Fracture of Metallic Ring Samples under Magnetic Pulse Shock Action

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Abstract

Metallic rings made of aluminum alloy are studied upon the application of a distributed radial load by a magnetic pulse technique. Two modifications of the magnetic pulse method were implemented on the basis of the GKVI-300 high voltage short pulse generator providing the formation of voltage pulses of 30-300 kV in amplitude. These two approaches making it possible to decrease the period of the harmonic load to 7,5 μs and 1 μs. Method to determine the instant of rupture of the ring from a flash arising at rupture with the help of a photo detector was developed and applied. Load signal and signal from the photo detector are displayed and saved with a digital oscilloscope.
Fracture stress value was estimated. It increased on load time shortens.
The surfaces of fracture of aluminum samples were investigated after the tests by optical microscope. It is shown, when the load time shortens, the ductile component of fracture declines and the samples fail in a more brittle manner.
Keywords: Magnetic Pulse Technique, Metallic Ring Samples, Dynamic Loading

1.Introduction

In the works of American authors [1-4], an original magnetic-pulse method is proposed for the tangential stretching thin metal rings up to destruction. The method allows them to achieve the radial velocities of ring expansion in the range of 80-200 m/s at strain rates of the order $10^4 s^{-1}$. The process of the formation of necks and fragmentation fixed using high-speed photography with high temporal and spatial resolution. It is shown that the destruction of the ring occurs in a time much less than the first period of the current oscillations in the ring. Fragmentation process takes less than 20 μs. The increase in the cross-section of the specimen significantly increases the deformation of localization start. Deformation of localization origin is independent of strain rate. An increase of deformation homogeneity takes place with increasing sample sizes.
The high-speed radial expansion of ring is analyzed in [5] in plane strain. The material behavior is ductile, deformation hardening takes into account also. Tensile tests of rings of aluminum alloy [6] with speeds $3\cdot10^3 - 2{,}3\cdot10^4 s^{-1}$ at pulse durations between 5 and 41 μs revealed the effect of the speed and size of the expanding rings on the deformation of an aluminum alloy. Loading rate below $2\cdot10^3 s^{-1}$ does not affect the deformation. Flow stress depends on the maximum strain rate and the size of the ring.
The work [7] shows the effect of pulse duration on the microstructure produced as a result of impact loading. The authors [8] have shown that the generation of dislocations and the formation of twins in copper alloy with low stacking fault energy depend on the pulse duration less than 0.3 μs. The main cause of hardening under the pulse duration of 0.5 μs is the twinning and slip contribution becomes more significant when pulse duration is large. Number of damage upon rings extension of aluminum alloy is independent of the ring radius and is proportional to its expansion rate as is shown in [9]. Paper [10] provides a method to represent the investigation of fragmentation in the rapidly expanding metal rings. A quick discharge system of the capacitor generates magnetic forces that accelerate the ring to the maximum radial velocity of about 200 m/s, which corresponds to the

peripheral strain rate at about $10^4 s^{-1}$ under fragmentation. The streak camera technique is used to record the movement of the rings. Experiments on the destruction and fragmentation were performed on the samples of OFHC copper and aluminum 1100-0. Thin rings have rapidly expanded in [11] using magnetic fields to study the effect of strain rate on the strain to failure of ductile metals. In the interval of studied expansion velocities (50 to 300 m/s), the experimental results showed that the plasticity of Al 6061 and OFHC Cu increases monotonically with increasing speed. In each case, the deformation of the specimen to the destruction is almost two times more at 300 m/s than in static conditions.
All peer-reviewed papers on the metal rings maximum tensile strain rate did not exceed $10^4 s^{-1}$. This paper presents the results of a study on the destruction of the metal ring samples of D16 aluminum alloy with a substantially reduced period of harmonic loading. Voltage of destruction was rated and it shows its increase with shortening of the loading duration. Short-term loading leads to dynamic recrystallization - the formation of new small grains. The method of determining when the sample breaks is developed and applied.

2. Technique of experiment and results

Figure 1 shows the loading scheme. The current flowing through the coil, in which the ring specimen is located coaxially, causes inductive current in it, and the interaction of these currents generates a force of repulsion between the solenoid and the ring.

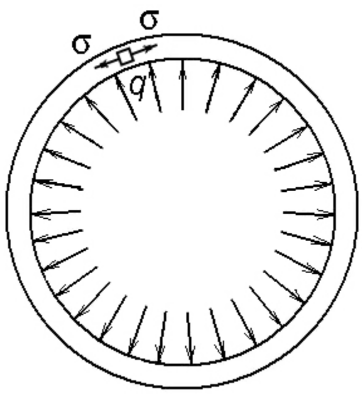

Fig. 1. Loading scheme of the sample (q- load, σ - tensile stress)

Two modifications of magnetic pulse method of loading were realized on the basis of short high-voltage pulse generator GKVI-300, which provides the formation of electrical voltages with amplitudes of 30 - 300 kV. Electrical block-schemes of the installation under the implementation of a sinusoidal load with a period of 7.5 μs (modification 1) and with a period of 1 μs (modification 2) are shown in Fig. 2 and 3, respectively.

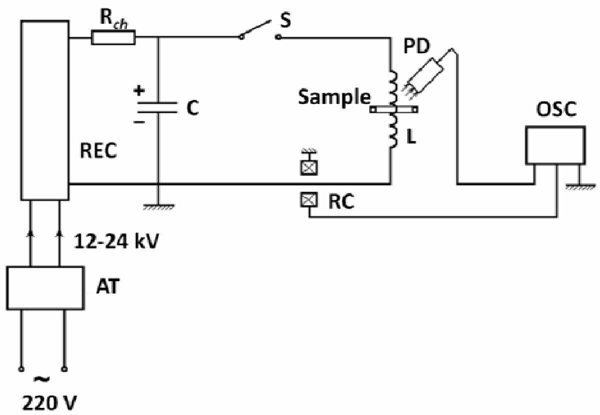

Figure 2. The block-scheme of the setup for sinusoidal electromagnetic load of period 7.5 μs: AT - autotransformer; REC - rectifier; R_{ch} - charge resistor; C - condenser; S - discharge; RC - Rogowski belt; L - coil (coil without core); Sample - sample (metal ring); PD - photodiode; OSC – oscilloscope

In testing of ring specimens with a period of sinusoidal current T = 7,5 μs (Fig. 2) the charge of capacitor (C) is carried out by rectifying device (REC) with variable voltage from 12 to 24 kV. Then the discharge of capacitor (C) was proceeded through the coil (L) with a high-voltage spark gap (S)

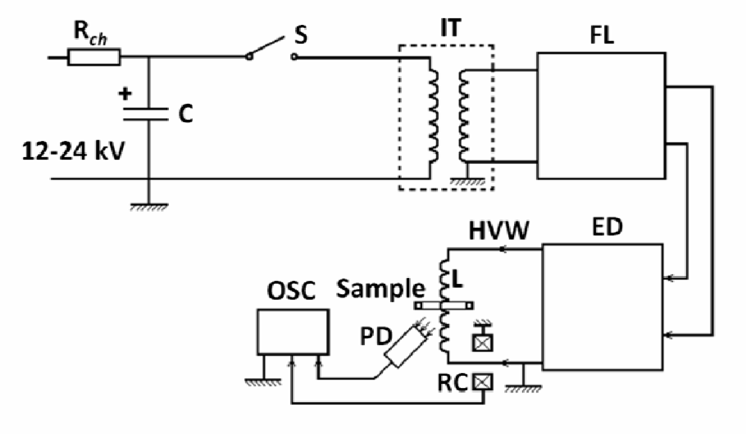

Fig. 3. The block-scheme of the setup for sinusoidal electromagnetic load of period 1 μs: IT - pulse transformer; FL - forming line; ED - output device; HVW - high-voltage electrode

The coil is made of copper wire 1mm in diameter, has 5 turns of the coil 25 mm in diameter. The current flowing through the coil, was measured by Rogowski coil (RC) and displayed on a digital oscilloscope (OSC), from which the information was recorded on an electronic bearer. When the ring (Sample), coaxially mounted on the middle of the coil (L) is broken, a spark is appeared, which permits record the time of the destruction of the sample using a photodiode (PD). More complex unit is used in the test samples, when current was passed through the coil with a period of the damped oscillations T = 1μs. Its block-scheme is shown in Fig. 3. With the help of a pulse transformer (IT) the voltage of sine wave signal increased in 10 times, compared with the above case (Fig. 3) and by forming line (FL), and an output device (ED) (Fig. 3) was supplied to the same coil. However, the period of the current oscillations is already a T = 1μs. Appearance of plants is shown in Fig. 4

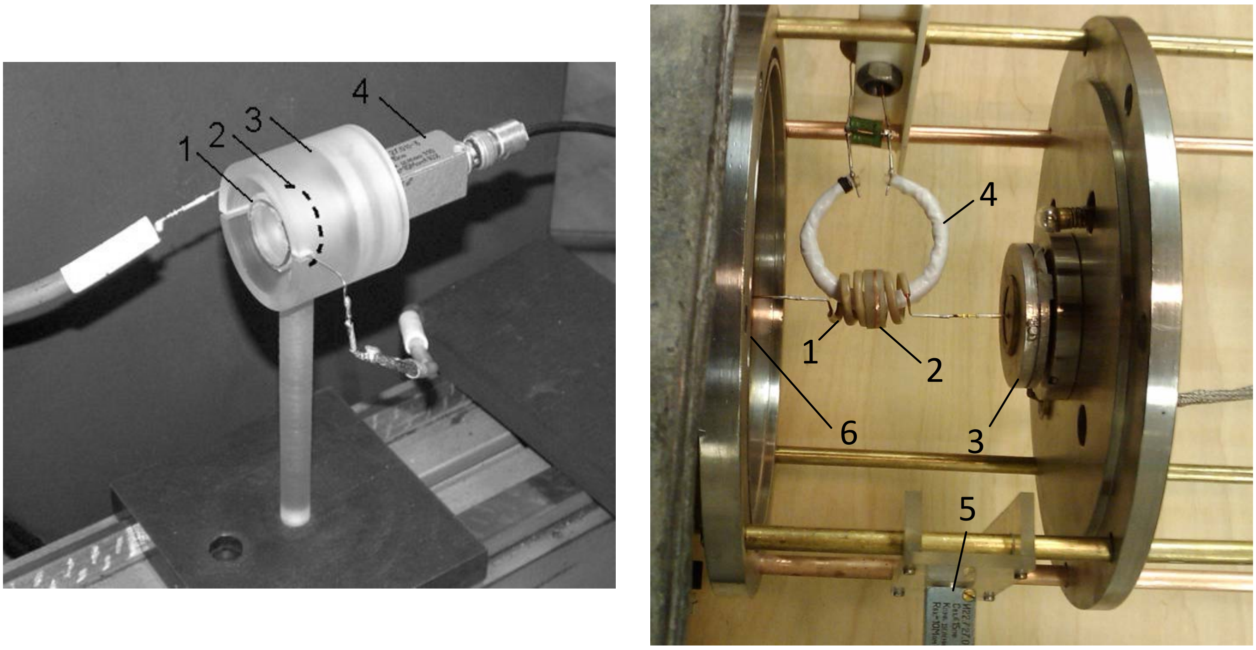

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Figure 4. Appearance of plants: a - at 7.5 μs (1 - solenoid, 2 - sample 3 - housing, 4 - photodiode), b - at 1 μs (1 - solenoid, 2 - sample 3 - Rogowski belt to measure the current in the coil 4 - Rogowski coil to measure the current in the ring, 5 - photodiode, 6 - output device).

The study of fracture surfaces of aluminum and copper samples after the test was carried out on an optical microscope Axio-Observer-Z1-M in a dark field, and study the structure of cross sections - in the bright field or polarized light. The structure has been studied in cross sections after appropriate etching. Grain size and the number of pores on the surface of cross sections were determined after etching. Microhardness was measured on a PMT-3 device with a load of 20g. Ring samples were tested from duralumin D16 brand with an inner diameter of 28 mm. The ring D16 had a thickness of 0.11 - 0.40 and a width of 0.5 - 1.0 mm, when they exposed to electric currents with a long period.

Fig. 5 shows the waveforms of current through the coil (2) and the signal from the photodiode (1) fixing the time of rupture of the sample for the two variants of tests: T = 7,5 μs and T = 1 μs.

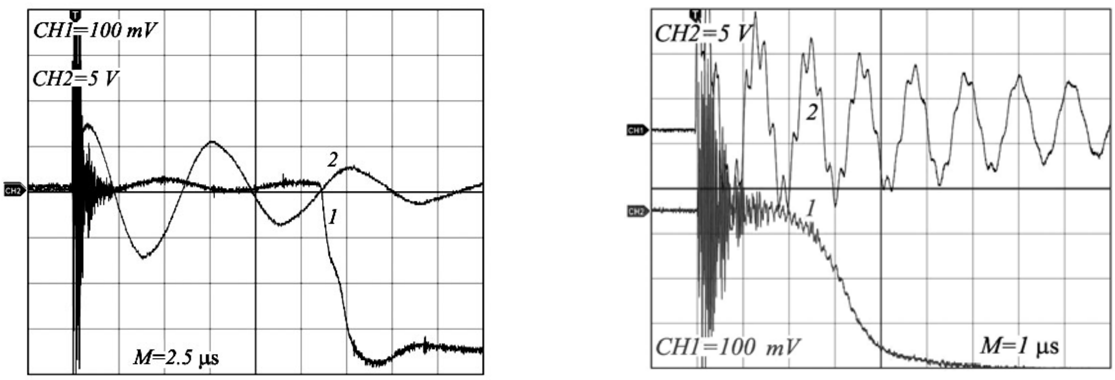

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Fig. 5. Waveform signal from the photodiode (1) and current from Rogowski belt (2), a - in the current period $T = 7.5$ μs; b - $T = 1$ μs. Sample size: b= 1.0, h=0,11 mm

3. Discussion of the results

Fig. 6 shows the samples in the initial (pre-test) state and after loading in different modes. The figure shows that failure occurs in one place for a period of change of the current 7,5 μs, and for the period of 1 μs, but in a shorter period can be seen multiple neck. When energy increases with the period of 7,5 μs the number of destruction fragments increases.

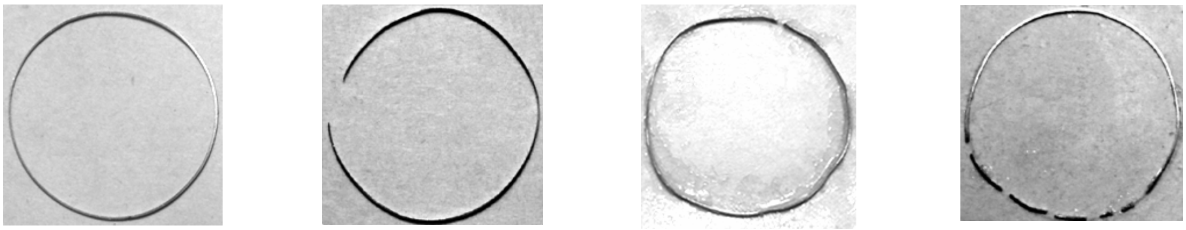

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Fig. 6. Photographs of aluminum samples: a - before loading; b - destruction at the threshold energy, T = 7,5 μs; c - the same at T = 1 μs; d - the destruction at an energy well above the threshold, T = 7,5 μs

Let us estimate the radial force acting on the ring from the side of the coil windings. Calculation scheme is shown in Fig. 7. Estimation of the force is held in the quasi-static approximation. It is believed that the main force is the Ampere force. The total force acting on the ring, adds together of the main force of the turns of the coil, which is located in the plane of the ring coaxially with it (Fig. 7) and on the side of turns. Calculations have shown that the main contribution is made to Ampere force by two side ring. From these considerations, the number of turns of the coil was chosen to be five.

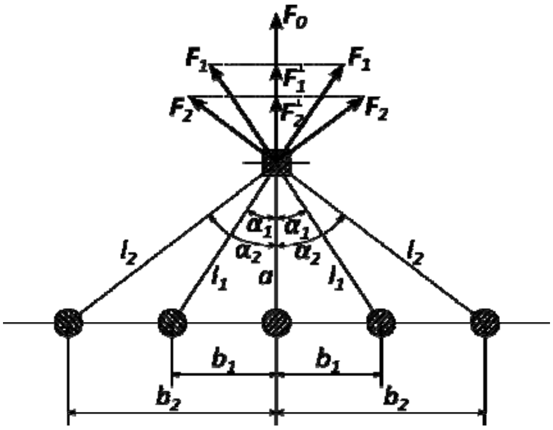


Figure 7. Scheme for calculation of the force acting on the ring

So the force acting on the ring will be

$$F(t) = F_0(t) + 2F_1^{\perp}(t) + 2F_2^{\perp}(t),$$

where

$$F_0(t) = \frac{\mu_0}{4\pi}\frac{2I_1(t)I_2(t)}{a}, \quad F_1^{\perp}(t) = F_1(t)Cos\alpha_1 = \frac{\mu_0}{4\pi}\frac{2I_1(t)I_2(t)}{l_1}Cos\alpha_1,$$

$$F_2^{\perp}(t) = F_2(t)Cos\alpha_2 = \frac{\mu_0}{4\pi}\frac{2I_1(t)I_2(t)}{l_2}Cos\alpha_2,$$

$\mu_0 = 4\pi 10^{-7} \dfrac{H}{m}$ - magnetic constant, $I_1(t)$ - the current in the loop coil, $I_2(t)$ - the current in the ring, a - the distance from the coil to the ring.

Distributed load acting on the inner surface of the ring,

$$q(t) = \frac{F(t)l}{S},$$

where l - length of the inner circumference of the ring, S = lc - area of the inner surface of the ring, c - the width of the ring.

Thus, $q(t) = \dfrac{F(t)}{c}$.

The tangential tensile stress (Fig. 1) can be calculated from the Laplace formula for thin shells:

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

where R - radius of the inner ring of the sample and h - its thickness.

In determining the tensile stress its pulsating value $\sigma(t)$ replaces averaged in the form of a rectangular pulse of amplitude σ_0 and duration equal to the time from the start of the current delivery in the coil until the breaking of the ring t_c (Fig. 8)

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

Time recorded in the experiments

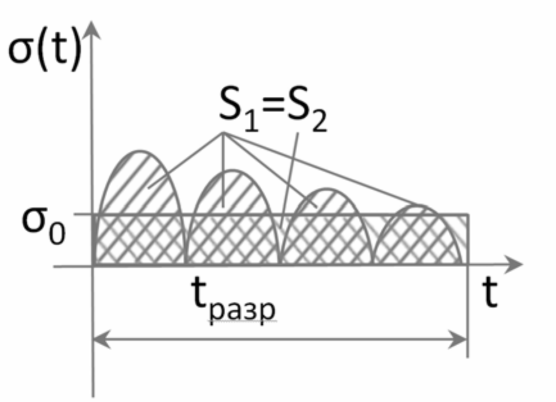


Fig. 8. Replacement scheme of ripple voltage: S_1 - the area under pulsed voltage, S_2 - the area under constant stress σ_0.

The following parameters of the device are used in made experiments and calculations: a = 3 mm, b_1 = 7.5 mm, b_2 = 15 mm.

Characteristics of the samples, the experimental conditions and results are summarized in Table 1, where T - the period of oscillation of the current in the coil; h - thickness of the ring; c - width of the ring; ∅ - ring diameter; U - capacitor charging voltage; σ_0 - tensile stress for rupture of the ring; τ - time to failure; W - energy of a charged capacitor; I - maximum amplitude of the current through the coil

Table 1. The experimental results

Material	T, μs	h, mm	c , mm	∅, mm	U, kv	σ_0, MPa	τ, μs	W, J	I, A
Al	7,5	0,12	1,0	28	20	104	13,75	100	5700
Al	1	0,11	1,0	28	27	142	2,05	182	6000

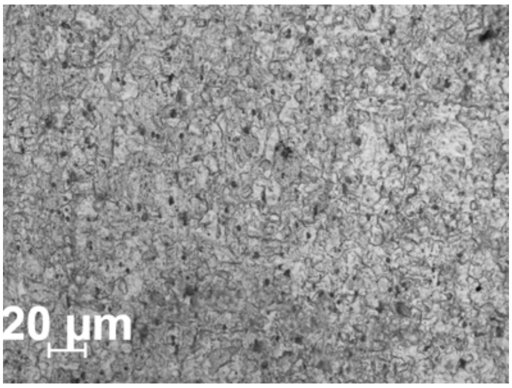
Measurement results of ductile component in the fracture of aluminum samples are described in [12], which shows that the shortening of the current period the share of fiber in the fracture surface decreases monotonically, i.e. samples become more fragile.

In Table 2 and in the micrographs (Fig. 9) the results of microstructural studies is presented, where T - the period of oscillation of the current in the coil; S = hxb - section of the sample; D - grain size; n - number of pores in the area of 400 μm^2; HV - microhardness.

Table 2. Characteristics of the structure

Material	T, μs	$h \times b, \mu m^2$	D, μm	n, 1/400μm^2	HV, MPa
Al	7,5	$193{,}5\times10^3$	1,2	121	1318,6
Al	1	$68{,}4\times10^3$	3,0	70	639,1
Al initial		120 x10^3	4,6	53	720,4

Fig. 9 shows the structure of aluminum samples at initial state and after loading with different periods and different cross-section (scale factor).



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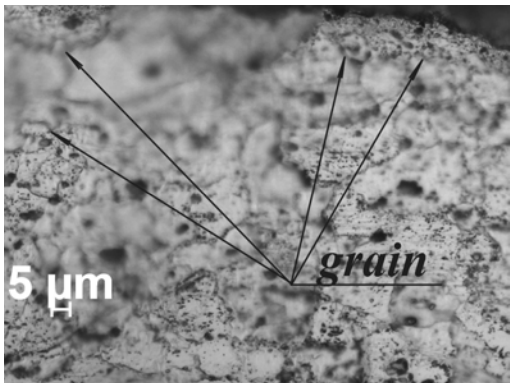

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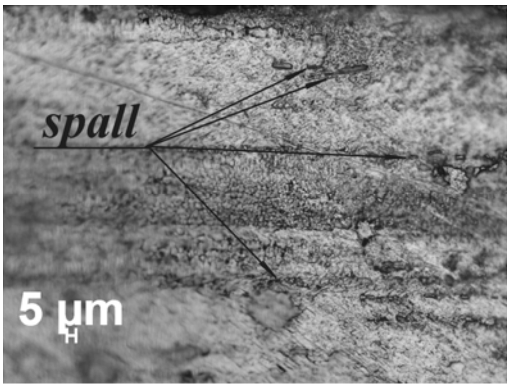

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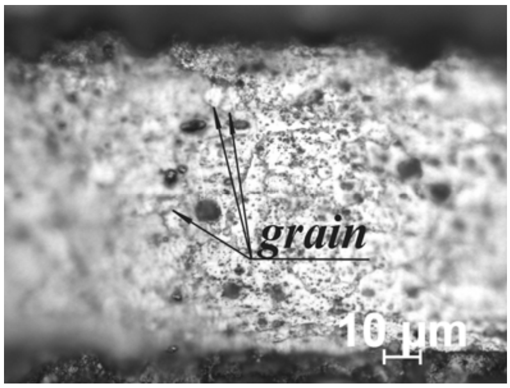

d

Figure 9. The structure of aluminum: (a) - in the initial state, (b) - after loading with the period T = 7,5 μs (S = 0,13 mm^2); (c) - after loading with the period T = 7,5 μs (S = 0, 19mm^2); (d) - after loading with the period T = 1μs (S = 0,07 mm^2), here the notation: spall - split, grain - recrystallized grains.

It is seen the dynamic recrystallization - the formation of new small grains for short-time loading. The highest degree of dynamic recrystallization is in the samples of aluminum with longer duration of loading and a maximum cross-section (scale factor). Samples of aluminum after loading showed a greater tendency to pore formation with increasing loading period compared with initial state. In addition, with increasing loading duration the samples had the generation of multiple spallation (Fig. 9c).

4. Conclusion

1. It was developed and tested a magnetic pulse method of destruction and photographic registration moment of destruction for ring metalllic samples at much shorter pulses of loading.
2. It was proposed the evaluation method of the radial force acting on the ring, and the tensile stress at break of the ring.
3. The dynamic recrystallization, the formation of shear bands and multiple spallation were revealed using magnetic pulse loading of the ring samples.

5. References

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