PROBLEMS OF MECHATRONICS
ARMAMENT, AVIATION, SAFETY ENGINEERING

ISSN 2081-5891 6, 4 (22), 2015, 7-18

Experimental Analysis of Local and Average Dynamic Longitudinal Engineering Compressive Strains in Ductile Porous Rod After the Taylor Direct Impact Experiment

Edward WŁODARCZYK, Marcin SARZYŃSKI*

Military University of Technology, Faculty of Mechatronics and Aerospace,
2 S. Kaliskiego St., 00-908 Warsaw, Poland
**corresponding author, e-mail: marcin.sarzynski@wat.edu.pl*

Manuscript received July 25, 2014. Final manuscript received March 5, 2015

DOI: 10.5604/20815891.1185937

Abstract. The recent experimental method for determining dynamic longitudinal engineering compressive local strain, $\varepsilon_l\,(x)$, (x is Lagrangian coordinate) and average one, ε_a, in a ductile porous rod, plastically deformed by Taylor direct impact experiment (Taylor DIE) is presented in this paper. Analysis of strain distribution, $\varepsilon_l\,(x)$, along axis of the rod was performed by means of this method. There are two essential singularities in this distribution, namely: the first – the maximum compressive strain, $\varepsilon_{l\ max}$, there is in a near of the striking end rod, but it does not locate on the target face; and the second – at high loading (impact velocity), value of the maximum, $\varepsilon_{l\ max}$, decreases together with increasing of initial rod porosity, inversely than at static loading. The values of the strains $\varepsilon_l\,(x)$ and ε_a are limited by the impact velocity U. Influence of the moderate porosity (e.g. for copper – $\Delta_{sa} < 20\%$) on values of the $\varepsilon_l\,(x)$ and ε_a is in the order of several percent and it may be neglected.
Keywords: powder metallurgy technology, porous metals, dynamic strains

1. INTRODUCTION

The Taylor direct impact experiment (Taylor DIE) developed by Taylor [1] is a useful experiment for estimating material behaviour at high strain rates. Circular cross-section bar impacts perpendicularly at the specified speed to rigid, flat plate – target. Followed by, the sample is measured and the dimensions are used to calculate dynamic parameters. The test is reproducible and reasonably economical after the initial investment has been made. That is why the Taylor test has been commonly employed to determine dynamic yield stress of solids at the high strain rate by a lot of researches, namely: Whiffin [2], Lee and Tupper [3], Hawkyard et al. [4], Hawkyard [5], Jones et al. [6], Lu et al. [7], Wang et al. [8], Zhang and Wang [9], Włodarczyk and Sarzynski [10], and others.

However, one ought to take into account that a theoretical model developed by Taylor is based on far-reaching simplifications contradictory to reality. The inexactitudes of this theoretical method have been presented by Włodarczyk and Sarzynski [10].

Among other things, Taylor's theoretical model assumes that the rod material is incompressible. This simplification approximates some properties of solid metals with accuracy sufficient for technical purposes.

The studies presented in this paper are particularly motivated by the recent development of porous materials and their potential applications in impact engineering due to their weight efficiency in strength and high energy absorption capacity. The important feature of a porous material is that its density changes as a compressive strain changes. This is why it is not possible to assume that the porous rod material is incompressible during the Taylor DIE.

In this paper, an attempt was made to apply the Taylor DIE for determining a distribution of a compressive nominal strain in a porous rod deformed during of the impact process. The paper also presents the influence of impact velocity and sinter porosity on the average strain of the rod after the Taylor test.

2. FORMULATION OF THE PROBLEM AND ASSUMPTIONS

The purpose of this paper is to develop an experimental method for determining of the longitudinal local and average compressive engineering strains in a ductile porous rod after the Taylor DIE. The method is presented by means of the porous rod made of sintered copper and loaded by the Taylor DIE. Sintered copper can be used in the defence industry for the production of small arms bullets or liners of shaped charge, therefore knowledge about dynamic parameters of this material is required.

The cylindrical samples for the tests were fabricated by powder metallurgy technology with initial porosity running from 6% to 20%.

The initial porosity of the samples was obtained by measuring the gross weight and volume using the water immersion method. Bearing in mind an influence of the initial porosity, Δ_{sa}, on mechanical properties of the samples after the tests has been discriminated three groups of the porosity characterized by the following medium values: $\Delta_{sa} = (1 - \rho_{sa}/\rho_s) \approx 7\%$, 12%, and 17%, where ρ_{sa} is the average density of the sample; ρ_s is the density of the solid copper.

The electrolytic powder of the copper (ECu1) was used for preparing the compacts (green samples). The size of the powder grain is equal to 40 μm. The powder was compacted by isostatic pressing under various pressures from 100 to 300 MPa. The sintering of the compacts was carried out by means of the sintering furnace into the atmosphere of dissociated ammonia during the three stages: 0.5 h, 300°C; 0.5 h, 650°C and 1 h, 950°C. The final cylindrical samples were precisely machine – made of the copper sinters. All specimens had the same nominal dimensions, namely: the length $L \approx 60$ mm and the diameter $D \approx 12$ mm. Subsequently, before the impact experiment, length of each sample was divided into elements, $\Delta x_0 \approx 5$ mm by indented nicks on the side surface specimen. The nicks had the dimensions: width ≈ 0.35 mm, and depth ≈ 0.1 mm. Thus, the prepared samples were loaded by the Taylor DIE. In turn, after the test, one ought exactly to measure the lengths of the each one of the deformed elements, $\Delta x_e\,(x_i)$, of the sample, where x_i is the given suitable value of the Lagrangian coordinate, x, aligned with the axis of the rod and having origin on the striking end of the rod.

The longitudinal engineering compressive local strain is determined by definition formulae, i.e.:

$$\varepsilon_l(x_i) = \frac{\Delta x_0 - \Delta x_e(x_i)}{\Delta x_0} = 1 - \frac{\Delta x_e(x_i)}{\Delta x_0} \tag{1}$$

Alike, the longitudinal engineering compressive average strain is determined by a definition formula, namely:

$$\varepsilon_a = \frac{L - L_f}{L} = 1 - \frac{L_f}{L} \tag{2}$$

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

The presented method bases on the following assumptions:

1) We are considering a short flat-ended cylindrical rod (projectile) striking a flat rigid target at a normal angle with the initial velocity U.
2) The rod is made of a ductile porous sinter with the moderate initial porosity ($\Delta_{sa} < 20\%$).
3) The pore size of the rod material is much smaller than the diameter of the rod, hence the material of the rod can be treated as a continuum. This assumption is recommended by Lu et al. [7].

3. ANALYSIS OF DISTRIBUTION OF THE DYNAMIC LONGITUDINAL COMPRESSIVE RUNNING NOMINAL STRAIN IN DEFORMED POROUS COPPER ROD AFTER THE TAYLOR DIE

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

Table 1. The example of the distribution of the ratio $\rho_{ia}(x_i)/\rho_{sa}$ along sample length: $\rho_{ia}(x_i)$ 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
$\rho_{ia}(x_i)/\rho_{sa}$	1.00	0.98	1.00	0.99	1.00	1.01	0.99	0.99	0.99	0.99	0.98	1.01
$1 - [\rho_{ia}(x_i)/\rho_{sa}]$ %	0	2	0	1	0	1	1	1	1	1	2	1

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

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

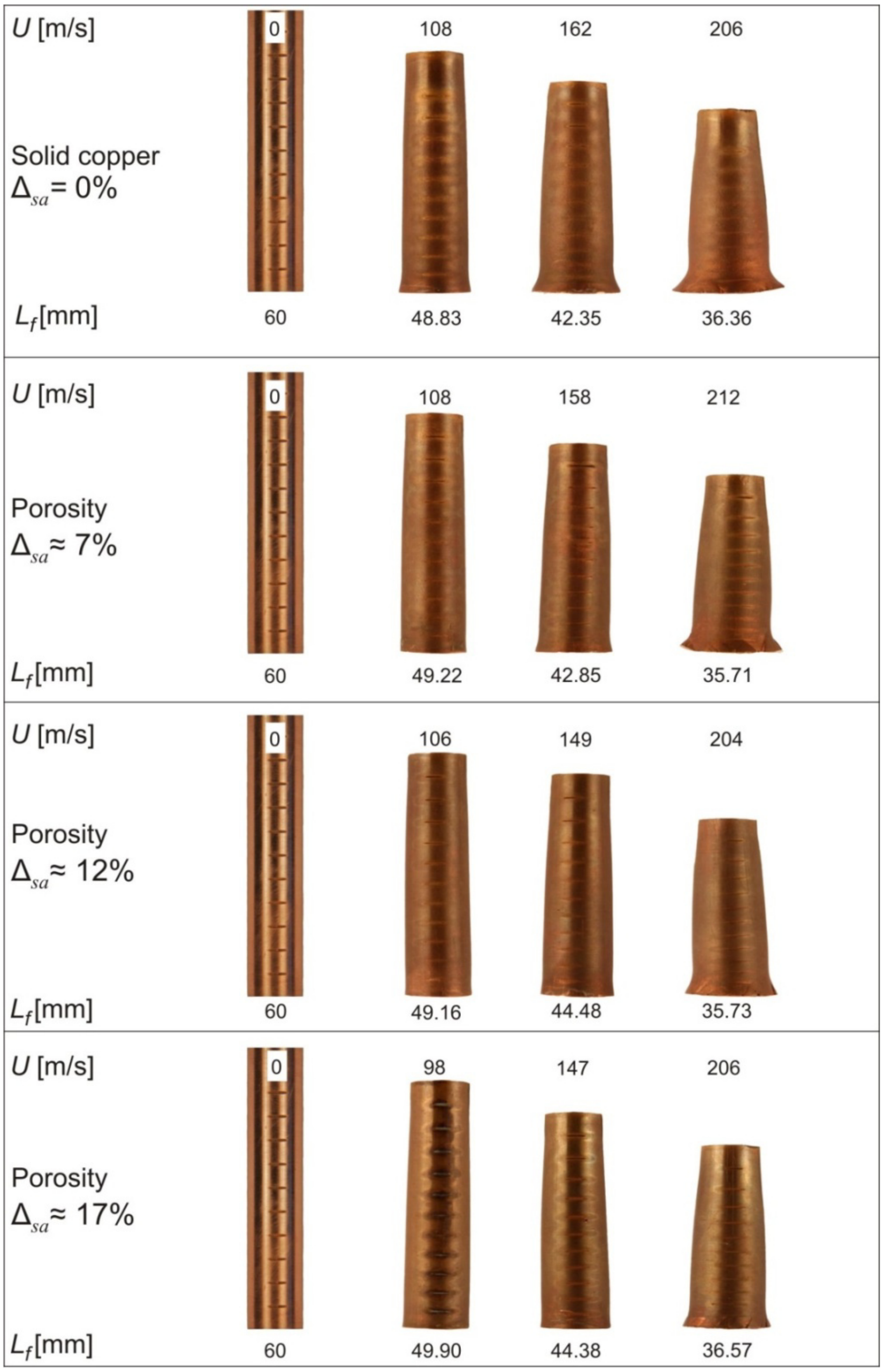

Fig. 1. Pictures of deformed samples

Table 2. The discrete distributions of the magnitudes: $\Delta x_e(x_i)$ and $\varepsilon_l(x_i)$ in the plastically deformed copper samples after the Taylor DIE

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
Solid copper $\Delta_{sa} = 0$	U = 108 [m/s]	$\Delta x_e(x_i)$	3.78	3.64	3.81	3.86	3.89	3.98	4.01	4.15	4.25	4.42	4.55	4.64
		$\varepsilon_l(x_i)$	0.26	0.27	0.24	0.23	0.22	0.20	0.20	0.17	0.15	0.12	0.08	0.02
	U = 162 [m/s]	$\Delta x_e(x_i)$	3.00	2.55	2.91	3.20	3.22	3.35	3.50	3.63	3.82	4.07	4.42	4.69
		$\varepsilon_l(x_i)$	0.42	0.49	0.42	0.36	0.36	0.33	0.30	0.27	0.23	0.19	0.13	0.02
	U = 206 [m/s]	$\Delta x_e(x_i)$	2.68	1.76	2.11	2.53	2.78	2.85	2.95	3.12	3.42	3.76	4.16	4.41
		$\varepsilon_l(x_i)$	0.48	0.65	0.58	0.49	0.44	0.43	0.41	0.37	0.32	0.25	0.15	0.05
Porosity $\Delta_{sa} = (1 - \rho_{sa}/\rho_s) \approx 7\%$	U = 108 [m/s]	$\Delta x_e(x_i)$	3.60	3.70	3.79	3.83	3.88	3.96	4.05	4.20	4.30	4.46	4.66	4.91
		$\varepsilon_l(x_i)$	0.26	0.26	0.24	0.23	0.22	0.21	0.19	0.16	0.14	0.11	0.07	0.01
	U = 158 [m/s]	$\Delta x_e(x_i)$	3.08	2.87	3.11	3.21	3.28	3.44	3.56	3.65	3.97	4.13	4.48	4.80
		$\varepsilon_l(x_i)$	0.37	0.43	0.38	0.36	0.34	0.31	0.29	0.27	0.20	0.17	0.10	0.00
	U = 212 [m/s]	$\Delta x_e(x_i)$	2.44	2.01	2.28	2.57	2.64	2.70	2.81	2.97	3.20	3.57	4.12	4.73
		$\varepsilon_l(x_i)$	0.49	0.60	0.54	0.48	0.47	0.46	0.44	0.40	0.36	0.29	0.17	0.02
Porosity $\Delta_{sa} = (1 - \rho_{sa}/\rho_s) \approx 12\%$	U = 106 [m/s]	$\Delta x_e(x_i)$	3.72	3.65	3.78	3.78	3.86	3.96	4.01	4.12	4.23	4.43	4.70	4.85
		$\varepsilon_l(x_i)$	0.25	0.27	0.24	0.24	0.23	0.21	0.19	0.18	0.15	0.11	0.06	0.01
	U = 149 [m/s]	$\Delta x_e(x_i)$	3.15	3.07	3.25	3.31	3.33	3.43	3.57	3.76	3.91	4.34	4.63	4.88
		$\varepsilon_l(x_i)$	0.34	0.38	0.35	0.34	0.34	0.31	0.28	0.25	0.21	0.14	0.07	0.01
	U = 204 [m/s]	$\Delta x_e(x_i)$	2.57	2.20	2.32	2.55	2.59	2.76	2.82	2.95	3.12	3.52	4.04	4.52
		$\varepsilon_l(x_i)$	0.48	0.56	0.54	0.49	0.48	0.45	0.43	0.41	0.37	0.29	0.19	0.05

Table 2. (*continuation*) The discrete distributions of the magnitudes: $\Delta x_e(x_i)$ and $\varepsilon_l(x_i)$ in the plastically deformed copper samples after the Taylor DIE

Porosity $\Delta_{sa} = (1 - \rho_{sa}/\rho_s) \approx 17\%$	U = 98 [m/s]	$\Delta x_e(x_i)$	3.50	3.72	3.77	3.83	3.93	4.00	4.10	4.25	4.45	4.63	4.81	4.90
		$\varepsilon_l(x_i)$	0.28	0.26	0.25	0.23	0.21	0.20	0.18	0.15	0.11	0.07	0.04	0.00
	U = 147 [m/s]	$\Delta x_e(x_i)$	3.03	3.04	3.20	3.23	3.33	3.40	3.59	3.71	4.00	4.29	4.68	4.83
		$\varepsilon_l(x_i)$	0.39	0.39	0.36	0.35	0.33	0.32	0.28	0.26	0.20	0.14	0.06	0.01
	U = 206 [m/s]	$\Delta x_e(x_i)$	2.54	2.27	2.42	2.59	2.66	2.77	2.77	2.98	3.22	3.58	4.15	4.74
		$\varepsilon_l(x_i)$	0.48	0.55	0.52	0.48	0.47	0.44	0.44	0.41	0.36	0.28	0.16	0.03

The experimental data, $\Delta x_e(x_i)$, obtained by a precise measurements of the deformed marked elements of the samples post-impact, and results of $\varepsilon_l(x_i)$ calculated by means of formula (1) for several values of the porosity at suitable of the impact velocities are listed in Table 2. The analogous results obtained for the solid copper (Cu-ETP) are placed in Table 2 too. They are with comparative background for the results of the porous copper. In turn, the values of the impact velocity mentioned in Table 2 determine the level of dynamic load of the given sample during the test. These velocities one may approximate by means of the following average values: $U \approx 100$ m/s, $U \approx 150$ m/s and $U \approx 200$ m/s.

After interpolation of the discrete values of the local strain, $\varepsilon_l(x_i)$, listed in Table 2, the three sets of the curves $\varepsilon_l(x)$ were obtained which are depicted in Fig. 2. The principal parameter which separates the sets of the curves is the impact velocity, U. As the impact velocity U increases, the strain $\varepsilon_l(x)$ as well increases in the all range variation of the Lagrangian coordinate x, approximately proportionally to the U, independently from the initial average porosity of the samples.

We can see two essential singularities in the distribution of the longitudinal engineering compressive strain $\varepsilon_l(x)$. The first phenomenon is that the maximum this strain, $\varepsilon_{l\,max}$, is located not directly on the contact surface but at some distance from it. This peculiar phenomenon is caused by the friction force which there is on contact target face with a sample. The friction force together with radial inertial one decreases the radial outflow of the material of the sample element which contacts with a target face. This is due to increasing thickness of this element in relation to neighbourhood one. Thus, in agreement with formula (1), the compressive strain ε_l of this element decreases as a result of working friction force. For that reason, the strains of the elements non contacting with a target face are larger than $\varepsilon_l(0)$. In the theoretical limiting case, when friction force goes to infinity, the strain $\varepsilon_l(0)$ tends to 0. Figure 2 clearly shows the presented phenomenon.

From graphs depicted in Fig. 2 it follows that for largest impact velocity ($U \approx 200$ m/s) which generated greatest friction force in considered case, the border strain $\varepsilon_l(0)$ is essentially smaller than the $\varepsilon_{l\,\max}$ and location of maximum strain is most distant from a target face. On the contrary, for $U \approx 100$ m/s (small friction force) we obtain $\varepsilon_l(0) \approx \varepsilon_{l\,\max}$, as might be expected.

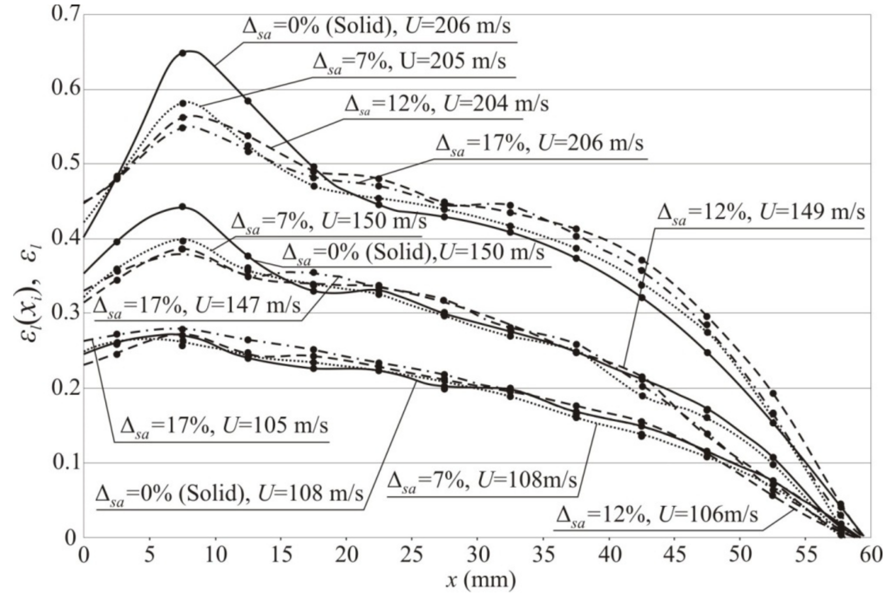

Fig. 2. Interpolation curves $\varepsilon_l(x)$ versus Lagrangian coordinate x in the samples with different initial porosity after the Taylor DIE for the selected group of the impact velocity U

The published theoretical model of the Taylor DIE does not take into consideration this phenomenon so far. Due to the presented in available literature, the maximum strain, $\varepsilon_{l\,\max}$, is located on the striking end of the sample ($x = 0$, Fig. 3). As it can be seen, it is contradictory to reality.

One ought to take notice that the applied size grid at a division of the sample does not change the character of the strain distribution, on the contrary it has influence on a value of the $\varepsilon_{l\,\max}$ and its distance from a target face.

The second interesting phenomenon is that the maximum value of the strain, $\varepsilon_{r\,\max}$, at high dynamic loading (high impact velocity), considerably decreases as increases the initial porosity of the sample material (see Fig. 2), inversely than at static loading. This is probably due to the shock heating of gas in pores during impact experiment. This heating induces additional pressure increase in closed gas, and effectively decreases the sample deformability.

On the contrary, if the sample was compressed quasi-statically, then the gas closed into the pores was compressed according to isotherm and in such thermodynamic state facilitates the deformability of the sample. In this case, the $\varepsilon_{l\,\max}$ increases as the initial porosity of the sample material increases too [8].

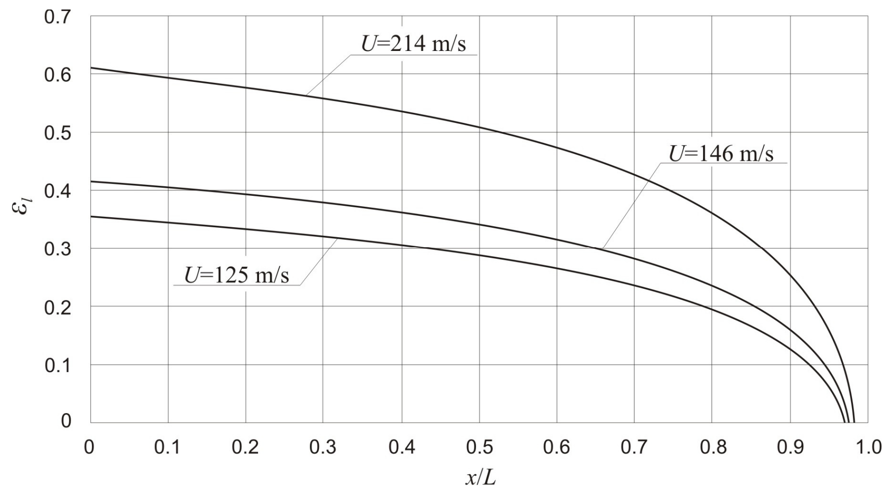

Fig. 3. Theoretical distribution of the compressive running strain ε_l in the solid copper rod after Taylor DIE, without taking into consideration the friction force [3, 10]

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

Likewise, the average strain, ε_a, is limited by the impact speed. For the porosity $\Delta_{sa} < 20\%$, practically is not dependent on it (see Table 3).

Table 3. The values of the average nominal strain of the copper samples after the Taylor tests

Solid copper			$\Delta_{sa} \approx 7\%$			$\Delta_{sa} \approx 12\%$			$\Delta_{sa} \approx 17\%$		
U [m/s]	L_f [mm]	ε_a	U [m/s]	L_f [mm]	ε_a	U [m/s]	L_f [mm]	ε_a	U [m/s]	L_f [mm]	ε_a
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

4. FINAL CONCLUSIONS

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

- On the basis of the Taylor DIE it was developed the recent simple experimental method (model) for determining the longitudinal engineering compressive local, ε_l, and average, ε_a, strains in a ductile porous rod, plastically deformed by an impact loading. Formula (1) defines the longitudinal compressive strain along the rod axis versus the Lagrangian coordinate x. The advantage of this method is that experimental data for formulae (1) are obtained in whole range of the variable x_i of the given single sample loaded by the Taylor DIE.
- It was revealed by means of this model that the maximum of the longitudinal strain, $\varepsilon_{l\ max}$, is not on the contact plane between the rod and target surface, as it is published in the present available literature, but it occurs in the cross-section of the rod placed in a neighbourhood of the target. This singularity is caused by the friction force on rod-target contact surface. This force together with radial inertial force limits a radial outflow of the rod material in the neighbourhood of the target.
- Furthermore, it was found that the maximum value of the longitudinal compressive strain, $\varepsilon_{l\ max}$, at high loading (high impact velocity) decreases while the initial porosity of the sample increases, inversely than at static loading. As it has been stated before, the reason of this phenomenon is the shock heating of a gas closed into the pores during impact compressing of the sample, which leads additional pressure increasing in pores.
- In the copper rods with the moderate initial porosity ($\Delta_{sa} < 20\%$), the values of the local strain and the average one are limited by the impact velocity, U. Influence of the moderate porosity on values of the parameters ε_l and ε_a is in the order of several percent and it may be neglected.
- The results of this paper have applicable and cognitive significance. According to the best knowledge, the results presented here have not been published so far in the available literature.
- The method presented in this paper allows us to determine, in the closed form, the dynamic relationship between the current density of the deformed rod and its longitudinal compressive local strain. Further work is in progress in order to develop this relationship.

Acknowledgements

Special acknowledgments are due to Prof. Jacek Janiszewski and PhD Michał Grązka for great help in carrying out the experiments.

REFERENCES

[1] Taylor G.I., The use of flat-ended projectiles for determining dynamic yield stress, I. Theoretical considerations, *Proc. Roy. Soc., Series a*, 194, London, pp. 289-299, 1948.

[2] Whiffin A.C., The use of flat-ended projectiles for determining dynamic yield stress, II. Tests on various metallic materials, *Proc. Roy. Soc., Series a*, 194, London, pp. 300-322, 1948.

[3] Lee E.H., Tupper S.J., Analysis of plastic deformation in a steel cylinder striking a rigid target, *J. Appl. Mech. Trans. ASME*, 21, pp. 63-70, 1954.

[4] Hawkyard J.B., Eaton D., Johnson W., The mean dynamic yield strength of cooper and low carbon steel at elevated temperatures from measurements of the mushrooming of flat-ended projectiles, *Int. J. Mech. Sci.* 10, pp. 929-948, 1968.

[5] Hawkyard J.B., A theory for the mushrooming of flat-ended projectiles impinging on a flat rigid anvil, using energy consideration, *Int. J. Mech. Sci.* 11, pp. 313-33, 1969.

[6] Jones S.E., Muadlin P.J., Foster J.C., An engineering analysis of plastic wave propagation in the Taylor test, *Int. J. Impact Eng.*, 19, 2, pp. 95-108, 1997.

[7] Lu G., Wang B., Zhang T., Taylor impact test for ductile porous materials – Part 1: theory, *Int. J. Impact. Eng.*, 25, pp. 981-991, 2001.

[8] Wang B., Zhang T., Lu G., Taylor impact test for ductile porous materials – Part 2: experiments, *Int. J. Impact Eng.*, 28, pp. 499-511, 2003.

[9] Zhang E., Wang B., On the compressive behaviour of sintered porous coopers with low to medium porosities – Part I: Experimental study, *Int. J. of Mechanical Sciences*, 47, pp. 744-756, 2005.

[10] Włodarczyk E., Sarzyński M., Analysis of dynamic parameters in a metal cylindrical rod striking a rigid target, *Journal of Theoretical and Applied Mechanics (JTAM)*, 51, 4, pp. 847-857, 2013.