SPACE DISTRIBUTION OF DAMAGE AT EARLY STAGE OF SPALL FRACTURE IN COPPER

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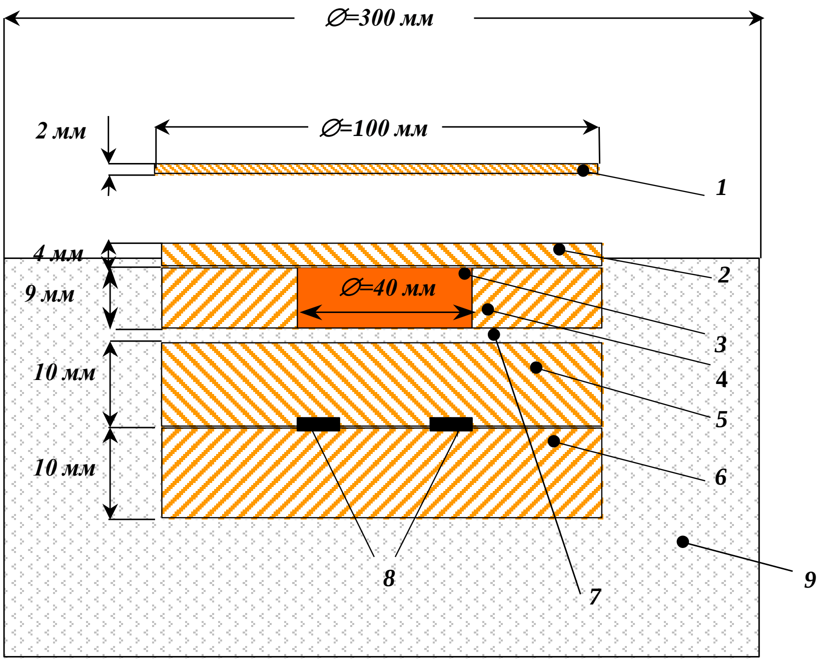
The currently available experimental data is testimony to a complicated character of formation and development of micro-defects at spall fracture caused by shock-wave loading [1]. As this takes place, there are very little data on initial stages of damage, when a quantity of damage accounts for not more than $\omega \approx 0.15$. The majority of up-to-date models of formation and development of spall fracture consider damage as a scalar quantity, which characterizes a degree of damage of an isotropic medium [2], [3]. In this case, it is anticipated that damage nucleation takes place uniformly in a zone of tensile stresses. The experiments performed recently showed that this is not right: pores are grouped under specified conditions at initial stages of damage development in copper in some zones alternated with areas being free from damage [4], [5]. Within the framework of known physical models this effect was not explained. Afterwards it received the name «zonal damage».

The present work is a logical continuation of researches in a structure of « zonal damage». The current task was to implement additional metallographic investigations of tested samples [4]. The authors investigated only one surface of a metallographic section obtained in a plane perpendicular to the direction of wave motion. In the work the results are presented for the studies of space distribution of damage, which were achieved through a number of successive metallographic measurements in parallel sections of post-test samples. Accordingly, the data were received with regard to a form of damage zones, their arrangement. A set of the new metallographic information provides a possibility to understand deeply a mechanism of damage development in metals and improve damage models.

Experimental set-up

Coarse-grained annealed copper M1 having an average grain size of 110 μm has been the subject of investigation. High-intensive shock-wave loading and the action of a pulse of tensile stresses with small amplitude have been performed successively in copper samples by the help of the experimental device shown in Fig. 1. A scheme has been proposed in such a way as to retain a sample for post-test studies. In order to achieve tensile stresses (~1.5 GPa, what is in conformity with small damage in copper) at amplitude of a compression wave of about 30 GPa, a scheme is given with sample's unloading into a gap of a variable thickness (140 ÷ 320 μm), following which a substrate made of sample's material has been installed. In this case, referring to the results of preliminary numerical simulation [4], the availability of a gap leads to the formation of a pulse of tensile stresses having a various interval depending on a thickness of a gap. The more the gap, the more duration of tensile stresses effect (t = 0.15÷0.7 μs).

Sample (3) is being loaded by a liner made of *Cu* (1) 2 mm in thickness accelerated by explosion products up to the velocity of W_{yo}=1.60 km/s through copper screen (2) 4 mm in thickness. To create conditions of a plane loading, sample (3) has been pressed in copper ring (4), which has been decreasing radial sample's deformation, caused by side unloading. To implement tensile stresses in a sample, copper plate (5) has been mounted through an air gap of a specified thickness (7).



1 – *Cu* liner ($W_{уд}$=1.6 *km/s*); 2 - *Cu* screen; 3 - *Cu* sample; 4 - *Cu* ring;
5, 6- *Cu* plates; 7 – gap of a variable quantity;
8 – manganin-based gages (*D*1 and *D*2); 9 - cement.

Figure 1 – Scheme of tests

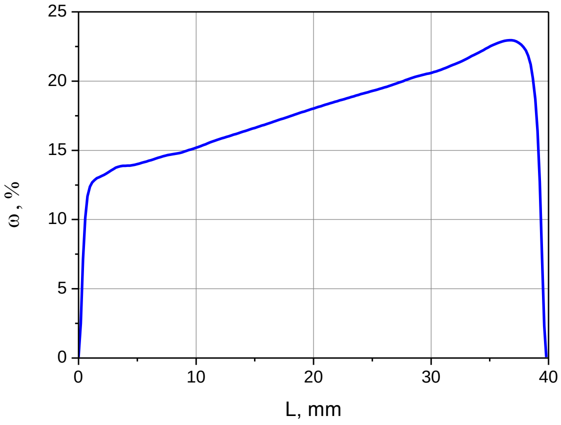
With the goal of a control over a stress-strained state in an assembly the profile $\sigma(t)$ of a transmitted shock-wave pulse was recorded with the help of two manganin-based pressure gauges (8), which were installed at the interface of copper plates (5 and 6).

High-intensive shock-wave loading of samples made of *Cu* was performed in two identical tests. The thickness of gaps between a sample and a substrate amounted accordingly:

Δ_{gap}≈140-320 µm – test № 1 (variable gap),

Δ_{gap}≈300 µm – test № 2 (constant gap).

Let us consider test № 1 with a variable gap. The calculation with the use of models of shear strength and spall strength [6], [7] gives the distribution of damage, which is monotonically increasing to a sample's diameter– from a boundary with a less gap till a boundary with a more gap. The characteristics of the present model are shown in work [4]. Fig. 2 demonstrates the expected calculated distribution of damage in a sample (Δ_{gap}=140-320 µm) at the point of time t=10 µs (from the moment of collision).



Δ_{gap}=140 μm Δ_{gap}=320 μm

Figure 2 –Calculated damage distribution according to sample's diameter in region of tensile stresses

Metallographic study of recovered samples

A damage structure in copper was investigated using specially prepared metallographic sections with magnification 50^x-200^x on the optical microscope МЕТАМ-ЛВ31 with fixation of an image on a digital photo camera. To determine spatial distribution of damage in samples, several parallel metallographic sections of one sample were researched. Sample № 1 was sawn into 7 portions (a depth of cut is H_1=0 mm, H_2≈1,01 mm, H_3≈2,67 mm, H_4≈3,63 mm, H_5≈6,15 mm, H_6≈8,04 mm, H_7≈10,08 mm); sample №2 − into 5 parts (a depth of cut is H_1=0 mm, H_2≈3,76 mm, H_3≈5,99 mm, H_4≈7,9 mm, H_5≈11,57 mm). The cut H_1=0 mm corresponds to a diametric section of the sample's disk.

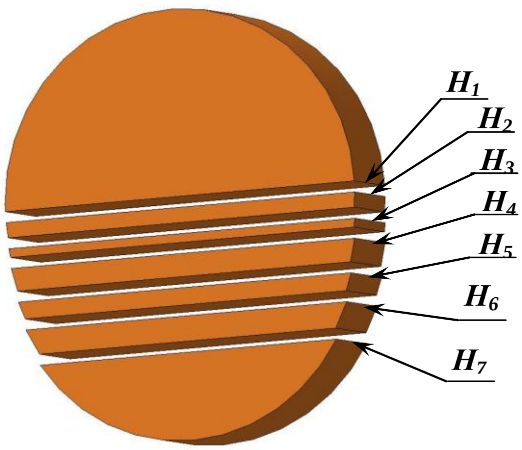


Figure 3 – Scheme of cutting of sample for metallographic study

In the course of the metallographic analysis damage was calculated as defect diameter ratio to a length of the cell under review at each step on a coordinate. The step of measurement on a width of a sample was h_i=0.1 mm, while along the length–L_i=1 mm. A plane of a transverse metallographic section of samples was considered in a coordinate system, which was presented in Fig. 4: the thickness of a sample *h* was counted off from a loading surface; the length of a metallographic section *L* was counted off from an edge corresponding to a smaller gap.

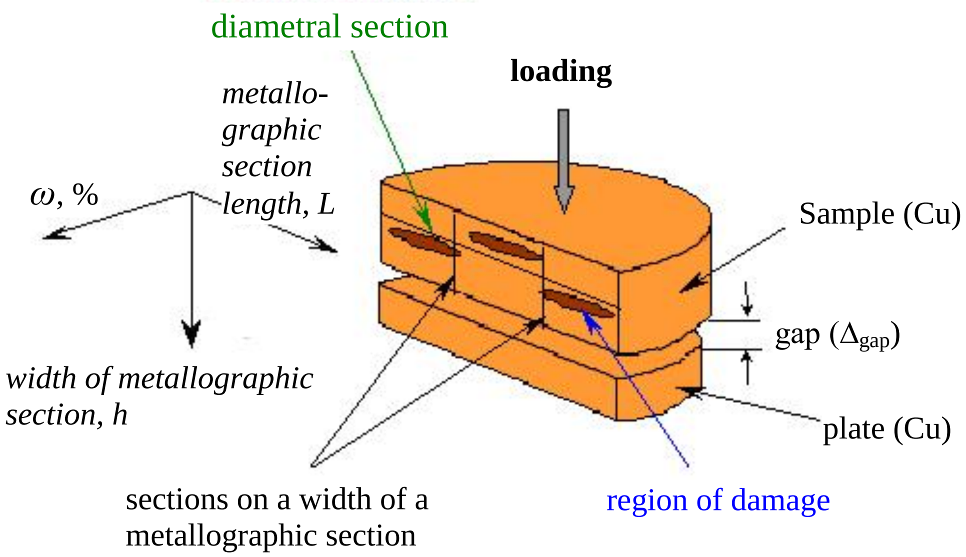


Figure 4 – Schematic image of typical distribution of damage in sample’s cross-section

Results of metallographic studies

Damage in copper at initial stages of spall fracture represents separate pores having a spherical form or an ellipsoidal one as well as chains of pores, sometimes connected with strips of deformation.

Pores are being formed both at the interfaces of grains (more often) and into the interior of them (infrequently). A photo of damage was presented in Fig. 5. A structure is typical for copper after shock-wave loading. The observable intragranular bands of localized deformation represent packets of deformation twins [8].

Figure 5 – Damage in sample № 1
Direction of loading– from left to right

The measurement results of damage on a whole plane of sample's cross-section at varied depths of a cut are presented in three-dimensional diagrams in Fig. 6 and 7. As may be seen from figures, damage has a non-monotonous character, what does not correspond to forecasts made on the basis of calculations using a kinetic model (s. Fig. 2). The zones with visible damage alternate on metallographic sections (ω~0.07÷0.16) with the zones which do not contain any traces of damage (ω=0). In other words, damage is localized in separate zones. In spite of a non-monotonous character one can observe a tendency to an increase of damage with increasing a gap (expetiment №1).

Notice that a scale in axes is various in Fig. 6-7.

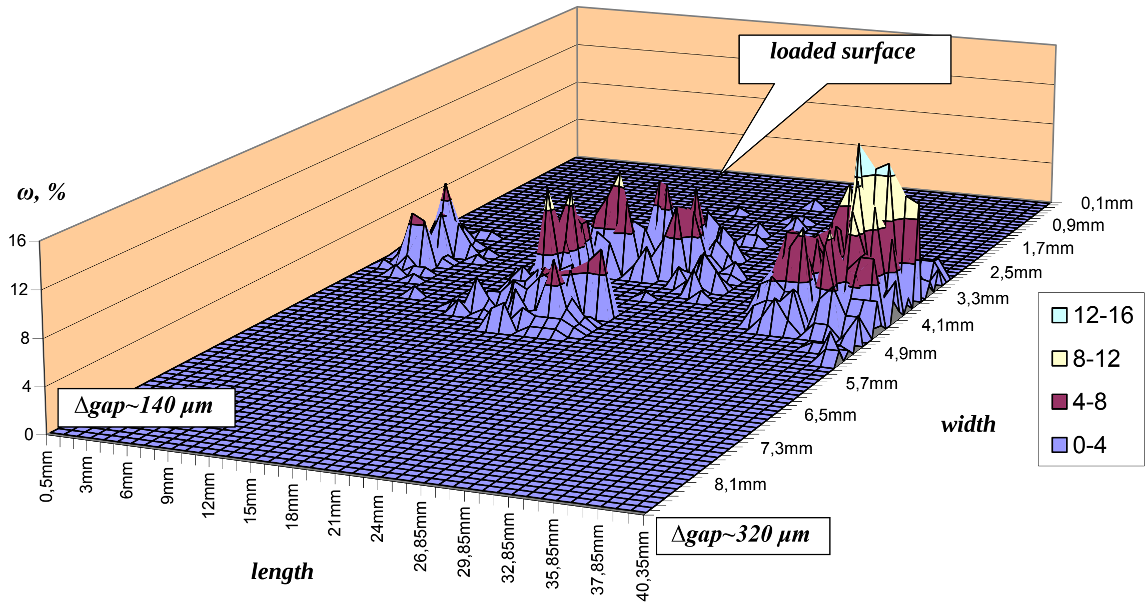


Figure 6 – Damage distribution in the plane of a transverse metallographic section of sample №1 at the depth of the cut H_1≈0 mm

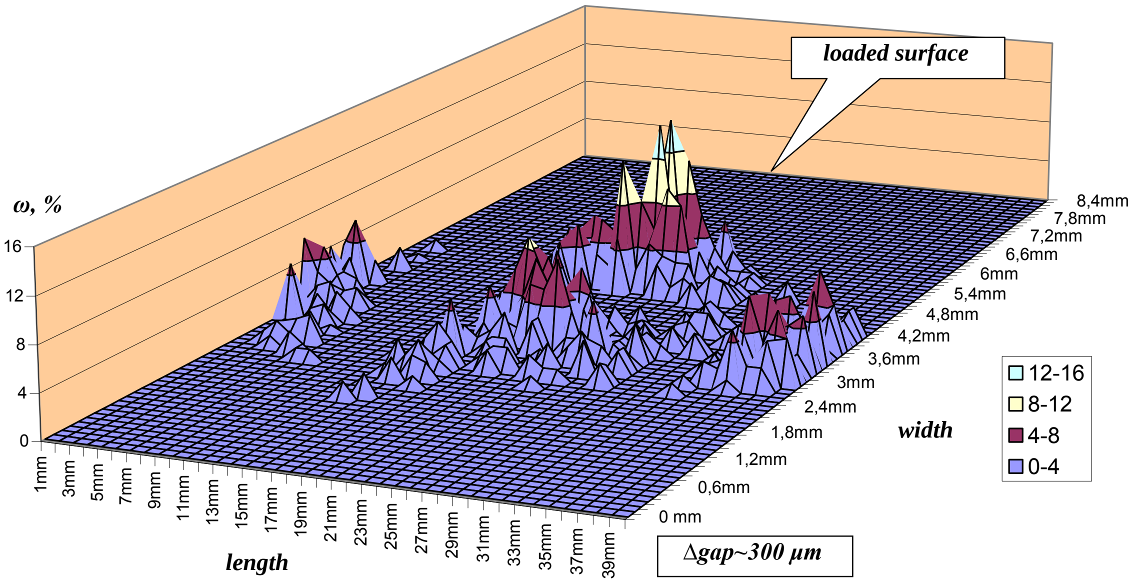
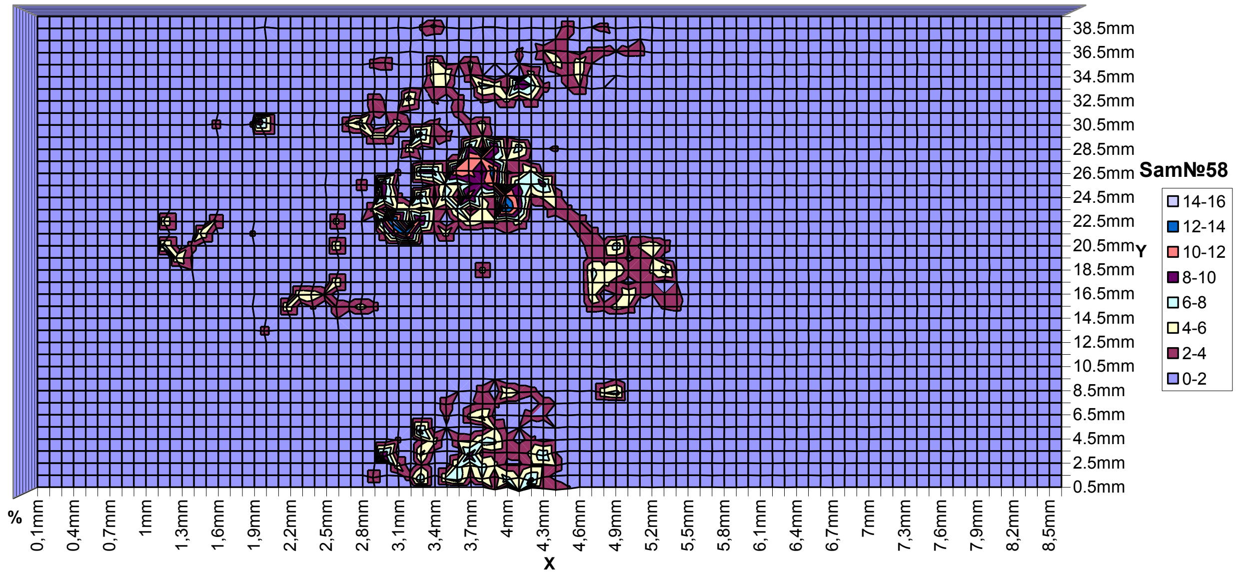
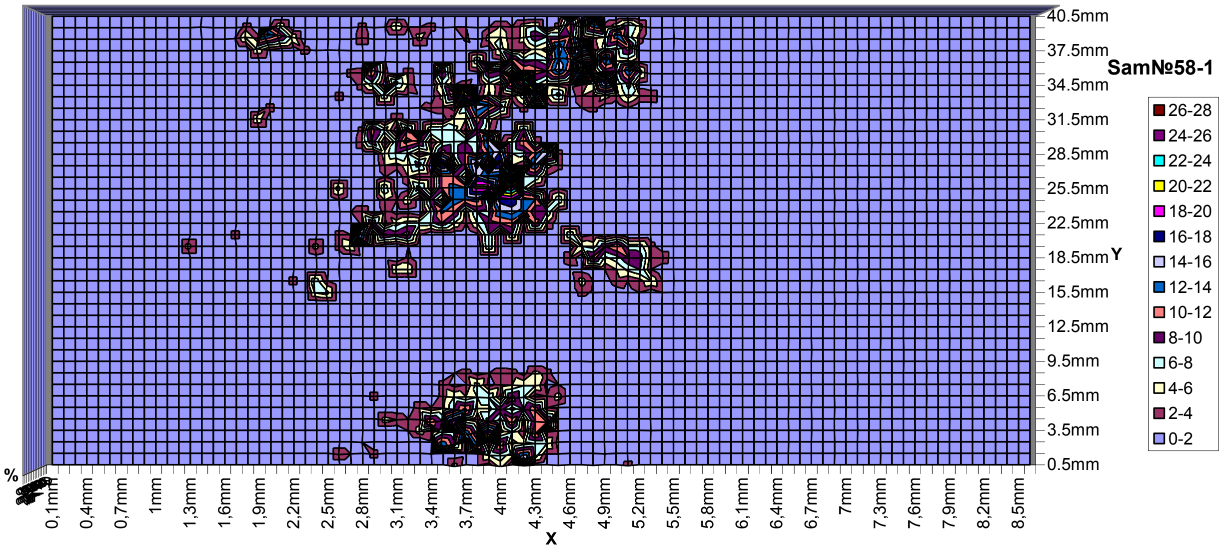


Figure 7 - Damage distribution in the plane of a transverse metallographic section of sample №2 at the depth of the cut H_1≈0 mm

Once samples were cut up and metallographic sections on parallel cuts were studied in an analogous way (s. Fig. 3), we have obtained at our disposal patterns of damage distribution in samples in some parallel layers. Accordingly, we attempted to restore spatial damage distribution in them. As an example Fig 8 presents damage distributions on two parallel cuts of sample № 1.



a) Cut depth H=1,01 mm



b) Cut depth H=2.67 mm

Figure 8 – Damage distribution in planes of metallographic sections obtained at separate cross-sections of sample № 1. Shock wave motion direction in sample– from left to right

Images of this Figure can give an idea of a form of damage zones. It is obvious that if the cross-sections presented in Fig. are being arranged one under another, some zones of damage «go by» from one cut to the other.

An attempt to determine spatial distribution is given in Fig. 9. It turned out that zone sizes in varied directions are unequal: minimal sizes of zones are being observed in the direction of shock wave propagation, maximal ones – in the perpendicular direction, that is, they are parallel to a shock front.

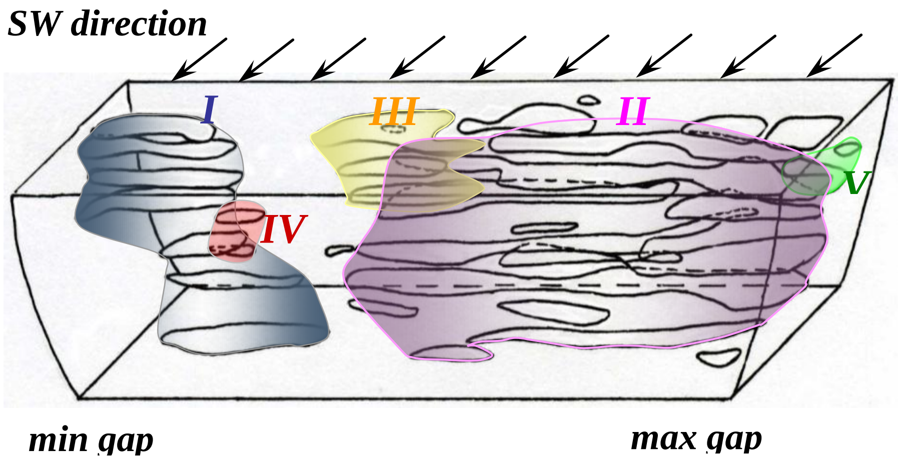


Figure 9 – Space distribution of damage in sample №1. Separate zones are marked by numbers

We picked out 5 zones of damage having a different size in the considered volume of a sample. Two of them, saying conditionally, - are large, - these are zones I and II; and three zones are of small size– zones III, IV and V. Zones IV and V were discovered only in two planes of metallographic sections, therefore they have a completed form. Zones II and III have got an uncompleted shape only on the one side, and zone I was not completed on both sides, in other words it is impossible to define fully the dimensions of these zones in the vertical direction. Table 1 shows zonal sizes in three dimensions in such volume, which was available in our experiment.

T a b l e 1 – Geometrical dimensions of separate zones of damage.
Sample №1

№ of zone	Linear dimensions of damage zones, mm			ω_{max}
	For the length of a metallographic section	For the width of a metallographic section	For the «height» of zone	
I	6 – 11	1,3 – 1,9	>10,8	23
II	17 – 25	1,9 – 4,9	>9,8	34
III	6 – 9	0,8 – 2,8	>2,7	12
IV	2 – 4	0,4 – 1,4	1,9	9
V	2 – 5	0,5 – 1,5	1,0	16

A similar picture of space damage distribution in sample № 2 is given in Fig. 10.

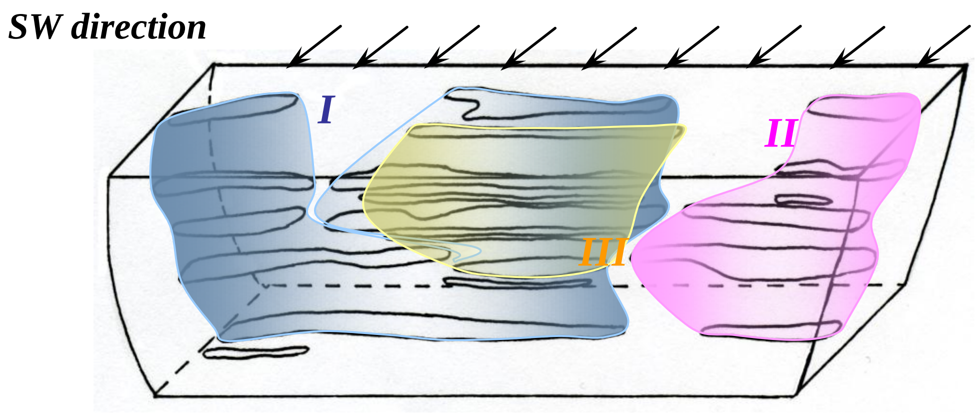


Figure 10– Space distribution of damage in sample № 2. Separate zones are marked by numbers

We also found a zonal structure of damage in the considered volume of sample №2. We chose 3 zones having a various size. Two of them are large - these are zones I и II; and one zone is small-sized– zone III. Zones have got an uncompleted shape except for III, which was not completed on the one side. Apparently, zone I was formed through the coalescence of two zones. Table 2 presents zonal sizes in three dimensions.

T a b l e 2 – Geometrical dimensions of separate zones of damage. Sample №2

№ of zone	Linear dimensions of damage zones, mm			ω_{max}
	For the length of a metallographic section	For the width of a metallographic section	For the «height» of zone	
I	6 – 22	0,9 – 2	>11,6	23
II	5 – 15	1,2 – 2,1	>11,6	17
III	6 – 16	0,3 – 0,7	>7,9	15

Conclusion

Thus, a set form of space distribution of damage at the early stage of the formation of a spall crack in samples shows that damage zones «grow» in a plane, being perpendicular to a shock wave direction. The zonal sizes are less in the direction of shock wave propagation.

By taking into account the fact that the sizes of damage zones are various, it is possible to suppose that different temporal stages of forming zones were fixed in the experiment, and that zones are formed and they grow independently of each other.

The obtained results point out imperfection of up-to-date physical models of spall damage that consider materials as isotropic media.

In this case the following questions are not clear completely:

– Under what conditions are damage zones formed (pressure, tensile stress value and duration)?

– Whether zonal centers exist, from which damage starts to develop? What is a growth mechanism of damage zones?

– How does the initial structure influence on the zones formation?

– Is a zonal structure typical for other materials?

The answers to these questions will help to improve models of spall strength.

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