we made an assumption that the defects are distributed in the satellite volume evenly and considered the volumetric strength loss. But a more accurate model should include the mechanism of ions penetration which allows figuring out how the material will be destructed in reality.

For this purpose the Bethe-Bloch theory of ionization energy loss was chosen:

\[
\frac{dE}{dx} = \frac{4\pi n z^2 e^4}{m v^2} \left[ \ln \frac{2m v^2}{I} - \ln (1 - \beta^2) - \beta^2 \right]
\]

(12)

\( z \) is particle charge, \( e \) – electron charge, \( v \) – velocity of the particle, \( \beta = v/c \) - the relativistic factor, \( I \) – ionization energy.

Only the kinetic energy is considered. \( M \) is the particle mass.
After conversion the formula takes the following form:
\[
E = \frac{Mv^2}{2}
\]  
(13)

After integrating we obtain relation between the energy and the penetration depth:
\[
R = \int_0^E \frac{1}{f(E)} \, dE
\]  
(14)

The calculations were made numerically. The result is presented in the graphic form.

**Figure 3.** Function of penetration depth

Then by using the energy distribution function the average value was obtained:
\[
R_{mid} = 2.147 \cdot 10^{-7} \, m
\]

The Gauss distribution of penetration depth with \( \sigma = \left| R_{mid} - R(E_{mid}) \right| = 2.349 \cdot 10^{-8} \, m \) has the following form:
Figure 4. Gauss distribution for penetration depth

It allows accepting that all particles will be able to interact only with the 0.2 micrometers layer of the hull surface.

Previously the amount of Kinchin-Pease defects was calculated. The volume of the material destroyed during the interaction in the experiment being considered (structural steel, 10x10 mm square in cut) can be estimated as:

$$V_D = 6.41 \times 10^{-9} \text{ m}$$

Total destroyed layer thickness in the assumption that the defects are formed independently amounts to 64.13 mkm, which is much more than 0.2 mkm from the previous calculations. We assume the worst variant, when all the particles with sufficient energy form their dislocations. In this case we conclude the following: the whole depth of destruction is determined by the number of Kinchin-Pease particles which knock out every molecule of the steel surface. In each moment only a 0.2 micrometer layer is destroyed, and this layer moves into the depth of the material until all the particles with sufficient energy make the interaction. In our experiment the whole depth of destruction amounted approximately 64 micrometers.

5. Conclusion
Volumetric strength loss can be easily ignored. But the surface destruction should be taken into account because microcracks are formed on the surface and this type of damage is the most dangerous in case of pulse load. Such strength loss does not make the pulse launch of nanosatellites impossible, but it must be noticed while constructing especially for composite hulls of nanosatellite, which are more subjected to failure by formation of microcracks.

One of the solutions is to use the protective wafer, which will be dropped after the satellite leaves the railgun bore.

To sum up, we have to say that:

1. The number of defects in the crystal of the nanosatellite hull appearing due to the penetration of plasma piston ions into the railgun pulse launcher was calculated.
2. The form of the damage and its quantitative estimation was obtained.
3. The volumetric strength loss from plasma formation ions penetration is negligible.

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