STRATIFICATION IN THE ELECTRICAL EXPLOSION OF THIN WIRES

V.M. Romanova, A.R. Mingaleev, A.E. Ter-Oganesyan, T.A. Shelkovenko, S.A. Pikuz

P.N. Lebedev Physical Institute (FIAN), Moscow, Russia

The investigation of striation dynamics upon electrical explosion of thin wire (EEW) performed by the authors over the past decades permitted us to concretize some details of striation formation. Experimental study of stratification of matter upon the nanosecond electrical explosion of thin wires was carried out on various installations with $I_{\text{max}}$ from 10 to 300 kA and current rise from $10^{10}$ A/s to more than $10^{12}$ A/s; also there were used data of our experiments on wire-array explosions on mega-ampere machines. We assume that the mechanism of strata formation is primarily a “surface” mechanism developing in the tubular core; i.e. strata are not layers with more or less uniform density of matter but rather hollow rings (or possibly toroids). Besides, all observations of stratified matter should be attributed to the currentless, late enough stage of the process, when due to shunting of the discharge channel or, in conditions of current pause setting in (for EEW in a dense medium), already developed-structure of the strata continues to exist as if "by inertia".

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INTRODUCTION

Transverse stratification of matter which is often observed upon electrical explosion of thin wires has still not been convincingly explained. The extensive experimental data accumulated in over a half-century in observing this phenomenon remains fragmentary with regards to the parameters and conditions of EEW, poorly systematized and not critically comprehended. This applies even to the concept itself: what are “strata”? In shadow images of x-ray and laser probing they look like a sequence of dark and light transverse bands. That is traditionally interpreted as an alternation of layers of high and low density matter (thus, we often find in the literature the terms "discs" or "pancakes"). However, is this really so? Only systematic experimental study of the problem in the broadest possible coverage of the EEW conditions can answer on this and other similar questions.

Presented experimental study of stratification of matter upon the nanosecond electrical explosion of thin wires was carried out on various installations: from not very large low-inductance pulse generator ($I_{\text{max}}$ 10 kA, current rise in $10^{10}$ A/s) to a high-current vacuum diode (300 kA and more than $10^{12}$ A/s). Also there were used data of our experiments on wire-array explosions on mega-ampere machine COBRA (1.2 MA and $10^{12}$ A/s). Wires with initial diameters from 10 to 50 μm made from materials differing greatly in thermal and electrophysical properties were used. Conditions of strata formation in vacuum and air were studied, including EEW regimes with current pause. The structure of the wire dense core has been studied using the technique of high resolution x-ray backlighting with X-pinch as a source ($2.5 < \lambda < 5$ Å), as well as laser shadow imaging ($\lambda = 5324$ Å).

1. STRATA OBSERVATION IN DIFFERENT EXPERIMENTS

Stratification of explosion products is characteristic for slow as well as for fast EEW. The maximum density of the discharge current in experiments in which strata were observed lies in a broad range from 5 to 1000 kA/mm² [1]. Wire material and surrounding environment are of no principle importance for strata formation. The size of the strata period, which may be from several tens to hundreds of micrometers, also depends weakly on the explosion parameters.

Fig. 1. Laser shadow image of 25 μm Cu wire explosion in vacuum. $I_{\text{max}} = 10$ kA, t=975 ns after current beginning

Fig. 2. X-ray shadow images of Ti (left) and Cu (right) wire explosion. $I_{\text{max}} = 250$ kA

Figs. 1–4 show several typical shadow photographs of nanosecond wire explosions “with strata” in vacuum. On several of them (where the transverse dimension of the strata is relatively large) it can be seen that the strata are very thin and somewhat curved and grouped in the
form of a “lentil” (see Figs. 1, 4). In other cases strata look like rather small, strictly transverse wire strips, at times quite “stout” (see Figs. 2, 3). The first type of strata is more often observed when the electrical explosion is of easily-melted and good-conducting wire material (Al, Cu, Ag); the second for high-melting temperatures and resistive metals. However, such a division does not always work; moreover, it is quite probable that we are not observing different types of strata but simply different stages of their evolution.

Fig. 3. Fragments of laser (top) and x-ray (bottom) shadow images of thin wires upon electrical explosion in vacuum

For EEW in air a somewhat different kind of stratification is typical (Fig. 5). In this case, the contrast of alternating “dark” and “light” transverse areas on the shadow images is usually much weaker than in vacuum, and the boundaries of strata are never sharp.

Fig. 4. Laser shadow images of 25 μm Ag wire explosion in vacuum at t=245 ns (top) and t=1065 ns (bottom). \(I_{\text{max}} = 10 \, \text{kA}, U_0=20 \, \text{kV}\)

2. DISCUSSION

The most important factor for the stratification phenomenon is the local energy contribution to the wire matter. The transverse structures occur if the magnitude of the current (for a given geometry of conductor and electro- and thermophysical properties of its material) is capable of imparting a certain level of energy to the matter. Moreover, this dependence is evidently quite critical: strata are often formed in only certain parts of the discharge channel (see Fig. 1). Since we are still unable to measure current distribution in the discharge channel, experimentally we can only determine the average value of energy contribution: thus, at present quantitative estimations of its effect on stratification are quite conditional.

An analysis of the experimental data permits to suggest that the mechanism of strata formation is primarily a “surface” mechanism developing in the tubular core. In this case, strata are not layers with more or less uniform density of matter but rather hollow rings (or possibly toroids). That the core is tubular is clearly seen, for example, on images obtained by means of x-ray (see Fig. 2) and laser (Fig. 5) probing. This also follows from molecular-dynamic calculation [2]. Based on the results of numerous experimental EEW observations, one can suggest the following evolution of an explosion of a conductor in vacuum: light fractions of adsorbed matter, and also filth emitted from the conductor surface during explosive heating, form a sheath around the conductor in the form of a relatively thin-walled tube. Our estimate of the wall thickness is that it is within the limits of tens to hundreds of micrometers. Evidently, it is necessary to distinguish this initial “tube”, which has not yet turned into plasma and has not had time to move far from the core, from own plasma “corona”, effectively capturing discharge current already in the first ten to twenty nanoseconds after its beginning. Visualization of the corona by means of UV diagnostics showed that its diameter is several times greater than the diameter of the dense core (including its tubular sheath), and velocity of expansion more than by one to two orders of magnitude [3].

Fig. 5. Laser shadow image of 25 μm Cu wire explosion in open air. \(U_0=13 \, \text{kV}, t=615 \, \text{ns after current beginning}\)

The thin tube, broken by ejected core material, begins to burst and gradually break up into separate toroidal ringlets, like “nanos” on the core. Core matter at this time undergoes a phase explosion and is in a foam state, i.e., practically does not conduct current. Further emptying of the space surrounded by the system of strata-ringlets to a great extent depends on how much energy was imparted to matter in the resistive stage of EEW. This can be clearly seen, for example, when comparing shadowgrams of silver (see Fig. 4, below) and nickel (see Fig. 3, above) wires, obtained under identical conditions of explosion but with about 500 ns difference in time. In the first case, in spite of a significantly earlier time, the core had already disappeared, while in the second it can still be clearly seen on the background of strata (note the core here also has a tubular structure).

Another important conclusion following from the results of many experiments is the absence of current in the core when observing transversal stratification. At first glance, this assertion may seem quite unexpected since it is considered that it is precisely current flowing
in the discharge channel that is the main cause for inducing all the instabilities in the EEW process. However, this occurs, evidently, at a very early stage (possibly still linear) of the explosion and does not have as yet direct experimental confirmation: scientists today do not have at their disposal instruments with sufficient temporal and spatial resolution for investigating processes in the dense core of the unexpanded wire. All observations of stratified material should be attributed to a much later stage of the process, when due to shunting of the discharge channel or, in conditions of current pause setting in, already developed-structure of the strata continues to exist as if “by inertia”. Moreover, from EEW experiments with internal character of secondary breakdown [4], it follows that current flowing through products of explosion (i.e., in already greatly expanded core), on the contrary, hinders the maintenance of any regularity in their structure, even if at an earlier stage it could have been the cause of its arising.

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REFERENCES


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СТРАТИФИКАЦИЯ ПРИ ЭЛЕКТРИЧЕСКОМ ВЗРЫВЕ ТОНКИХ ПРОВОЛОЧЕК

В.М. Романова, А.Р. Мингалеев, А.Е. Тер-Оганесьян, Т.А. Шелковенко, С.А. Пикуз

Работа посвящена стратификации при электрическом взрыве тонких проводников (ЭВП); выявляются некоторые детали формирования strat. Экспериментальный материал, лежащий в основе представленного сценария развития стратификации, получен в исследованиях наносекундных ЭВП, которые ведутся авторами на протяжении нескольких десятилетий на установках самого различного класса: с максимальным током от 10 до 300 кА и скоростью нарастания тока от $10^{10}$ до более $10^{12}$ А/с, а также в экспериментах по взрывам проволочных сборок на мегамперных машинах. Анализ экспериментальных данных позволяет предположить преимущественно «поверхностный» механизм стратообразования, развивающегося в трубчатом керне. В этом случае страты являются не слоями с более или менее однородной плотностью вещества, а, скорее, полыми кольцами (или торообразными) структурами. Кроме того, все наблюдения стратификации вещества должны быть отнесены к бестоковой стадии взрыва, когда уже произошло шунтирование разрядного канала или (при ЭВП в среде) наступила пауза тока, а возникшие к этому времени страты продолжают существовать как бы «по инерции».

СТРАТИФИКАЦИЯ ПРИ ЭЛЕКТРИЧЕСКОМ ВИБУХУ ТОНКИХ ПРОВОЛОК

В.М. Романова, А.Р. Мингалеев, А.Е. Тер-Оганесьян, Т.А. Шелковенко, С.А. Пикуз

Работа присвячена стратификации при электрическом взрыве тонких проводников (ЭВП); заслуживая десятков деталей формирования strat. Экспериментальный материал, что лежит в основе представленного сценария ростуку стратификации, отражен в доскональных наносекундных ЭВП, которые ведутся авторами протягом десятков десятилетий на установках самого рзного класса: с максимальным струмом в 10 до 300 кА и швидкістю наростання струму від $10^{10}$ до більш ніж $10^{12}$ А/с, а також в експериментах з вибухами зборок проволок на мегамперних машинах. Анализ экспериментальных данных позволяет припустить переважно «поверхностный» механизм стратоустроения, что розвиваются в трубчатому керні. У цьому випадку страти є не шарами з більш або менш однорідною густинною речовини, а швидше пустими кільцями (або торооподібними) структурами. Крім того, всі спостереження стратификации речовини повинні бути віднесені до струмової стадії вибуху, коли вже відбулося шунтування розрядного канала або (при ЕВП в середовищі) наступила пауза струму, а страти, що виникли до цього часу, продовжують існувати ніби то «за інерцією».

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