ENGINEERING TRANSACTIONS • *Engng. Trans.* • **60**, 4, 333–344, 2012
Polish Academy of Sciences • Institute of Fundamental Technological Research (IPPT PAN)
National Engineering School of Metz (ENIM)
SIXTY YEARS OF THE ENGINEERING TRANSACTIONS

Selection of Shaped Charge Liner Material with the Use of Electromagnetic Expanding Ring Technique

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The present work deals with an experimental study on various sorts of copper was carried out with the use of an electromagnetic launching ring technique in order to select the material with a desirable property for performance of a shaped charged jet. The obtained results proved that the copper with the smallest grain size revealed the highest ductility under electromagnetic expanding ring loading conditions. The performed observations seem also to suggest that the electromagnetic expanding ring test may be applied as a tool for a choice of liner materials.

Key words: electromagnetic ring test, metals ductility, high strain rate deformation, shaped charge liner materials.

1. Introduction

The knowledge of correlation between a mechanical liner material property and behaviour of a shaped charged jet is remarkably important for designing high-performance HEAT projectiles. The penetration capability of these projectiles depends mainly on density of a liner material ρ_j and the maximum length of the jet L. The value of the theoretical possible penetration depth P can be determined applying the following simple equation:

$$P = L\sqrt{\frac{\rho_j}{\rho_t}}, \tag{1.1}$$

where by ρ_t denotes the target material density [1].

The maximum length of the jet is theoretically determined by the velocity difference of jet tip $v_{j\,\max}$ and cut-off velocity $v_{j\,\min}$, and jet fragmentation time t_f (Fig. 1), however, both $v_{j\,\max}$ and t_f are limited by other parameters. The maximum jet tip velocity $v_{j\,\max}$ is limited by a factor of the bulk-sound velocity of the liner material, whereas jet fragmentation time t_f is restricted by ductility of the liner material.

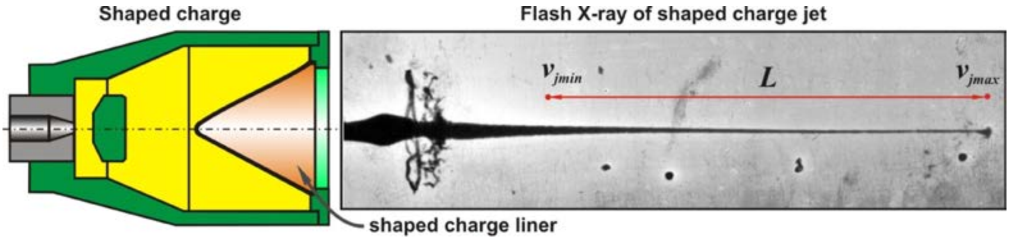

Fig. 1. Typical shaped charge configuration and rentgenogramof shaped charge jet.

The liner material ductility is critical owing to the penetration potential of shaped charges [2]. Therefore, the main purpose of the liner fabrication technology (besides achievement of required liner geometry) is the transformation of a metallurgical state of the starting liner material into the correct metallurgical characteristics of the final liner material, which is characterized by the high ductility properties under high-strain-rate loading conditions. The above-mentioned transformation of metallurgical properties of liner material is, however, not a straightforward procedure, since a lot of various requirements have to be met in order to guarantee the high ductility behaviour of the shaped charge jets.

The problem of assessment of the manufactured liner materials with respect to penetration property of shaped charges is also complex due to the fact that many different factors are possible to significantly affect the ductility and fragmentation of jets [1]. Nevertheless, many investigators attempt to formulate a simple method of assessment of some liner materials on the basis of the results obtained with the use of standard material tests. For example, Lichtenberger [3] found that, in the case of copper and nickel, the choice of liner material with a low temperature of recrystallization determined using standard hardness measuring guarantees high ductility of a jet. It is a very useful method constituting also a criterion of liner material selection for these types of metals. Unfortunately, for a number of other liner materials, such as, e.g. molybdenum, tantalum or tungsten, Lichtenberger's criterion is not valid. Therefore, various other experimental techniques for materials testing, especially the ones performed at high rates of strain, are commonly used. The split Hopkinson pressure bar is most frequently applied in this type of research [4, 5], however, an expanding ring test is particularly appropriate for the studies of materials ductility [6, 7].

The expanding ring test involves sudden radial acceleration of a ring due to detonation of an explosive charge or electromagnetic loading. The ring rapidly becomes a free-flying body expanding radially and decelerating owing to its own internal circumferential stresses. Measuring the radial displacement $r(t)$ or velocity history $v(t)$ of the ring specimen for the inertial stage of expansion results in the fact that circumferential stress σ_θ and true strain ε_θ for the ring material are possible to be determined at the imposed strain rate using the following relationships:

$$\sigma_\theta = -\rho r \frac{\partial^2 r}{\partial t^2}, \tag{1.2}$$

$$\varepsilon_\theta = \int_{r_0}^{r} \frac{dr}{r} = \ln\frac{r}{r_0}, \tag{1.3}$$

$$\dot{\varepsilon}_\theta = \frac{v_r}{r}, \tag{1.4}$$

where ρ – density of ring sample material, r_0 and r – initial and current radius of ring specimen, respectively, v_r – current expansion velocity.

During conducting the research on liners materials, the electromagnetic ring test was originally applied by Gourdin [8] who suggested that the strain at fracture of specimen rings could be another liner material characteristic, which describes the breakup behaviour of a shaped charge jet. In accordance with the above suggestion, Janiszewski and Włodarczyk [9] made also a successful attempt to select liner material built of a copper and its sinters. In this case, however, the dynamic loading of a ring sample resulted from the explosion of a cylindrical explosive charge, on which a ring was directly placed (Fig. 2a). Identification of dynamic properties of tested materials (ductility and fragmentation) desired with regard to the high penetration of shaped charges was performed on the basis of the radiographs taken using the X-ray impulse technique (Fig. 2b).

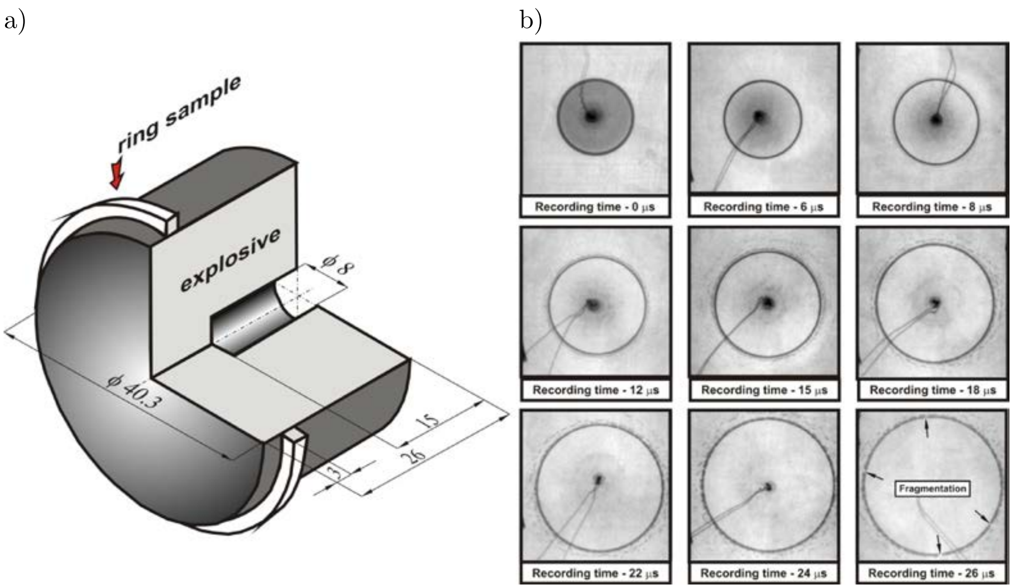

Fig. 2. Scheme of the experimental set-up driving explosively the ring sample (a) and radiographs of explosively expanding rings made of copper sinter (b) [9].

Application of a ring experiment in the liner materials studies results from the fact that the elementary advantage of the ring experiment is that a ring specimen has no boundaries in the primary stress direction and can be stretched uniformly without stress wave effects. Thus, the expanding ring test guarantees model conditions of dynamic experiments. Moreover, with the use of this technique, it is possible not only to achieve strain rates comparable to those occurring in stretching shaped charge jet but also ring specimens can be easily manufactured directly from as-formed liners.

Therefore, it was decided to use the electromagnetic launch ring technique in performing experimental studies for three various sorts of copper in order to identify their ductility properties desired with regard to the high penetration of shaped charges.

The paper is organized as follows: Section 2 is devoted to characterization of material properties of three different sorts of copper specimens and the description of the experimental techniques applied to determine ductility parameters for the tested coppers. The results of the performed experimental tests on ductility of the coppers tested under electromagnetic expansion conditions is described in Sec. 3, whereas the major conclusions of the present work are summarized in Sec. 4.

2. Experimental procedure

The experimental investigations were carried out on three sorts of copper, i.e. cold-rolled copper Cu-ETP, the annealed at 500°C for 1 hour Cu-ETP copper and the high-purity OFHC copper. In order to provide base-line material properties, the quasi-static material response of selected coppers was characterized in a standard tensile test, hardness measurement and a metallographic study. Material samples for the tensile strength test and electromagnetic ring experiments were machined from the same bar of a 40 mm diameter. The exception is OFHC copper which was prepared from the bar of a 60 mm diameter. The ring samples for electromagnetic expansion were machined to be close to the dimensions used by other investigators [6, 13]. The internal diameter of rings was 31.2 mm, while the cross-sectional area of the rings was 1 mm $\times$ 1 mm. In the present investigation, five ring experiments for each sort of a copper specimen were carried out under the given loading conditions. The results presented below are, therefore, the average values from the performed tests. The engineer properties of the studied coppers are collected in Table 1.

In turn, high-strain-rate experiments for the tested coppers were carried out with the use of an electromagnetic ring expansion technique originally proposed by Niordson [10]. In accordance with it, a ring specimen made of the tested material is placed concentrically over a mandrel containing a wire coil (Fig. 3).

Table 1. Quasi-static mechanical properties of tested coppers.

Metals	Ultimate tensile strength [MPa]	Yield strength [MPa]	True strain e_f [–]	Uniform strain e_u [–]	Hardness HV1	Grain size [μm]
Cold-rolledCu-ETP	263	239	0.27	0.15	90	25–120
Annealed Cu-ETP	221	77	0.49	0.36	65	20–80
OFHC copper	223	67	0.50	0.33	56	60–180

At the beginning of the experiment, a capacitor bank is charged to high voltage and next rapidly discharged through the wire solenoid and, as a result, the magnetic field is produced around the coil. Simultaneously, this magnetic field induces oppositely directed current in the metal ring specimen which generates the magnetic field as well. As a result of interaction between the magnetic fields originated from the coil and the ring currents, a uniform radial body forces are created. These applied for a very short time forces accelerate the ring specimen to high velocity and next they vanish when the solenoid current drops to a low value. Since that time the ring continues the expansion only by its inertia. If the inertia forces are large enough, the ring is possible to fracture into several small fragments.

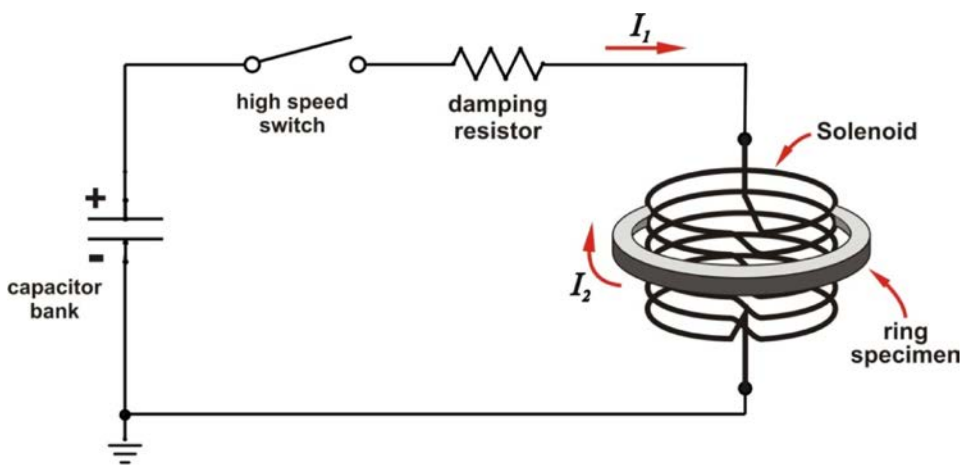

Fig. 3. Schematic diagram of the arrangement for electromagnetic ring expansion.

The above presented idea of radial ring expansion was exploited in the laboratory apparatus developed at Military University of Technology (Fig. 4) [11]. The apparatus consists of three main components: a pulse power system, a loading assembly, and a charging system. Previous experimental studies on copper rings indicate that launching properties of the developed apparatus allowed rapid acceleration of rings in 35 μs to maximum velocity equal to approximately 300 m/s for 0.91 kJ discharge energy.

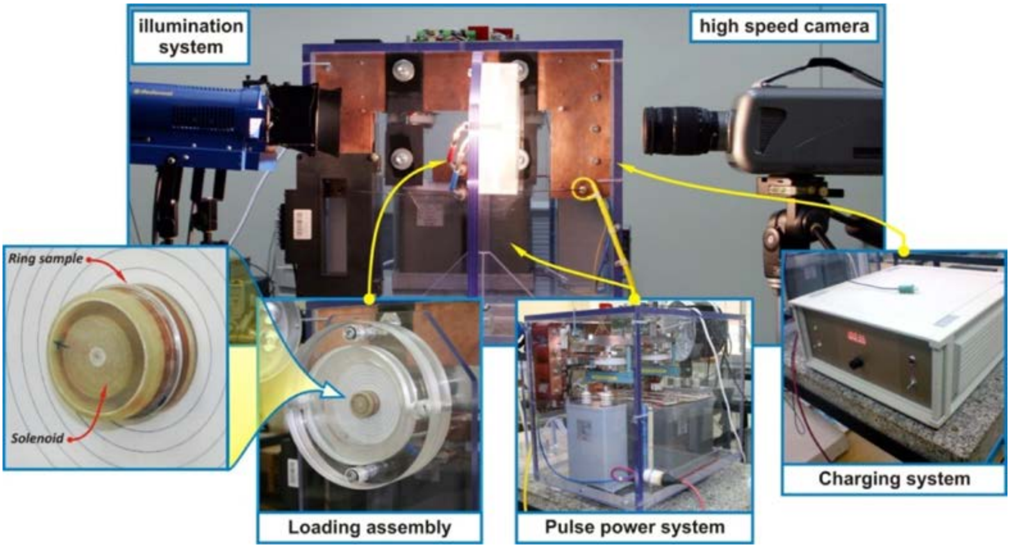

Fig. 4. View of the arrangement for electromagnetic ring experiment.

The displacement of the ring during the expansion process was recorded with a high-speed camera, whereas the ring velocity history was calculated from the high-speed images using the TEMA Automotive software (Fig. 5) [12].

In order to obtain good quality images and to ensure satisfactory measuring accuracy of the ring displacement with the use of an available equipment, first of all, a shadow method of optical observation was applied. This method consists in recording a ring shadow on a highlighted background which is illuminated by Dedocool lighting system (a left side of Fig. 4) allowing concentration of an intense amount of light over a small area. Moreover, the observation field of a high-speed camera was limited to a small area in which there was visible only a moving ring segment and two scaled points (Fig. 5b). Owing to these endeavors and application of the Tema Automotive software, the high measuring accuracy (uncertainty of ± 0.01 mm for the results presented here) and the reliable data concerning the ring expansion history could be obtained.

The expanding ring experiments were performed at similar loading conditions, i.e. maximum expansion velocities involved a range from 171 m/s to 195 m/s, what corresponds to an average strain rate of the order of 8×10^3 s^{-1}. Experiments were carried out under room temperature conditions, i.e. 21°C, however, ring temperature during electromagnetic expansion was increasing in a range from approximately 21°C to 150°C [14].

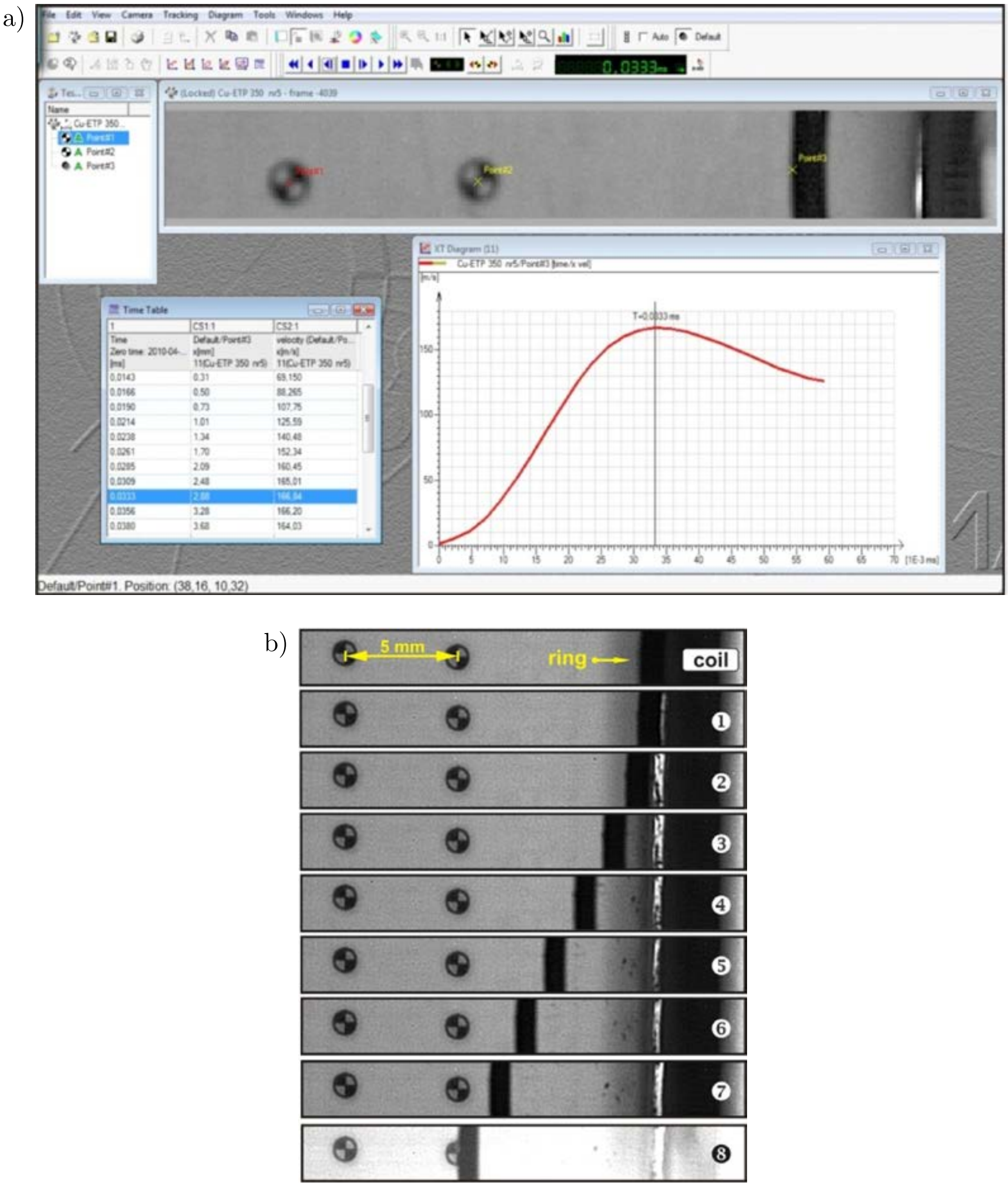

FIG. 5. The example of screen shot of graphical user interface presented video window with the moving ring segment and expansion velocity curve calculated with the use of TEMA Automotive software (a), and the sequence of images showing the observation area with the moving ring segment (b).

Ductility of the studied materials was expressed by uniform strain ε_u and strain at fracture ε_f. The final logarithmic ring strain at failure ε_f was determined on the basis of the data obtained from an optical measuring comparator by direct measurement of lengths of the recovered fragments captured into the wax ring. On the other hand, uniformed strain ε_u was calculated on the basis of the measurements of cross-sectional dimensions of recovered ring fragments using the following formula:

$$\varepsilon_u = \frac{(A_0 - A)}{A}, \tag{2.1}$$

where A_0 and A are the initial and deformed cross-sectional areas, respectively. It should be noted here that a cross-sectional area was determined in the uniform portion of fragments, that is, in the middle of the ring fragment or between neighbouring arrested necks.

3. Results and discussion

As it was mentioned earlier, dynamic experiments for all tested copper specimens were carried out for the same discharge energy equal to 0.48 kJ. Nevertheless, the achieved launching velocities were slightly different for each tested sorts of copper rings (Table 2). The highest maximum expansion velocities were reached for the rings made of high-purity OHHC copper, on the other hand, the rings manufactured from cold-rolled Cu-ETP copper were expanded at the lowest velocities. As a consequence, a strain rate also varied in the range from 7.6×10^3 to 9.0×10^3, which was calculated for strain equal to 0.25 (it is a strain value which corresponds to ring deformation during the inertial stage of ring expansion).

Table 2. Average maximum velocities of expansion of rings made of different sorts of copper.

Ring material	Max. expansion velocity [m/s]	Standard deviation [m/s]	Strain rate for $\varepsilon_\theta = 025$ [s^{-1}]
Cold-rolled Cu-ETP	171	1.9	7.6×10^3
Annealed Cu-ETP	180	2.2	8.2×10^3
High-purity OFHC copper	195	4.6	9.0×10^3

The above-mentioned differences in ring expansion velocities originate from various mechanical responses of the studied copper sorts, what is confirmed by the data presented in Table 3 (the second column from the left). The lowest expansion velocity was achieved for the copper which revealed the highest flow stress (cold-rolled Cu-ETP copper), whereas the highest ring expansion velocity was found for copper with the lowest flow stress value (OFHC copper).

Parameters characterizing ductility and fragmentation properties of the tested materials are collected in Table 3. These parameters allow for concluding gen-

Table 3. Dynamic properties parameters for different sorts of copper.

Ring material	Flow stress σ_θ for $\varepsilon_\theta = 025$ [MPa]	Strain at fracture ε_f [–]	Uniform strain ε_u [–]	Average ring fragments length (number) [mm] ([–])
Cold-rolled Cu-ETP	402	0.40	0.31	13.7 (11)
Annealed Cu-ETP	345	0.47	0.49	13.9 (11.5)
High-purity OFHC copper	335	0.43	0.32	14.8 (10.5)

erally that ductility of all copper specimens increases under an electromagnetic ring expansion condition in relation to the static one. Surprisingly, however, the dynamic ductility of OFHC copper is almost at the same level of ductility determined under quasi-static tensile conditions (compare values e_u and ε_u in Table 1 and Table 3). In turn, the highest increase in ductility was found for the cold-rolled ETP copper (increase of 106%), whereas the annealed ETP copper revealed the highest dynamic ductility (the highest values of ε_f and ε_u) in comparison to other sorts of copper.

The high ductility of the annealed ETP copper under ring test conditions is also confirmed by a shape of the recovered ring fragments (Fig. 6). The fragments from the annealed ETP copper rings were the most stretched and they included many small necks so-called arrested necks (Fig. 7). In the case of other copper samples, less number of the arrested necks was observed, especially for OFHC copper. For this type of copper, there was also found the lowest average number of fragments on one ring (10.5) despite of the highest expansion velocity, while an average ring fragments length was the longest and equal to 14.8 mm.

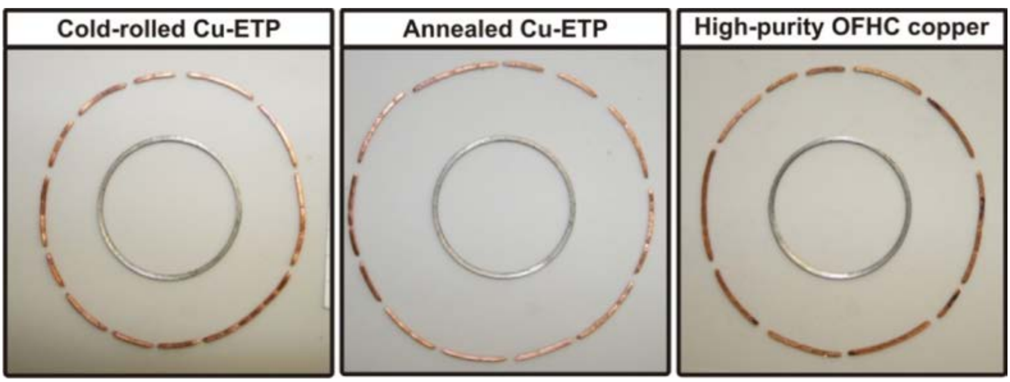

Fig. 6. View of recovered fragments generated from different sorts of copper rings.

The above-presented ductility behaviour of copper rings has been already reported in the literature [6, 15, 16]. Generally, it has been reported on the increase of ductility property of copper under high strain rate tensile conditions

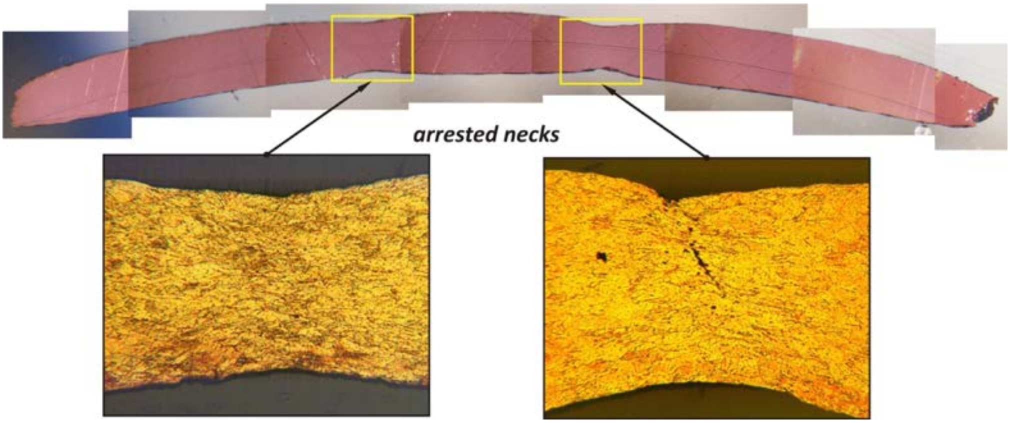

FIG. 7. View of the annealed copper ring fragment and the structures of the arrested necks arisen into ring fragment.

[15, 16] in comparison to the static testing test. There are also scientific reports [6] which present the experimental results demonstrating that the strain at the necking onset of copper rings was nearly equal to the quasi-static necking strain, that is, dynamic copper ductility was at the same level as the ductility determined under a quasi-static tensile test.

The various ductility behaviour of copper may arise from differences in the metallurgical state of the studied copper samples which could have, for example, different grains morphology or a different impurities level. The studied sorts of copper differ from each other in respect to both impurities contents (purity of Cu-ETP – 99.95%; OFHC – 99.99%) and a grains size (see Table 1). In the subject literature, the role of a grain size in ductility behaviour of metals has been especially emphasised [17, 18]. Similarly, the significant influence of a grain size of liner material on ductility of a shaped charge jet has been reported [1–3]. Generally, it was stated that with decreasing of a grain size of a copper liner, jet ductility was increased, and thus penetration of a jet was also improved. The results of the experiments performed with the use of an expanding ring technique confirmed the above-mentioned relation between a grain size of copper samples and their ductility under a high rate of strain since the highest ductility revealed the annealed copper Cu-ETP, which had got the smallest grain size (20–80 μm). Thus, it can be believed that the application of this sort of copper as the liner material ensures the high penetration capability of a shaped charge jet.

4. Conclusions

In the present work, the electromagnetic ring test was applied in order to select shaped charge liner material from among three sorts of copper. In accordance with the data presented in the literature [1–3, 8, 17, 18], the obtained results show that the copper with the smallest grain size (the annealed Cu-ETP) reveals the highest ductility under electromagnetic expanding ring loading conditions. Taking the above mentioned problems into consideration, it may be concluded that the observations carried out in the present work constitute another proof that the electromagnetic ring test is a good tool for the choice of liner materials.

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Received May 25, 2012; revised version November 27, 2012.