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Experimental analysis of density and compressive strain of porous metal with the use of Taylor test

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The article presents a new experimental method of analysis of density and longitudinal engineering compressive strain (LECS) in porous ductile rod, plastically deformed with a Taylor direct impact experiment (Taylor DIE). Two essential singularities in the distribution of the LECS are revealed, namely: maximum of the LECS $\varepsilon_{r\ \max}$ occurs near the rod striking end (Fig. 2), and at high impact velocities ($U > 100$ m/s) $\varepsilon_{r\ \max}$ decreases along with an increase of the rod initial porosity, this behaviour is inverse to that under static loading. The dynamical density – LECS curves for porous copper are also presented in the paper. According to the authors' best knowledge, these singularities have not been published in available literature so far.

Key words: porous metals, dynamical density – longitudinal engineering compressive strain curves, Taylor direct impact experiment.

1. Introduction

The Taylor DIE, developed by Taylor in 1948 [1], is a useful experiment for estimating material behaviour at high strain rates. The Taylor DIE is reproducible and it is reasonably economical after conducting the initial investment. Therefore, many researchers and engineers commonly employed the Taylor DIE to determine dynamic yield stress of a solid at the high strain rate. Whiffin [2] conducted investigations, by means of the Taylor DIE, to study the effect of high strain – rates on dynamic yield strength of various metals. Lee and Tupper [3] presented modifications to the Taylor formulation considering elastic strains in the analysis. Hawkyard *et al.* [4, 5] examined the Taylor model taking into consideration the energy equilibrium rather than the momentum equilibrium at the plastic wave front adopted by Taylor. More recently, Jones et al. [6] proposed an elementary theory for the Taylor test. This theory was based on an additional assumption that the speed of the plastic wave front is proportional to the speed of the undeformed section of the striking rod. Lu *et al.* [7] and Wang *et al.* [8] extended Taylor's theory to the case of compressible materials such porous metals and metal foams.

However, it should be taken into account that a theoretical model, developed by Taylor, describing material behaviour during the Taylor DIE, is based on far-reaching simplifications, contrary to reality. The inconsistencies of this theoretical model are presented in paper [9].

It was assumed that, among others, in the Taylor theoretical model, the rod material is incompressible. This simplification approximates some properties of solid metals with sufficient accuracy for technical purposes. The investigations presented in the paper are particularly motivated by recent development of porous materials and their potential applications in impact engineering due to their weight efficiency in strength and high energy-absorption capacity. An important feature of porous material is its density change along with compressive strain changes. Therefore, it is not possible to assume that the porous rod material is incompressible during the Taylor DIE.

In the paper, an attempt was made to apply the Taylor DIE for determination of current LECS distributions $\varepsilon_r(x)$, and current density $\rho_r(x)$, in the porous ductile rod, deformed during the impact process. The independent variable x is a Lagrangian coordinate consistent with the rod axis and originated on a contact face of the rod with the target. The dynamic density – LECS curves for porous ductile material have been also studied.

2. Specimen materials characterization

The sintered porous copper samples were used during the Taylor DIE. The sintering process was chosen to fabricate these samples, because of its convenient use of compaction pressures to produce porosity at various levels. The samples were prepared from electrolytic copper powder, type ECu1 (grain size 40 μm). The powder was subjected to reduction (500°C, 1 h, dissociated ammonia atmosphere) to remove oxides from the surface of grains.

Cylindrical compacts (green samples) were made by means of suitable flexible PVC moulds. The moulds were filled with the powder by the vibratory shaker, FRITSCH Analysette3, in order to remove random voids and to achieve the maximum possible homogeneous density in the whole volume. The filled moulds were compacted by cold isostatic press (National Forge) under various pressures: from 100 to 300 MPa.

Sintering of the compacts was carried out by means of the LEW furnace in the dissociated ammonia atmosphere during three stages: 0.5 h, 300°C; 0.5 h, 650°C and 1 h, 950°C. In the end, cylindrical samples were precisely machine-made (CNC lathe CBKO TPS 20N) of the compacts. All specimens had the same nominal dimensions, namely: length $L \approx 60$ mm and diameter $D \approx 12$ mm. The upper and the bottom faces of the samples were ground in such a way that their final texture was in the shape of concentric circles. Such a texture ensures optimal distribution of friction forces during the impact, which is beneficial for uniform radial deformation.

The real dimensions of the samples (diameter and length) were precisely measured with Mitutoyo electronic micrometer and Sylvac displacement sensor. The accuracy of these instruments is 0.001 mm. Average initial density of each whole sample ρ_{sa} was estimated with a hydrostatic method with the aid of the laboratory balance Axis AD200 (scale 0.001 gm). Considering the influence of the average initial porosity $\Delta_{sa} = 1 - \rho_{sa}/\rho_s$ on mechanical properties of the sample after the test, there have been distinguished three groups of the porosities characterized by the following mean values: $\Delta_{sa} \approx 7\%$, 12% and 17%. Symbol ρ_{sa} denotes average density of the whole sample and ρ_s is density of the solid copper.

Before the test, the length of each sample was divided into elements, $\Delta x_0 \approx 5$ mm, by prepared nicks on the side surface of the sample. The nicks had the dimensions: width ≈ 0.35 mm and depth ≈ 0.1 mm. Such prepared samples were loaded by Taylor DIE.

To estimate homogeneity of distribution of discrete density in the sintered sample $\rho_{ea}(x_i)$, along its axis, before conducting the Taylor DIE, the selected sample ($\Delta_{sa} \approx 17\%$) was cut along the nicks into 12 elements and their average densities were measured with the hydrostatic method. Table 1 presents the discrete distribution of the ratio $\rho_{ea}(x_i)/\rho_{sa}$ along of the sample length. As it can be observed, the relative deviation of the absolute value of the initial discrete density of the sample element $\rho_{ea}(x_i)$ does not exceed 2% in respect to the average density of the whole sample. Thus, it can be assumed that the above quoted technology of manufacturing the samples of moderate porosity ($\Delta_{sa} < 20\%$) ensures sufficient homogeneity along their length.

Table 1. **The example of distribution of the ratio $\rho_{ea}(x_i)/\rho_{sa}$ along sample length: $\rho_{ea}(x_i)$ is average initial density of the undeformed element $\Delta x_e(x_i)$, x_i is discrete value of Lagrangian coordinate, $\Delta_{sa} \approx 17\%$.**

x_i [mm]	2.5	7.5	12.5	17.5	22.5	27.5	32.5	37.5	42.5	47.5	52.5	57.5
$\rho_{ea}(x_i)/\rho_{sa}$	1.00	0.98	1.00	0.99	1.00	1.01	0.99	0.99	0.99	0.99	0.98	1.01
$1 - [\rho_{ea}(x_i)/\rho_{sa}]$ [%]	0	2	0	1	0	1	1	1	1	1	2	1

3. Analysis of the LECS and density in deformed porous copper rod after Taylor DIE

In order to obtain the experimental data required to perform the above-mentioned analysis, the Taylor DIE ought to be carried out at various impact velocities for the copper porous rods of different initial average porosities. The specimens of equal initial nominal dimensions (length, $L \approx 60$ mm and diameter, $D \approx 12$ mm) have been prepared by the method represented in Section 2. The samples in the form of flat-ended projectiles were driven by the firing gun with a smooth bore to the initial speeds within the range from 98 m/s to 212 m/s. The initial average porosity of the samples ranged from 0% to 20%.

The pictures of the rods deformed during the Taylor DIE are depicted in Fig. 1.

The average LECS of the element $\Delta x_e(x_i)$ is determined by the following definition formula:

$$\varepsilon_{ea}(x_i) = \frac{\Delta x_0 - \Delta x_e(x_i)}{\Delta x_0} = 1 - \frac{\Delta x_e(x_i)}{\Delta x_0}, \tag{3.1}$$

where $\Delta x_e(x_i)$ is the length of the deformed initial element of the sample Δx_0 during the Taylor DIE, symbol x_i denotes a suitable value of Lagrangian coordinate x.

Similarly, the average LECS of the whole sample is determined by an analogous definition formula:

$$\varepsilon_{sa} = \frac{L - L_f}{L} = 1 - \frac{L_f}{L}, \tag{3.2}$$

where L_f is the overall length of the sample deformed after the Taylor DIE.

The discrete values of $\Delta x_e(x_i)$ were obtained by precise measurements of the lengths of the initial elements Δx_0 deformed by an impact experiment. The analogous results were also obtained for the solid copper (Cu-ETP) rod. They constitute a comparative background for the results obtained for porous copper. However, the values of the impact velocity determine the level of the dynamic load of the given sample during the impact test. These sets of the velocities may be approximated by means of the following mean values: $U \approx 100$ m/s, $U \approx 150$ m/s and $U \approx 200$ m/s.

After interpolation of the discrete experimental values of the strain $\varepsilon_{ea}(x_i)$, there were obtained three sets of curves characterizing variation of the current LECS $\varepsilon_r(x)$ versus Lagrangian coordinate x. These sets of the curves are depicted in Fig. 2. The principal parameter separating the sets of the curves is the impact velocity U. As the impact velocity U increases, the strain $\varepsilon_r(x)$ increases also in all range of variations of Lagrangian coordinate x, approximately proportionally to U, independently of the initial average porosity of the samples.

The essential singularities in the distribution of LECS $\varepsilon_r(x)$ can be observed. The first singularity is that the maximum strain $\varepsilon_{r\,\max}$ is located in the neighborhood of the sample's striking end. This singularity is caused by friction force which occurs on contact of the target face with the sample. The friction force together with lateral inertial force decreases the radial outflow of the material

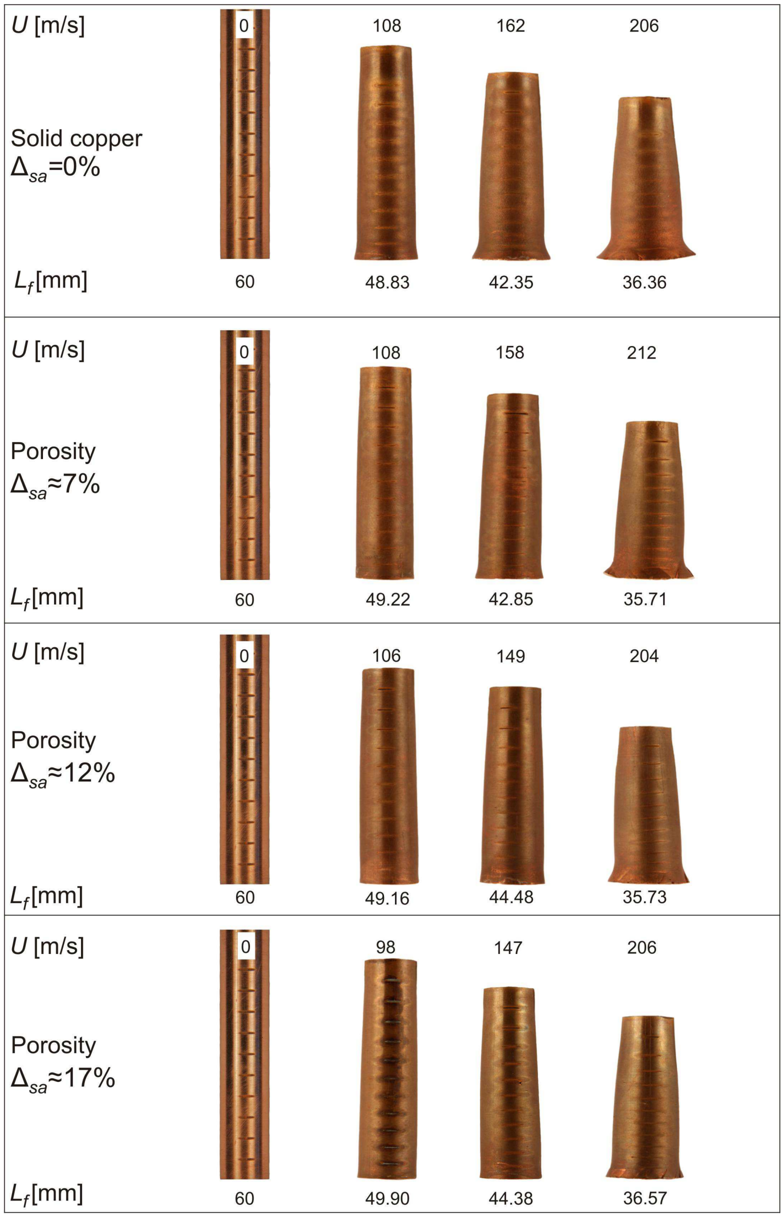

Fig. 1. Pictures of deformed samples.

of the sample element which comes in contact with the target face. This fact causes increasing thickness of this element in relation to a neighbouring one. Thus, in agreement with formula (3.1), the compressive strain ε_r of this element decreases as a result of working friction force. Owing to this reason, the

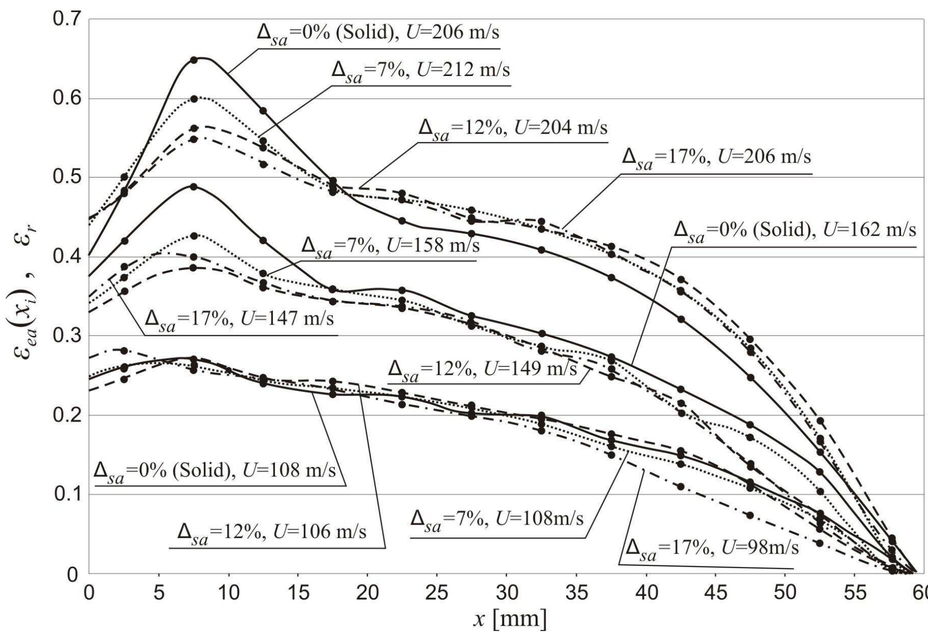

Fig. 2. Interpolation of the discrete values of strain $\varepsilon_{ea}(x_i)$ along the samples deformed during Taylor DIE, where x is Lagrangian coordinate.

strains of the elements that do not come in contact with the target face are larger than $\varepsilon_r(0)$. In the theoretical limiting case, when friction force approaches infinity, then strain $\varepsilon_r(0)$ approaches zero. Figure 2 clearly shows the presented singularity. Considering the graphs depicted in Fig. 2 it can be concluded that for the largest impact velocity ($U \approx 200$ m/s) which generated greatest friction force in the considered case, the border strain $\varepsilon_r(0)$ is significantly lower than $\varepsilon_{r\,\max}$ and location of strain maximum is most distant from the target face. On the contrary, for $U \approx 100$ m/s (small friction force) $\varepsilon_r(0) \approx \varepsilon_{r\,\max}$ is obtained, as it might be expected.

A published theoretical model of the Taylor DIE has not taken into consideration these singularities so far. In available literature, the maximum strain $\varepsilon_{r\,\max}$ is presented as located on the sample striking end ($x = 0$, Fig. 3). It can be observed that this is inconsistent with reality.

From Fig. 2 it follows that the singularity can be determined if the initial element $\Delta x_0 < 10$ mm. In the paper, it has been assumed that $\Delta x_0 = 5$ mm. It should be noticed that the size of the grid $\Delta x_0 < 5$ mm applied during division of the sample does not change the character of the strain distribution, however it does insignificantly change the value of $\varepsilon_{r\,\max}$ and its distance from the target face.

The other singularity is that under high dynamical load (high-impact velocity) the maximum value of strain $\varepsilon_{r\,\max}$ considerably decreases with the increase

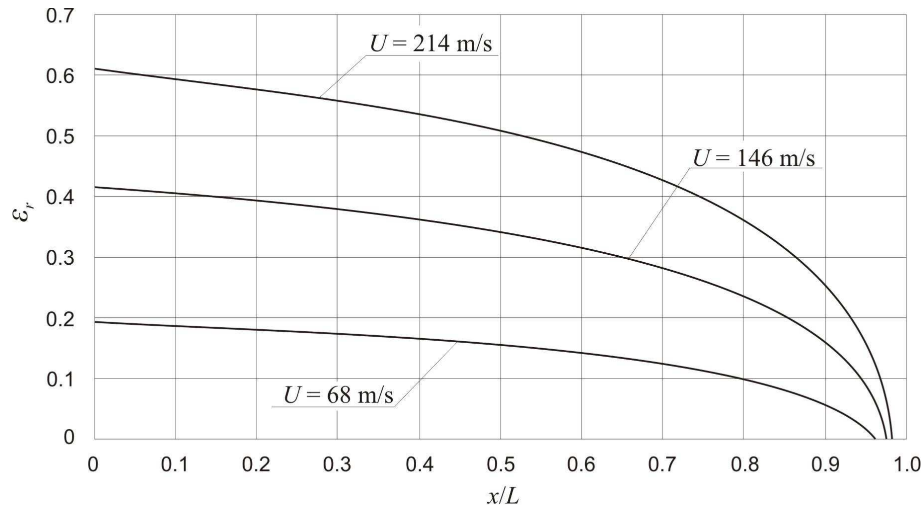

Fig. 3. Theoretical distribution of compressive current strain ε_r in the solid copper rod after Taylor impact test, without allowing for the friction force [9].

of the initial porosity of the sample material (see Fig. 2), inversely than under static load. This is probably caused by the heating of gas closed into the pores due to friction force and shock compression during the impact experiment. The heating induces an additional pressure increase in closed gas and effectively decreases the sample deformability. On the contrary, if the sample was compressed quasi-statically, the gas closed into the pores was compressed isothermally. In this case, $\varepsilon_{r\ \max}$ increases with the increase of the initial porosity of the sample material [8].

The influence of the moderate initial porosity ($\Delta_{sa} < 20\%$) of the porous copper samples on strain $\varepsilon_r(x)$ is insignificant at impact velocity $U < 150$ m/s, and in engineering calculations of $\varepsilon_r(x)$ it may be neglected. In this case, the sets of functions $\varepsilon_r(x)$ for porous copper can be replaced by curve $\varepsilon_r(x)$ obtained for solid copper at adequate impact velocity. The approximation error does not exceed, in this case, several percent.

Similarly, the average LECS ε_{sa} is also limited by the impact speed. For porosity $\Delta_{sa} < 20\%$ it practically does not depend on it (see Table 2).

In order to determine the distributions of the discrete mean values of the samples' density along their axes after the Taylor DIE, the deformed samples were cut along the prepared nicks into elements $\Delta x_e(x_i)$ and their mean densities $\rho_{ea}(x_i)$ were measured with a hydrostatic method. After approximation of the discrete values of ratio $\rho_{ea}(x_i)/\rho_{sa}$, there were prepared three sets of curves characterizing variation of relative current densities $\rho_r(x)/\rho_{sa}$ in accordance with an increase of Lagrangian coordinate x, analogously as for strain $\varepsilon_r(x)$, (see Fig. 2). These sets of curves are depicted in Fig. 4.

Table 2. The values of average LECS of copper samples after the Taylor DIE.

Solid copper			$\Delta_{sa} \approx 7\%$			$\Delta_{sa} \approx 12\%$			$\Delta_{sa} \approx 17\%$		
U [m/s]	L_f [mm]	ε_{sa}	U [m/s]	L_f [mm]	ε_{sa}	U [m/s]	L_f [mm]	ε_{sa}	U [m/s]	L_f [mm]	ε_{sa}
108	48.83	0.186	108	49.22	0.180	106	49.16	0.181	98	49.90	0.168
162	42.35	0.294	158	42.85	0.286	149	44.48	0.259	147	44.38	0.260
206	36.36	0.394	212	35.71	0.405	204	35.73	0.405	206	36.57	0.391

As it is observed, the initial porosity of the sample significantly changes the current density distribution along the sample, which is deformed during the Taylor DIE. On the contrary, the current density of the solid copper sample ($\Delta_{sa} = 0\%$), analogously deformed as porosity samples, is approximately constant, and ratio $\rho_{ea}(x_i)/\rho_{sa} \approx 1$, where the deviation does not exceed a few percent fraction (see Fig. 4).

Figure 4 shows that maxima of the current relative density of the deformed samples $\rho_{r\ \max}(x)/\rho_{sa}$ are located at their striking ends, as it is expected. The maximal values of the relative density increase with an increase of the impact velocity. These maxima as well increase with an increase of the initial average porosity of the samples, inversely as in the case of the strains. The current relative density of the deformed samples monotonously decreases along their axes from maximum $\rho_r(0)/\rho_{sa}$ at the samples striking ends to $\rho_r(L)/\rho_{sa} \approx 1$ at their rear ends. The values of the function $\rho_r(x)/\rho_{sa}$ depend on two parameters: impact velocity U and initial porosity Δ_{sa}. The ratio $\rho_r(x)/\rho_{sa}$ increases for each value of the independent variable x with an increase of these parameters.

In turn, Fig. 4c shows that at impact velocity $U \approx 200$ m/s, the samples are approximately uniformly compacted in about a half of their volume from the side of the target face and, subsequently, their density intensively decreases to the initial average value ρ_{sa} near the ends of the samples. On the contrary, at the impact velocity $U < 150$ m/s the density $\rho_r(x)$ decreases approximately linearly in accordance with an increase of Lagrangian coordinate x, from $\rho_r(0) = \rho_{r\ \max}$ to $\rho_r(\sim L) = \rho_{sa}$, for each initial porosity Δ_{sa} (see Figs. 4a and 4b).

4. Analysis of dynamic density – LECS curves

The experimental data were used to plot the sets of dynamic relative density – LECS curves $\rho_r/\rho_{sa} - \varepsilon_r$ for porous copper. These curves sets are depicted in Fig. 5. Similarly as density, $\rho_r/\rho_{sa} - \varepsilon_r$ curves depend on parameters U and Δ_{sa}. Every pair of the values these parameters uniquely defines single $\rho_r/\rho_{sa} - \varepsilon_r$ curve. Figure 5 clearly shows that for the ductile porous material the relative

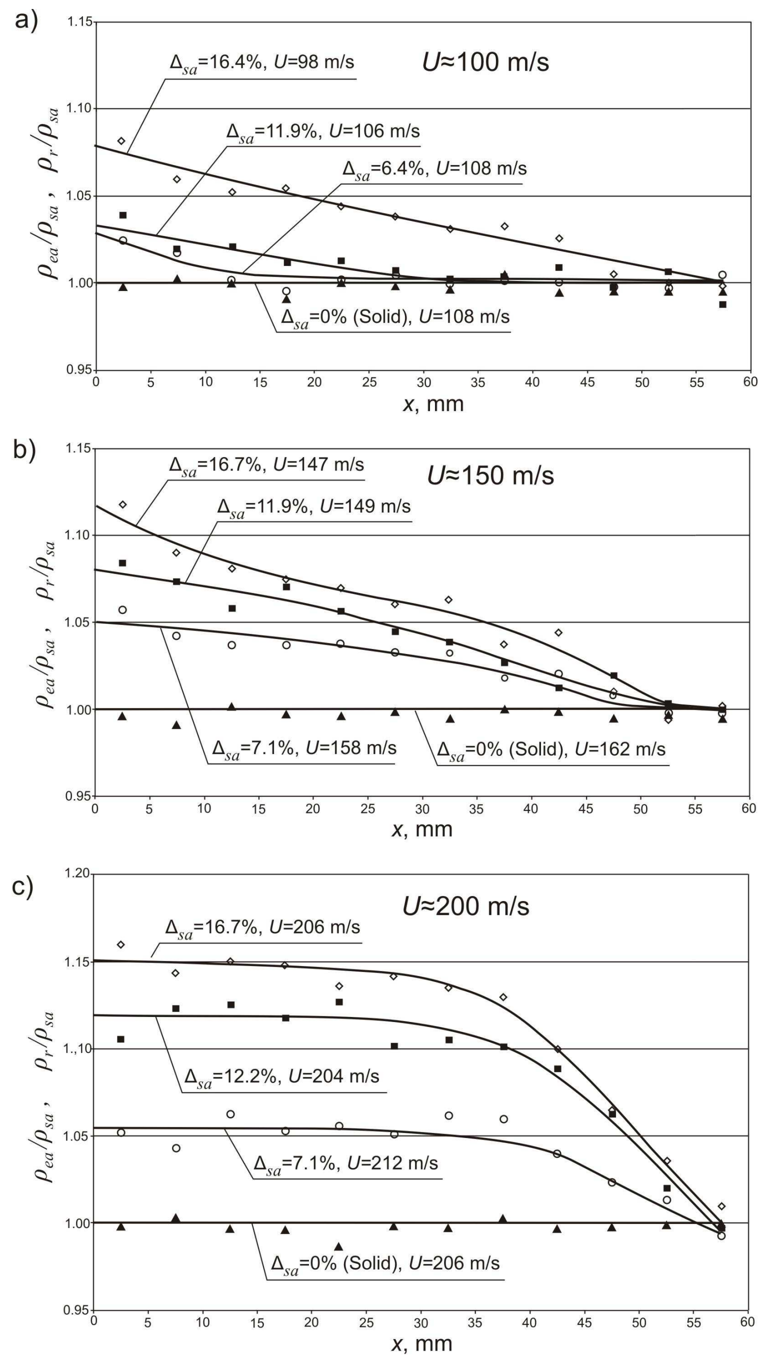

FIG. 4. Approximation of discrete values of ratio $\rho_{ea}(x_i)/\rho_{sa}$ along deformed samples during Taylor DIE, where x is Lagrangian coordinate.

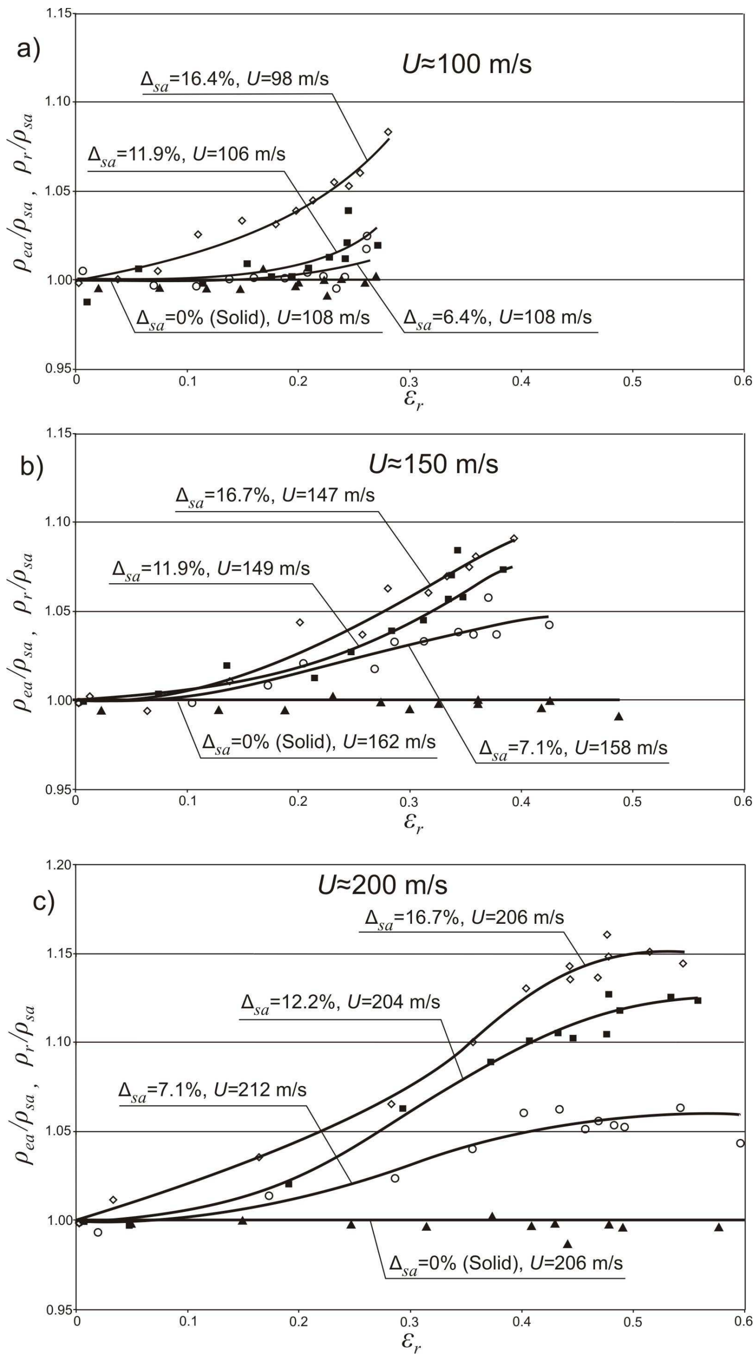

Fig. 5. Relative density – LECS dynamic curves for porous copper.

density ρ_r/ρ_{sa} is a non-linear function of LECS ε_r. For the sake of simplicity, relationship $\rho_r/\rho_{sa} - \varepsilon_r$ has been approximated in papers [7, 8] to be a linear function of LECS ε_r (see Fig. 6), i.e.,

$$\rho_r/\rho_{sa} = 1 + a\varepsilon_r, \tag{4.1}$$

where a is a relative density parameter, which, according to the authors of papers [7, 8] can be obtained from a quasi-static compression test. As it can be observed, this far-reaching simplification is contradictory to $\rho_r/\rho_{sa} - \varepsilon_r$ dynamical curves presented in Fig. 5.

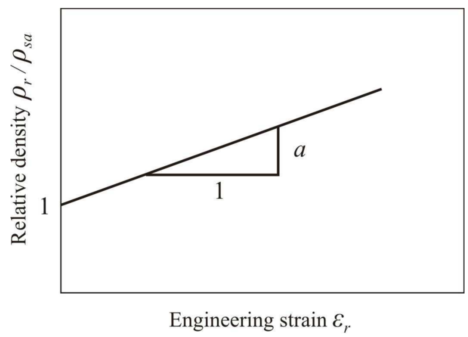

Fig. 6. Relative density versus compressive engineering strain [8].

5. Final conclusions

The main conclusions derived from the above presented experimental investigations may be briefly summarized as follows:

• Based on the Taylor DIE, there was developed a new simple experimental method for determining LECS distributions and density according to Lagrangian coordinate x in a ductile porous rod, plastically deformed during the impact process.

• This method was applied to reveal that the maximum of the LECS $\varepsilon_{r\,\max}$ is not located at the contact face of the rod with the target, as it has been stated so far in available literature, but it is near the rod striking end (Fig. 2). This singularity is caused by the friction force between the rod face and the target, which limits a radial outflow of the rod material in the neighbourhood of the target. It causes a decrease of LECS of the elements in the direct neighbourhood of the target face, and moves the location of $\varepsilon_{r\,\max}$ away from the target.

• Furthermore, it was found that the maximum strain $\varepsilon_{r\,\max}$ under high load (high- impact velocity) decreases with an increase of the initial porosity $\varDelta_{sa}$, this behaviour is inverse to that under static loading [8]. This singularity results from the heating of gas closed into the pores, due to with friction force and shock compression during the impact compressing the sample. It causes an additional increase of gas pressure in the closed pores and decreases LECS.

• For porous copper rods with the low initial porosity ($\Delta_{sa} < 20\%$), the values of the current strain $\varepsilon_r(x)$ and average values of ε_{sa} are limited by impact velocity U. The influence of moderate initial porosity on values of strain ε_r and ε_{sa} is in the order of several percent and it can be neglected.

• Current relative density ρ_r/ρ_{sa} of the each porous sample reaches its maximum at the sample's striking end. Subsequently, the density monotonously decreases in a nonlinear way along the sample to its initial value which is reached at the sample rear end.

• Relative density of porous copper ρ_r/ρ_{sa} is a nonlinear function of the LECS ε_r, and considerably depends on two parameters: impact velocity U and initial porosity Δ_{sa}.

• According to the authors' best knowledge, the results presented in the paper have not been published so far in available literature.

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