Fracture of Metallic Ring Samples under static and dynamic loading

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Abstract

A study on the destruction of thin aluminum and copper samples in a wide range of loading times was made. Static loading of samples in the form of strips on a tensile testing machine was carried out. For dynamic loading magnetic-pulse method with a period of 1 μs loading and 7,5 μs applied. The samples were made in the form of rings. The mechanism of fracture in each time range, and the peculiarities of the behavior of materials was studied. A mathematical model for fracture process was proposed. Comparison of the mechanical properties of materials under static and dynamic range tests was realized.

Keywords: static loading, dynamic loading, fracture, magnetic pulse technique, metallic ring samples.

1. Introduction

A large number of experiments on loading of continuum shows fundamental differences between destruction process under the influence of slow quasistatic loadings and "fast" dynamic destruction. In case of quasistatic deformation critical value of strength parameters is much less dependent on experimental conditions, than at dynamic influence. As observed critical characteristics of destruction at dynamic deformation it is essential volatile and behave it is rather unpredictable, one of the main objectives at definition of dynamic strength characteristics is research of interrelation of the limit power parameters conducting to destruction of a material with duration, amplitude and growth rate of enclosed loading. Results of microstructural research of the destroyed samples. The mathematical model, allowing to describe destruction of materials both at static, and under dynamic conditions of loading is considered.

Results of a experimental study on a rupture of thin aluminum and copper samples in the form of narrow strips as in the conditions of static loading by breaking machine, and at dynamic harmonic stretching impact with the period 1μs are given in this work. In the second case the magnetic-pulse method of loading was applied, and samples were carried out in the form of rings. The destroying static tension of materials is determined and the assessment of their dynamic breaking points with use of the offered method of measurement of time from the beginning of loading until destruction is made. Comparison of breaking points in static and dynamic conditions is carried out. Results of microstructural research of the destroyed samples are given. The mathematical model, allowing to describe destruction of materials both at static, and under dynamic conditions of loading is considered.

2. Deformation and destruction of thin aluminum and copper samples at quasistatic loading

2.1. The methodology of the experiments

The experimental study on mechanical deformation and strength properties of aluminum (Al) and copper (Cu) condenser foils by h=0,015 mm thickness in solid (cold-worked [1]) condition is conducted at stretching of strips in the breaking machine Tinius Olsen H10KN (fig. 1) at a speed of movement of mobile grab of the breaking machine of 10 mm/min.

Fig. 1. General view of the test machine: 1 - frame, 2 - PC 3 - moving cross-arm, 4 – machine`s grabs, 5 - sample clips, 6 – sample.

Control of operation of the machine and data acquisition was carried out by the computer. Charts of stretching of samples were received: "effort - lengthening" and "stress – deformation". The test machine`s computer automatically chose scales of charts in the set size of speed of deformation, thickness and sample width, its working length. Start of movement of mobile grab (cross-arm) was carried out at not completely straightened condition of samples - foils, because of complexity of exact definition of the effort beginning in them. Therefore at charts there was an initial area (fig. 2, 3), having, generally small nonzero ordinates (efforts and stress), the achievements caused by process by samples of the straightened condition, and also operation (friction) of additional tiny hinged devices (clips) for samples mount. Further, when processing charts, this area excluded.

2.2. About a type of samples and their production

In [2] requirements to aluminum foils for condensers, a view and sizes of samples (length of 150 mm, width of 15 mm) and conditions of mechanical (quasistatic) tests are provided. However, for an exception of influence of a large-scale factor by comparison of these quasistatic tests in comparison with dynamic experiments on the ring samples received by gluing together or the soldering of strips foils, in our case the sizes of samples – strips for quasistatic tests were accepted considerably the less size, namely: rather close with sizes of strips applied to rings. Preparations – strips for quasistatic tests of an aluminum foil were cut out 60 mm long and width b about 6 mm, and copper - respectively, 50 and b=1,7 mm, with width deviation no more, than $\pm$0,05 mm. The choice of bigger width (and lengths) aluminum preparations was connected with considerably smaller durability of this material, in comparison with copper, - for providing a sufficient correctness of tests. Length of working part of aluminum samples equaled l_0=28 mm, copper 20 mm. Thus, the speed of relative deformation of samples equaled $\dot{\varepsilon}(t)=\frac{\Delta l}{l_0}$ aluminum samples it was equal 0,357 min^{-1}, copper – 0,5 min^{-1}. Conditional stretching tension stress in samples was determined by a formula $\sigma=\dfrac{P}{h\cdot b}$ with initial values h and b. Other parts of samples (ends) were used for fastening of samples in grabs of the test machine so that the rupture of a sample was carried out not in capture zone, and in its working zone. For this purpose the ends were bent before acceptance of double thickness, with placement of cardboard laying in a bend, and, then, the ends were pasted over with a paper adhesive tape. Before the placing of samples in the test machine on these ends tiny aluminum clips with the hinges, necessary for more exact axial loading of samples that it is difficult to provide at direct use of large rigid grabs of the test machine Were attached. At test samples fastened in test machine grabs through tiny clips.

2.3 . Results of quasistatic experiments

In fig. 2 are provided received by means of the computer of the test machine the chart of "loading - lengthening" and "stress - deformation" for one sample from an aluminum foil, and on fig. 3 – for one of a copper foil.

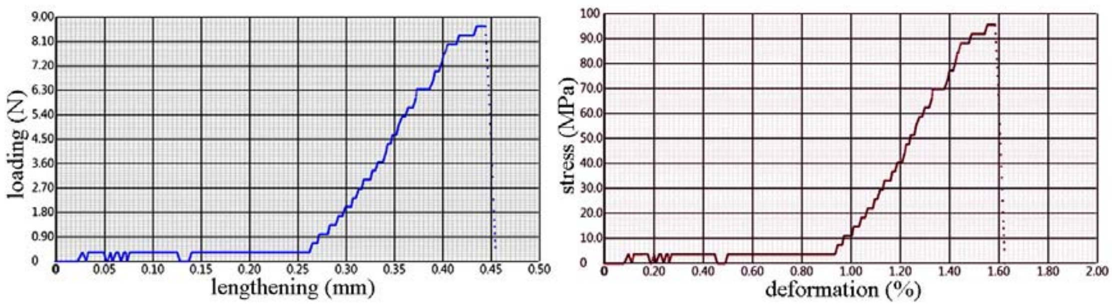


Fig. 2. Charts of stretching of an aluminum foil

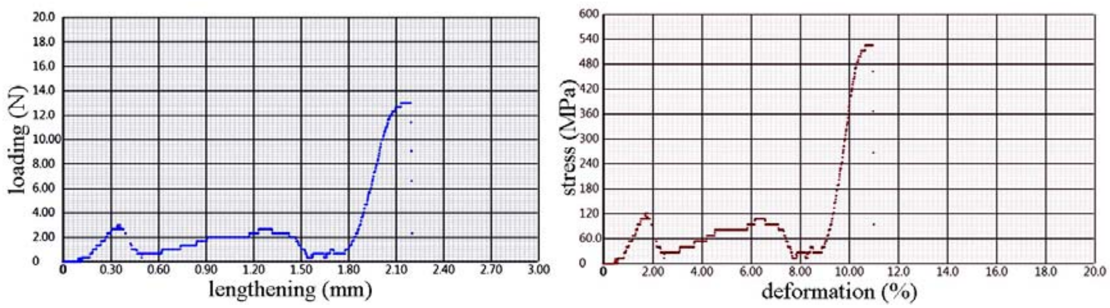


Fig. 3. Charts of stretching of a copper foil

When processing initial areas of the charts "stress - deformation" (0 – 0,9) for aluminum and (0 – 9) for copper were excluded. The same was carried out when processing charts of all other samples.
Stretching charts σ-ε aluminum and copper foils have an appearance typical for plastic materials: with an initial site of elasticity, viscoplasticity and destruction. On the chart for a copper foil before destruction small falling of conditional stress ((increase of true stress) before a direct prompt macrorupture of a sample – germination of the main crack, the events for an aluminum foil in time ~ 0,12 sec., and for copper 0,05 sec. is observed.

In table 1 are provided average on three measurements (to charts σ - ε) data on mechanical characteristics aluminum and copper foils at stretching with speeds of $\dot{\varepsilon}(t) = 0{,}357$ min^{-1} and 0.5 min^{-1} respectively, in parentheses – discrepancy in %. Designations are accepted: E - Young's modulus; σ_e - elasticity limit; $\sigma_{\max}$ - the maximum conditional stress on the chart "stress - deformation"; σ_c - conditional stress of destruction (temporary resistance) corresponding to the moment of the beginning of a macrorupture of a sample; ε_c - destruction deformation; t_c - destruction time.
Essential distinction of all mechanical characteristics foils is established to Al and Cu.

Table 1. Mechanical characteristics of an aluminum and copper foils

Material	E, GPa	σ_e, MPa	$\sigma_{\max}$, MPa	σ_c, MPa	ε_c, %	t_c, s
Al	13 ($\pm$12%)	60 ($\pm$15%)	99 ($\pm$1%)	99 ($\pm$1%)	0,76 ($\pm$14%)	1,275 ($\pm$14%)
Cu	38 ($\pm$28%)	400 ($\pm$18%)	527 ($\pm$3%)	508 ($\pm$3%)	2,27 ($\pm$18%)	2,730 ($\pm$18%)

Very insignificant dispersion of characteristics attracts attention $\sigma_{\max}$ and σ_c. It is possible to claim about experimental stability of these characteristics.

2.4. The microstructural analysis of destruction at quasistatic loading

The type of two samples of an aluminum foil and two samples of a copper foil after destruction is presented on figs. 4. In fig. 4 destruction of samples on a working site is noticeable l_0.
Research of destruction surfaces of aluminum and copper samples after tests was carried out on an optical microscope of Axio-Observer-Z1-M in a dark field, and research of structure cross microsection – in a light field or polarized light. The structure was studied on cross microsection after the corresponding etching. The size of grain and quantity of a pores defined on a surface microsection.
Microstructural studying is carried out on three aluminum and three copper destroyed samples. The analysis of samples structure of copper and aluminum showed that samples mainly collapse viscously – have a “cup” break. Comparison of samples of copper and aluminum revealed that the

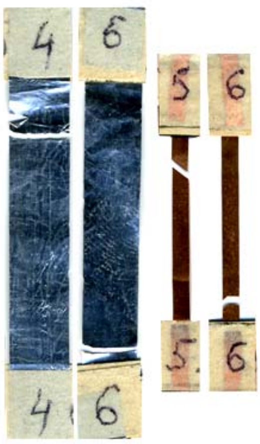
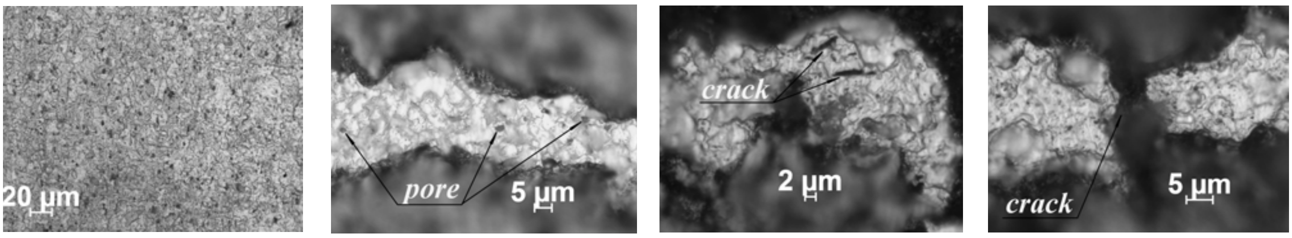


Fig. 4. The destroyed samples aluminum (at the left) and copper (on the right) foils

fiber percent in a break of statically loaded copper is less, than in aluminum, i.e. copper collapses is more fragile in these conditions.

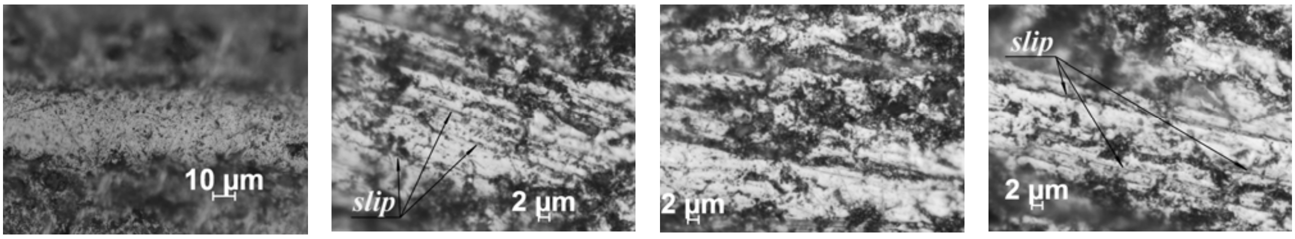
On fig. 5 structures of aluminum samples after static tests are presented. Porosity in a sample 4, cracks in a sample 5 and the main crack in a sample 6 is visible.



a b c d

Fig. 5. Structure of aluminum samples after static tests: a – in an initial condition; b – pores in a sample 4; c – crack in a sample 5; d – the main crack in a sample 6.

In figure 6 structures of samples of copper after static tests are presented.



a b c d

Fig. 6. Structure of copper samples after static tests: a – in an initial condition; b – sliding strips in a sample 4; c– homogeneous structure in a sample 5; d – sliding strips in a sample 6.

In samples 4 and 6 sliding strips are observed, and in a sample 5 the homogeneous structure prevails, as is noticeable by appearance of samples in fig. 4. The sample 5 is destroyed at an angle about 45^0, i.e. in the direction of the maximum tangent stress on the planes of more dense packing.

3. Deformation and destruction of aluminum and copper samples at dynamic loading

Experiments on deformation and destruction of samples were carried out with use of the modified magnetic-pulse method on the basis of the generator of short high-voltage impulses of GKVI-300 providing formation of electric voltage with amplitudes of 30 - 300 kV. As samples rings from thin aluminum and copper foils with a diameter of 28,6 mm and 1 - 2 mm wide were used.

On fig.7 the loading scheme is shown. The current passing on the coil on which the ring sample coaxially settles down, directs in it induction current, and interaction of these currents generates pushing away force between the solenoid and a ring.The coil is made of a copper wire by diameter 1mm, has 5 rounds, diameter of the coil - 25 mm. The current passing through the coil, was measured by a Rogovsky coil (RC) and displayed on a digital oscillograph (OSC) information with which registered on the electronic carrier. At a rupture of the ring (Sample) which has been coaxially fixed on the middle of the coil (L), there was a spark which allowed to fix the moment of destruction of a sample by means of the photo diode (PD). At test of samples installation when via the coil current with the period of fading fluctuations T=1µs was passed was applied. Its flowchart is provided on fig. 8.

Appearance of installation is given on fig. 9.

On fig. 10 current oscillograms via the coil and a signal from the photo diode fixing the moment of a rupture of a sample are represented.

Experiments on rings from aluminum and copper foils 0.015 mm thick and 1.0 - 2.0 mm wide were made. Samples tested with a cut and without a cut.

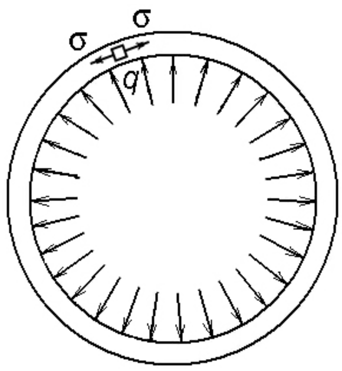


Fig. 7. Scheme of sample loading
(q – loading, σ– the stretching stress)

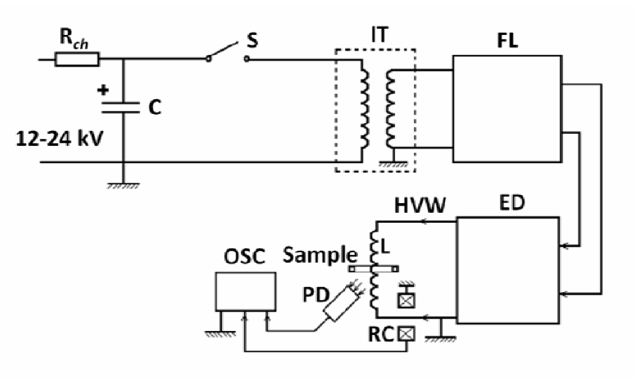


Fig. 8. The block-scheme of the setup for sinusoidal electromagnetic load of period 1 μs: Sample – a sample; IT – the pulse transformer; FL – the forming line; ED – the output device; HVW – a high-voltage electrode; PD – the photo diode; RC – a Rogovsky coil; OSC - an oscillograph

The assessment of the radial force operating on a ring from rounds of the coil, was carried out by a technique stated in work [3], submitted on ICF 13. Tangential stretching stress was calculated on Laplace's formula for thin-walled covers

$$\sigma(t) = \frac{q(t)R}{h},$$

where $q(t) = F(t)/c$ – the distributed radial loading acting on an internal surface of a ring, F (t) – force acting on a ring, c, R, h – width, internal radius and ring thickness, respectively.

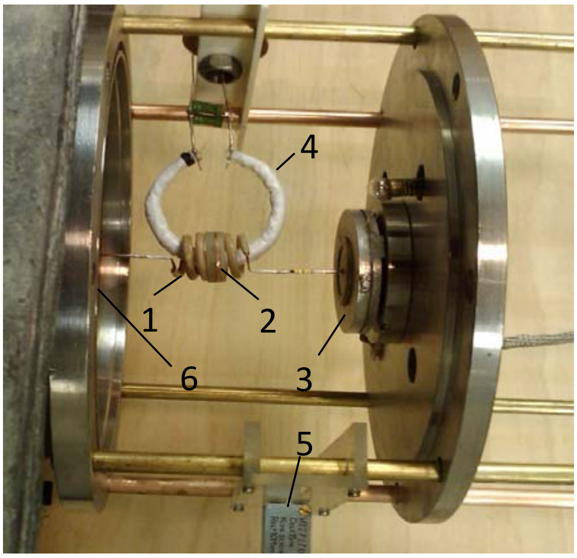


Fig. 9. General view of installation,
1 – solenoid; 2 – sample; 3 - Rogovsky coil, measuring current in the coil; 4 – Rogovsky coil, measuring current in a ring;
5 – photo diode; 6 – output device.

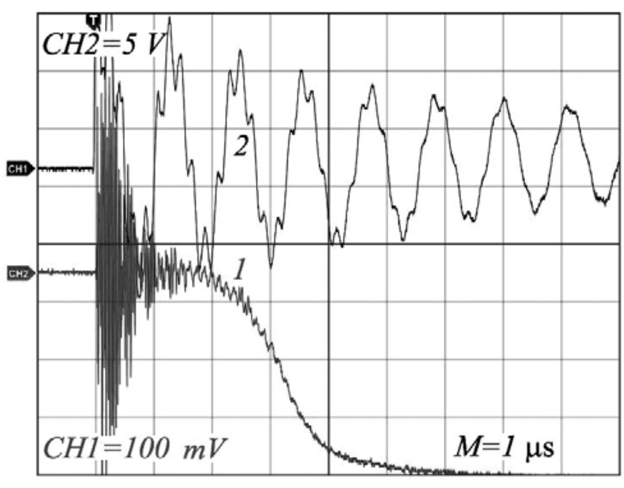


Fig. 10. Oscillograms from the photo diode 1 and current from a Rogovsky coil 2.

At determination of the stretching tangential stress its pulsing value $\sigma(t)$ it was replaced average in the form of a rectangular impulse with an amplitude σ_0 and duration equal to time from beginning of giving of current in coil until rupture of a ring t_c:

$$\int_0^{t_c} \sigma(t)dt = \sigma_0 t_c, \quad \sigma_0 = \frac{\int_0^{t_c} \sigma(t)dt}{t_c}$$

Time t_c was measured in experiences.

Characteristics of samples, conditions of experiments and results are provided in table 2, where: T - the period of fluctuations of current in the coil; h - ring thickness; c - ring width; ∅ - diameter of a ring; U - tension of a charge of the condenser; σ_0 - the stretching stress of a ring rupture; τ - time before destruction; W - energy of the charged condenser; I - current amplitude via the coil.

Table 2. Characteristics of samples, conditions of experiments and results

Material	T, μs	h, mm	c , mm	∅, mm	U, kv	σ_0, MPa	τ, μs	W, J	I, A
Al	1	0,015	1,50	28,6	20	162	4,17	100	4200
Cu	1	0,015	1,00	28,6	20	577	4,68	100	5800
Cu notch	1	0,015	1,55	28,6	20	376	6,60	100	8400

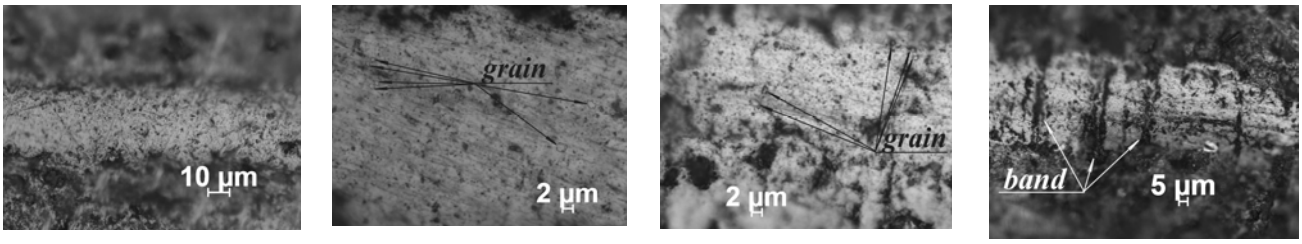
3.1. Results of microstructural research

Microstructural studying is carried out by the same technique that is presented in item 2.4. Microhardness measured on the PMT-3 device at loading 20g. Results of microstructural researches are given in photos (фиг.11) and in table 3, where: T - the period of fluctuations of current in the coil; S=hxb - sample section; D - grain size; n - quantity of a time on the area 400 μm2; HV – microhardness.

Table 3. Results of microstructural researches

Material	T, μs	hxb, μm^2	D, μm	n, 1/400 μm^2	HV, MPa
Al	1	$68,4\times10^3$	3,0	70	639,1
Al initial		120 x10^3	4,6	53	720,4
Cu	1	$29,9\times10^3$	2,5	96	340,2
Cu notch	1	75,8 x10^3	0,8	380	103,3
Cu initial		15 x10^3	-	282	644,6

The copper sample before loading represented a monocrystal, and after loading as a result of dynamic recrystallization there are fine grains – the size – 0,8-2,5 μm. And dynamic recrystallization in a sample with a cut – here grains smaller is more developed. Quantity of a time in a sample with a cut too much more, than in a sample without a cut. Besides, in a sample with a cut a large number of strips of shift (fig.11d).



a b c d

Fig. 11. Copper structure: (a) - in an initial condition; (b) - after loading with the period of T=1µs (S=0,03mm2); (c) – sample with a cut after loading with the period of T=1µs (S = 0,08 mm2); (d) - sample with a cut after loading with the period of T=1µs (S = 0,08 mm2). Designations: grain – the recrystallized grains, band – shift strips.

4. Results comparison of static and dynamic materials destruction

It should be noted essential distinction of dynamic and static strength characteristics.
Comparison of structural changes at static and dynamic loading shows that at short-term influence there is a dynamic recrystallization – formation of new fine grains. Extent of dynamic recrystallization the greatest in samples with the bigger duration of loading and the maximum cross section (a large-scale factor). Aluminum samples after loading show big tendency to cavitation at increase in the period of loading in comparison with the initial. Besides, at increase in duration of influence in samples there is an origin of a multiple splitting off.

5. Conclusion

1. Techniques of experimental studying of quasistatic and dynamic properties metal foils are developed and applied.
2. Deformation and strength characteristics aluminum and copper foils are defined.
3. Analytical expressions for mechanical characteristics of materials are received.
4. The microstructural analysis of destruction zones is made at quasistatic and dynamic loading.
5. Comparison of properties of materials in the conditions of the static and dynamic loading, shown their essential distinction is carried out.

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