The effect of crater creation on the surface of steel targets under irradiated of high-current pulsed electron beams

D A Teryaev
Moscow Aviation Institute (Technical University), 125993, Moscow, Volokolamskoe shosse, 4
E-mail: teryaevda@mail.ru

Abstract. The present paper reviews the experimental results dedicated by the effect of the irradiation conditions by intense pulsed electron beams on crater creation taking place on the surface of EP866sh refractory steel targets. The most probable mechanisms of crater creation are also described.

1. Introduction
The study of the crater creation process that occurs on the surface of solid things when interacting with energy flows is of great interest. This is due to the actively developing methods of surface engineering, which are most often associated with the use of pulsed electron beams, pulsed laser radiation and etc. for modification surface layers of metal parts. These methods make it possible to significantly change the properties of irradiated targets. However, past work shows that increasing the energy density to a critical value leads to the formation of microcraters on the surface. In [1–5], the process of crater creation on the surface of metal samples and parts after processing with high-power ion beams (HPIB) was studied in great detail. The authors give a clear classification of craters depending on their shape, size, time of occurrence, and possible causes of their appearance. These works [1–5] made it possible to determine the main causes of craters on the surface and give recommendations on how to reduce their negative impact on the properties of parts processed by pulsed ion beams.

In this scientific work, in contrast to [1–5], high-current pulsed electron beams of microsecond duration with an energy of 115–120 keV were used. This allows you to modify the surface layer of significantly greater thickness. When samples are irradiated with high-power pulsed ion beams, a modified layer of 1–2 μm is formed, but the application of high-current pulsed electron beams in the GESA – MMP accelerator is 20–25 μm. Therefore, the purpose of this study was to study the possible causes of crater formation on the surface of EP866sh steel samples irradiated with HPEB and compare the results obtained with those previously presented using HPIB [1–5].

2. Materials and methods
To study the crater formation process under the influence of a microsecond HPEB, GTE compressor blades made of heat-resistant steel Ep866sh of the ferritic class with carbide hardening, which has the following chemical composition and heat treatment modes, were selected: (Fe; 1,7 – Ni; 0,13 – C; 15 – Cr; 1,35 – Mo; 4,5 – Co; 0,6 – Mn; 0,18 – V; 0,2 – Nb; 0,6 – Si; 0,03 – N; 0,02 – S; 0,03 – P; 0,65 – W); hardening in argon from 1100 °C; tempering at 700 °C for 2 hours and 30 minutes; tempering at 650 °C for 2 hours and 30 minutes [6].

Samples in the form of 15×5 mm disks were also used in some experiments.
To determine the physicochemical state of the surface layers of the samples under study, the following methods were used: Auger electron spectroscopy, scanning electron microscopy, optical metallography, and microhardness and roughness measurements.

All samples were irradiated using the GESA-MMP accelerator. It allows you to affect the surface of parts with parameters: \( W = 15–50 \text{ J/cm}^2 \); \( E = 115–120 \text{ keV} \); \( t = 15–40 \text{ microseconds} \).

3. Results

The authors of [1–5] presented several hypotheses about possible mechanisms of cratering on the surface of samples under HPIB irradiation: stratification of the ion beam; release of gas bubbles dissolved in the surface layer; selective melting of local areas of the surface, due to differences in the melting temperatures of the phase components of the alloy; explosive emission from sharp areas of the surface, their local overheating; plasma formation; bombardment of the already molten surface and etc. The authors systematized the formed craters depending on the moment of their formation: primary craters that appear after the first impact of the pulse and secondary craters that are formed during subsequent irradiation or after diffusion annealing. Moreover, primary craters were classified by size and shape: round multi-ring, round with a bulge in the center, round with a concavity in the center, elliptical, contiguous, faceted and cracked. The results obtained by scanning electron microscopy and optical metallography of EP866sh steel samples irradiated at the GESA-MMP accelerator in the melting mode (\( W > 26 \text{ J/cm}^2 \)) [7–10] showed that in this case only the following types of craters are formed: round with a bulge in the center, round with a concavity in the center, and adjacent (figure 1).

![Figure 1](image.png)

**Figure 1.** Appearance of craters formed when samples and parts made of Ep866sh steel were irradiated with an electron beam at an energy density of 26–28 J/cm\(^2\) and a pulse duration of 25 microseconds (a – with a concavity in the center; b – with a bulge in the center; c – adjacent).

This is due to the thickness of the molten layer under the irradiation of HPEB (20–25 μm), which is much larger compared to the thickness after HPIB. This fact alone makes it possible to talk about the prospects of using HPEB to modify the surface layer of parts, because the greatest danger to fatigue resistance and corrosion resistance is represented by cracked, faceted and adjacent craters [8].

Also, the authors of [1–5] studied the effect of mechanical treatment on the crater formation process at the time of HPIB irradiation and made conclusions that were compared with the results of research in this paper.

In this work, to study the effect of mechanical treatment on the process of crater formation under the influence of HPEB, samples were prepared from EP866sh steel with a diameter of 15 mm and a thickness of 5 mm. They were processed by various methods, such as: milling, grinding, vibro-abrasive processing, surface plastic deformation with microbeads, polishing, chemical etching and air oxidation at 600 °C for 10 hours.

All samples were irradiated under the same conditions at an energy density from 26 J/cm\(^2\) to 32 J/cm\(^2\). After irradiation, the surfaces of all samples were examined. We determined the density of the crater distribution over the surface and the diameters. The most important results are shown in table 1 and figure 2.
Table 1. Influence of mechanical processing on the size and density of crater distribution over the surface of Ep866sh steel samples irradiated with HPEB.

| Type of treatment             | The minimum size of craters, μm | The maximum size of craters, μm | Distribution density, cm⁻² |
|------------------------------|---------------------------------|---------------------------------|-----------------------------|
| Cutting                      | 2.2                             | 447                             | 43                          |
| Grinding                     | 2.0                             | 440                             | 35                          |
| Vibroabrasive                | 6.6                             | 146                             | 15                          |
| Microbeads                   | 1.6                             | 93                              | 46                          |
| Polishing                    | 263                             | 801                             | 4                           |
| Polishing and annealing      | 309                             | 632                             | 3                           |
| Polishing and oxidation      | 268                             | 580                             | 6                           |
| Polishing and etching        | 300                             | 601                             | 7                           |

Figure 2. Topography on the surface of EP866sh steel samples, after mechanical processing (a – milling; b – milling and grinding; c – milling, grinding and surface plastic deformation of microbeads; d – milling, grinding, vibroabrasive processing, polishing) and irradiated HPEB with energy density of 26–32 J/cm² and a pulse duration of 30 microseconds.

If these results are compared with the recorded results after HPIB processing, the following conclusions can be drawn for EP866sh steel samples, the most likely mechanisms for the appearance of craters presented earlier in [1–5] are: selective melting and subsequent erosion of individual surface areas due to differences in the melting temperatures of phase components; selective melting and plasma formation due to a high degree of heterogeneity in the distribution of dislocation density over the surface within the range of the electron beam; non-stationary and different depth melting of individual surface areas with different orientations, and explosive emission from sharp surface areas.

These mechanisms can take place with the solidification of a wavy microrelief, or at the beginning of the pulse, a drop of molten material is ejected into a vacuum and then returned to the molten surface, which contributes to the formation of round craters with a bulge in the center.
To avoid undesirable impact of craters on the properties of parts, it is necessary to conduct irradiation with energy densities that do not exceed critical values at which crater formation does not occur yet. Also, it is better to carry out irradiation with several pulses, since with their increase, the probability of crater formation is significantly reduced due to melting of the surface layer and smoothing of the microrelief.

4. Conclusions
The process of crater formation on the surface of EP866sh steel parts under the influence of HPEB with energy densities greater than 26 J/cm² was experimentally proved and studied. It is established that the most probable mechanisms of crater formation are: selective melting and subsequent erosion of individual surface areas due to differences in the melting temperatures of phase components; selective melting and plasma formation due to a high degree of heterogeneity in the distribution of dislocation density over the surface within the range of the electron beam; non-stationary and different depth melting of individual surface areas with different orientations and explosive emission from sharp surface areas.

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