COMPARISON ANALYSIS OF COCKROFT – LATHAM CRITERION VALUES OF COMMERCIAL PLASTICINE AND C45 STEEL

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Abstract: The paper presents and compares the results of theoretical and experimental research in the field of cracking of model material (commercial plasticine) and C45 steel in hot forming conditions. The aim of the research was to determine the limit values of the Cockroft-Latham integral for both materials. The presented research methodology includes experimental tests (tensile tests) and numerical simulations carried out in the DEFORM-3D program. For laboratory tests, axially symmetric samples made of C45 steel and model material were used. On the basis of the obtained experimental and numerical results, a comparative analysis of both materials was carried out.

Key words: Physical Modelling, Cockroft-Latham Criterion, Plasticine, C45 Steel

1. INTRODUCTION

Solid elements obtained in metal forming processes are often subject to certain limitations. These limitations include material cracking occurring during its plastic working. These cracks are often invisible to the human eye, but have a very negative effect on the final product. The safety of people and things depends on the location, size and propagation of cracks. The paper (Antolik, 2014) presents the method of detecting cracks in finished elements and the impact of cracks on the user's safety.

There are two ways to break materials, they are brittle and ductile. In papers (Altan et al., 1996; Arikawa and Kakimotoa, 2014; Charoensuk et al., 2017, Cockroft and Latham,1968; Gontarz and Piesiak, 2010; Lis et al., 2018;Pires et al., 2016), the authors described the most common type of cracking method in hot plastic parts - ductile fracture. Plastic cracks occur as a result of the formation of cracks and necking of the matrix. In the case of non-metallic materials, the role of gaps is played by voids and gas bubbles created as a result of material production.

Currently, simulation programs (numerical) are the most frequently used tools to predict the place and type of cracks. This method is based on numerical modeling, it consists of replacing the actual model with a discrete model. The discrete model, on the other hand, is composed of a finite number of elements and nodes. The paper (Gontarz and Winiarski, 2015) presents a method of using computer simulations for testing and analysis of the process of extrusion of hollow elements with a movable sleeve.

Numerical methods allow obtaining results for elements with complicated shapes, where numerical calculations are often impossible. Computer simulations are characterized by the ease of testing. The main limitation of the numerical method is the uncertainty of the obtained results.

Another method used for researching and analyzing the process of plastic forming is physical modeling. Physical modeling is a method that facilitates the analysis and testing of technological processes.

The idea of physical modeling is to replace the real material with a model material. Model materials are divided into two groups: a group of metallic materials (including tin, lead, sodium) and a group of non-metallic materials (including plasticine, wax, resin). More information on model materials is presented in articles (Bylya, Davey and Krishnamurthy, 2017;Kowalczyk, 1995; Mizuno and Komori, 2009; Pater and Wojcik, 2017). This technique is based on four main criteria of similarity: similarity of flow curves for real and model material, similarity of friction conditions, similarity of tool shape and similarity of process kinematics.

In the scientific literature, the results of experimental research (Asai and Kitamura, 2014; Moon and Van Tyne, 2000; Rasty and Sofuoglu, 2000) have been presented many times to determine the mechanical properties of materials used for physical modeling of the hot forming of metal. In the laboratory analyzes, the subject of cracking of model materials was omitted.

In this work, it was considered useful to carry out research on the determination of the limit value of the Cockrofta-Latham integral for commercial plasticine and hot-formed C45 steel

Standardized Crockroft-Latham criterion determines well the moment of the cracking of the extended material, in which necking and next its plastic splitting take part.

According to the standard Cocroft-Latham criterion, the crack occurs when the value of integral (1) exceeds a certain value of C. The constant C is determined separately for each material under specific conditions, the appropriate temperature and strain rate.

$$\int_0^{\varphi^*} \frac{\sigma_1}{\sigma_m} d\varphi = \mathrm{C} \qquad (1)$$

where: σ_m – mean stress, σ_1 – the greatest main stress, φ^* – limiting deformation of cracking, C – fixed material

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2. MATERIAL AND TESTS METHODOLOGY

The model material used for the research is commercial plasticine based on white and black wax, while C45 steel was used as the real material.

Plasticine is a model material belonging to non-metallic materials. The exact chemical composition of the used plasticine is not known for the patent protection of the finished product. Plasticine is a mixture of clays, oils, waxes and coloring pigments.

The plastic mass used was previously subjected to plastometric tests, the procedure and the results of the tests were presented in the paper (Lis, Pater and Wójcik 2016). Plastometric tests showed high sensitivity to changes in temperature and deformation rate.

Fig. 1 shows a summary of the flow curves for the studied plasticine in the temperature range from 0 to 20˚C with a flow curve obtained for C45 steel shaped at 1150˚C.

The commercial plasticine used for the model tests is described by two constitutive equations (depending on the color), the white plasticine is described by equation (2), while equation (3) describes the black plasticine.

To determine the limit value of the Cockroft-Latham integral, experimental and numerical studies were carried out.

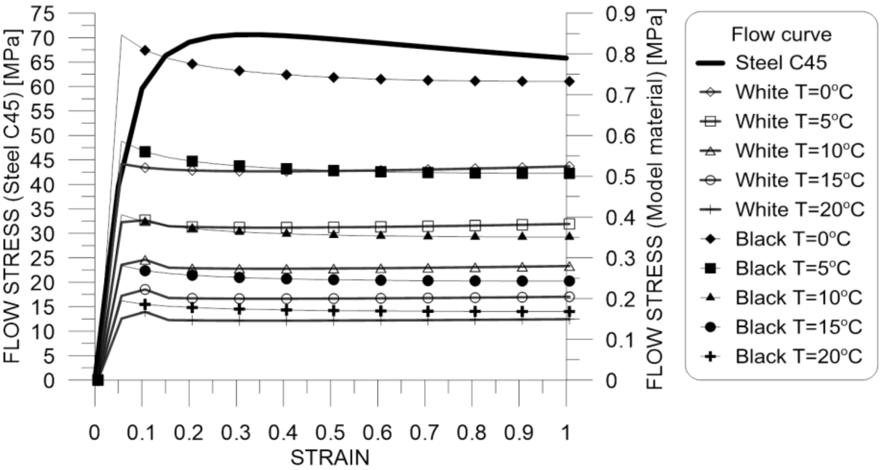

Fig.1. Flow curves for plasticine and C45 steel

$$\sigma_{pl} = 0.48057 \cdot \varepsilon^{-0.0313} \cdot \exp(0.087 \cdot \varepsilon) \cdot \dot{\varepsilon}^{(0.245-0.0026 \cdot T)} \cdot \exp(-0.0328 \cdot T) \quad (2)$$

$$\sigma_{pl} = 0.6817 \cdot \varepsilon^{-0.0711} \cdot \exp(0.072 \cdot \varepsilon) \cdot \dot{\varepsilon}^{(0.2701-0.003 \cdot T)} \cdot \dot{\varepsilon}^{(0.245-0.0026 \cdot T)} \cdot \exp(-0.07358 \cdot T) \quad (3)$$

where: σ_{pl}– yield stress [MPa], ε – equivalent strain, $\acute{\varepsilon}$ – strain rate [s^{-1}], T – sample temperature [°C].

2.1. Experimental tests

Experimental tests used to determine the limiting value of the Cockroft-Latham integral of the model material were carried out on an Instron 3369 testing machine. This machine is characterized by a maximum load of 50 kN. The measuring stand allows the measurement of force with an accuracy of ± 0.5% of the obtained value. The measuring device allows registering the movement of the slider and force as a function of time.

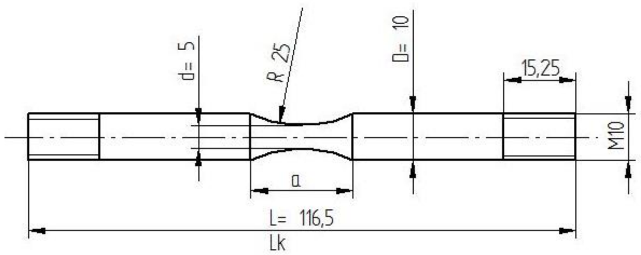

Fig. 2. The shape and dimensions of the sample used for testing (threaded parts refer to samples made of C45 steel

Axial symmetrical samples with constriction were used for experimental tests. The shapes of the samples have been repeat edly described in the articles (Bariani et al., 2014;Derpenski, et al., 2018;Eivani et al., 2018; Fu et al., 2011; Fuertes et al., 2015). The geometrical dimensions of the sample are shown in Fig.2.

In total, 15 plasticine samples of each color were used for experimental tests.

In the papers (Altan and Vazquez, 2000;Assempour et al., 2012;Assempour and Razi, 2003; Cherkashina and Mazur, 2012; Galan and Perig, 2017), the authors presented many different methods for the preparation of test samples. Based on the analysis of these methods, the following procedure for the generation of loads was adopted.

The first stage of sample preparation for experimental tests was heat treatment of plasticine billets supplied from the manufacturer. This treatment consisted of heating the plasticine to the temperature of about 30-35°C. The next step was multiple manual reworking of the material. The use of this operation allowed to get rid of the air bubbles created as a result of production. The presence of bubbles negatively affects the quality of the final sample.

In the next stage, cylindrical bodies were shaped, which were later subjected to the extrusion process, as a result of which a rod with a diameter of 10 mm was obtained.

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The obtained rod was then divided into 120 mm long samples. Samples were made by cross-wedge rolling. After the rolling, the samples were cut according to the dimensions shown in Fig.2. The samples were measured and their dimensions are listed in table 1.

In the last part of the preparations, samples from the model material were cooled to temperatures 0, 5, 10, 15, 20˚C for a period of 24 hours; this selected time allowed to obtain the same temperature in the entire sample volume.

Prepared samples for experimental research are shown in Fig. 3.

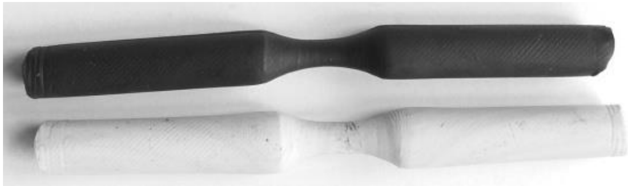

Fig. 3. Samples made of plasticine, used for experimental research

Tab.1. Parameters of samples from model material used for stretching (markings according to Fig. 2)

No.	T [˚C]	D [mm]	d [mm]	a [mm]	L [mm]	L_k [mm]	ΔL [mm]
White Plasticine							
1		9.96	4.65	21.7	100.1	105.2	5.1
2	0	10.19	4.54	21.3	100.5	105.3	4.8
3		10.21	4.60	21.5	100.7	105.1	4.4
1		10.1	4.7	20.9	100.7	106.5	5.8
2	5	10.2	4.65	21.1	100.8	106.4	5.6
3		10.4	4.68	21.6	100.7	105.3	4.6
1		10.15	4.64	21.5	100.3	106.7	6.4
2	10	10.06	4.58	21.7	100.5	107.9	7.4
3		10.21	4.69	21.7	100.5	107.2	6.7
1		10.18	4.85	20.9	100.5	109.3	8.8
2	15	10.3	4.73	21.8	100.3	107.7	7.4
3		10.28	4.78	21.7	100.7	108.6	7.9
1		10.13	4.91	21.8	100.6	108.0	7.4
2	20	10.18	4.75	21.9	100.9	109.9	9.0
3		10.2	4.73	21.2	101	110.2	9.2
Black Plasticine							
1		10.10	4.80	21.3	100.7	104.7	4.0
2	0	10.23	4.99	21.4	100.4	104.8	4.4
3		10.28	5.00	21.2	100.3	104.8	4.5
1		10.26	5.02	21.5	100.4	105.9	5.5
2	5	10.23	4.94	21.6	100.6	105.4	4.8
3		10.21	4.90	21.4	100.3	105.9	5.6
1		10.11	4.97	21.5	100.7	106.5	5.8
2	10	10.19	4.92	21.6	100.4	106.8	6.4
3		10.14	4.96	21.6	100.6	106.6	6.0
1		10.20	5.01	22.2	100.8	107.7	6.86
2	15	10.10	4.94	21.9	100.4	107.1	6.68
3		10.30	5.02	21.8	100.5	107.2	6.68
1		10.18	4.94	21.4	100.2	108.0	7.84
2	20	10.20	4.90	21.9	100.6	108.3	7.72
3		10.20	4.93	21.3	100.9	108.7	7.82

In order to properly fix the sample in the jaws of the testing machine, special inserts were designed and printed to enable it to be accurately captured in Fig.4.

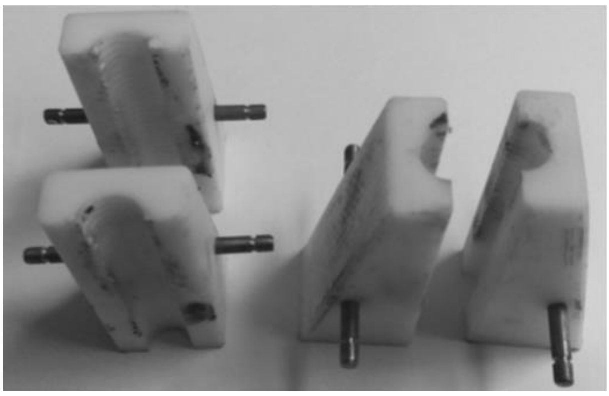

Fig. 4. Sample mounting inserts in a testing machine

The tensile test of samples made of model material proceeded according to the following scheme: cooling samples in a laboratory refrigerator to the test temperature (0, 5, 10, 15, 20˚C) for 24 hours, then stretching with a jaw movement speed of 5 mm/s until breaking, removing the sample.

During the tests, the force and displacement were measured, which corresponded to the displacement of the bar of the testing machine.

Experimental tests of stretching of samples made by machining from C45 steel were carried out in the Gleeble 3800 simulator located at the Faculty of Materials, Process and Applied Physics Engineering at the Częstochowa University of Technology (Fig.5).

The Gleeble 3800 simulator has the following parameters:

– movement speed: up to 2000 m/s,
– maximum pressure: 20 MG,
– heating speed: up to 1000°C/s,
– maximum temperature: 1700°C,
– a resistance heating system for samples,
– tests at reduced pressure or protective atmosphere.

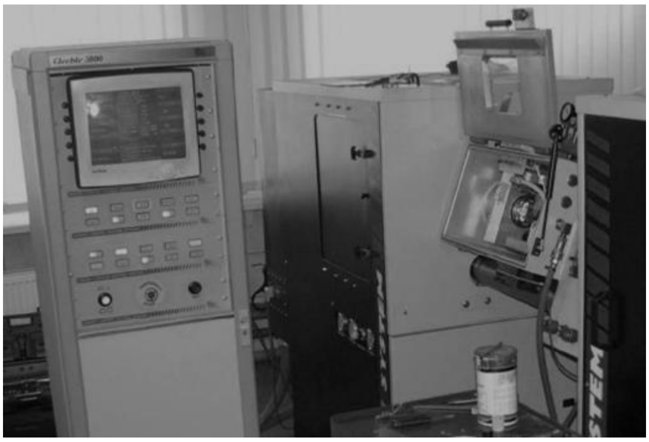

Fig. 5. Physical simulator Gleeble 3800, used in experimental research

Samples of identical shape and geometry as samples made of model material were used for the tests (Fig. 1). The samples were made by machining methods. 12 samples were used for experimental tests, three samples for each temperature

(900°C, 1000°C, 1100°C and 1200°C). The samples were measured and their dimensions are shown in Table 2.

Tab.2. Parameters of samples from, used for stretching (markings according to Fig. 2)

No.	T [°C]	D [mm]	d [mm]	a [mm]	L [mm]	L_k [mm]	ΔL [mm]
1	900	10.25	5.25	22.46	116.6	120.4	3.8
2		10.00	5.00	22.48	116.9	121.1	4.1
3		10.00	5.00	21.86	117.5	121.3	4.4
1	1000	10.05	5.14	22.35	116.5	120.2	3.7
2		10.00	5.00	22.31	116.4	120.4	4.0
3		10.03	5.02	21.73	116.2	120.9	4.7
1	1100	10.13	5.02	22.00	116.4	120.9	4.5
2		10.02	5.00	21.67	116.9	121.7	4.8
3		10.00	5.05	21.91	116.7	120.2	3.5
1	1200	10.15	5.08	22.38	116.5	120.5	4.0
2		10.00	5.00	22.28	116.7	120.7	4.0
3		10.05	5.01	21.97	116.5	121.3	4.8

Fig. 6 presents a set of samples made of C45 steel, used for experimental research.

Fig. 6. A set of samples made of C45 steel used for experimental research

Experimental tests of stretching of C45 specimens were carried out according to the following procedure: heating samples at 10°C/s to test temperature (900°C, 1000°C, 1100°C and 1200°C), withstanding at the target temperature for a period of 5 days s, stretching with the speed of movement of the jaw5 mm / s until it ruptures, removing the sample.

During the tensile test, the force, displacement and temperature of the material in the constriction were recorded.

After the completion of experimental tests carried out on samples made of plasticine and C45 steel, the broken samples were inspected (Fig.7-8)

Fig. 7. View of plasticine samples broken on a testing machine

Fig. 8. View of C45 steel samples broken in a tensile test using the Gleeble 3800 simulator at 1 - 900˚C, 2 - 1000˚C, 3 - 1100˚C, 4 - 1200˚C

2.2. Numerical calculations

To determine the limiting value of the Cockroft-Latham integral, the computer program DEFORM 3D was used. The numerical calculation methodology of the DEFORM 3D program uses the finite element method. The simulation program used has 13 different criteria implemented to determine the occurrence of cracks in the shaped material. Among the criteria available in the program is the normalized Cockroft-Latham criterion.

The standardized Cockroft-Latham criterion was chosen for its popularity in specialized FEM programs for the analysis of plastic forming of metals.

Numerical analysis was carried out for the process of stretching samples made of model material (commercial plasticine) and carbon steel C45.

The results of previous experimental studies were used for numerical studies.

In computer simulations, the geometry of the samples used for experimental studies was modeled in accordance with the geometrical parameters listed in Tab. 1-2.

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In order to facilitate the computer simulation, the computer models of the samples were redesigned so that the virtual grips could be mounted (Fig.9). The shape of the ends of the samples does not affect the results, because during stretching the deformations are located in the necking area.

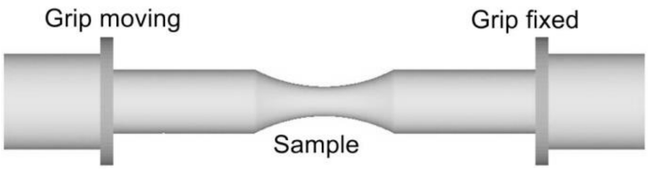

Fig. 9. Sample and mounting system in DEFORM-3D

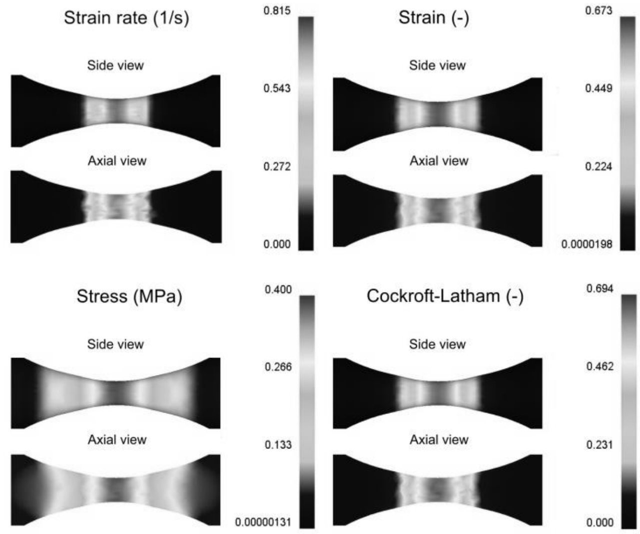

Fig.10. Distributions of intensity of strain rate, strain, stress and failure criterion for model material (white plasticine, T=0˚C)

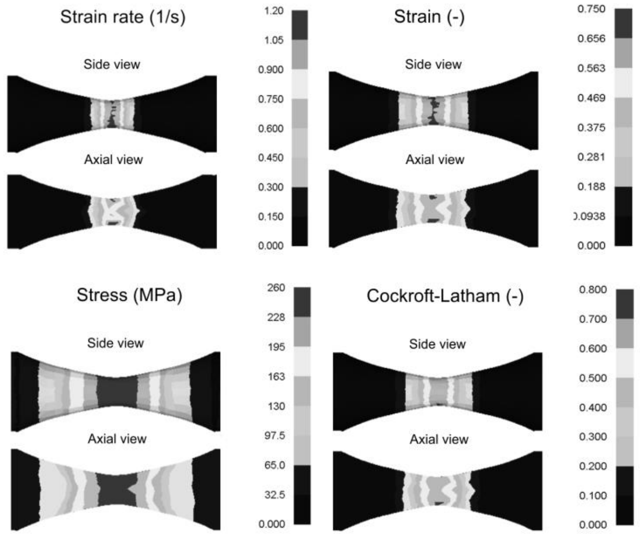

Fig. 11. Distributions of intensity of strain rate, strain, stress and failure criterion for the C45, T=900˚C

For the purpose of computer simulations, it was necessary to model 3D samples which models were imported into the DEFORM 3D solver. The samples prepared in this way were covered with a MES mesh with four-node elements (150,000 items). The material was modeled with a plastic model.

In the tensile calculations of C45 steel samples, a material model was taken from the library of the applied software. However, in the case of model material, own models developed and presented in the paper were used (Lis, Pater and Wójcik, 2016).

The tensile speed and the temperature according to the experimental parameters were adopted for numerical calculations.

Computer simulations allowed to accurately trace the stretching of the sample and determine the forces and maps of strains, stresses, strain rates and the Cockroft-Latham integral.

The use of necking has achieved its goal, for it forced the plastic deformation to be localized here. In the place of necking, the intensity of stress takes the largest values. Then the stresses reach the value of plasticizing stress, and the material suffers permanent deformations (Fig. 10-11).

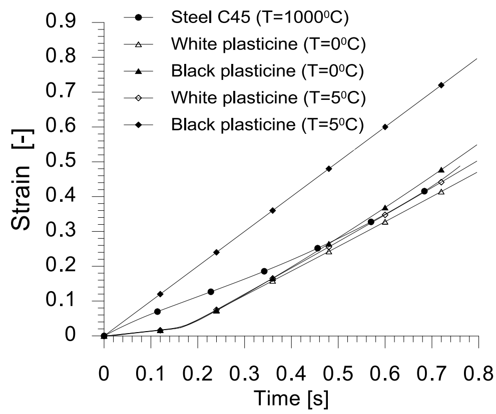

Fig. 12. Change in strain value during elongation of samples

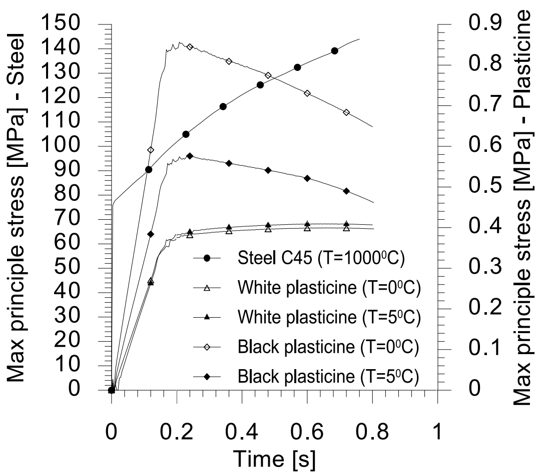

Fig. 13. Change in maximum values of main stresses during elongation of samples

Drawings Fig.12. and Fig. 13 show graphs of the change in strain value and maximum main stresses at a point located on the sample axis in the middle of its length.

The above maps obtained as a result of numerical research were presented, among others, distribution of the Cockroft-Latham integral in the samples subjected to the tensile test. The largest values of the Cockroft-Latham integral were observed in places of necking. Hence, there should be a violation of the consistency of the material. Assuming that the end of the simulation

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was the moment in which the sample was broken from the distribution, the value of the boundary integral can be determined.

3. RESULTS

Based on experimental tests and numerical simulations, limit values for the Cockroft-Latham integral (C) for the model material and C45 steel were determined. These values are developed and presented in Tab. 3 and Tab. 4.

Tab. 3. Limit values of Cockrofta-Latham determined for the model material - plasticine

Temp.	No.	Type	Limit values of Cockrofta-Latham determined	
			Attempt	Average
0˚C	1	White	0.694	0.646
	2		0.661	
	3		0.584	
	1	Black	0.627	0.691
	2		0.697	
	3		0.749	
5˚C	1	White	0.868	0.786
	2		0.838	
	3		0.652	
	1	Black	1.180	1.134
	2		0.921	
	3		1.300	
10˚C	1	White	1.150	1.27
	2		1.450	
	3		1.210	
	1	Black	1.120	1.250
	2		1.480	
	3		1.150	
15˚C	1	White	1.500	1.377
	2		1.280	
	3		1.350	
	1	Black	2.100	2.037
	2		2.010	
	3		2.000	
20˚C	1	White	1.230	1.453
	2		1.530	
	3		1.600	
	1	Black	1.970	2.000
	2		2.210	
	3		1.820	

Based on the analysis of the obtained results of the model material, the limit value of the Cockroft-Latham integral has been stigmatized along with the increase in temperature (tab.3). The C values for the temperature range 0 ÷ 15˚C change in the range of 0.646÷1.453 for white material and 0.691÷2.037 for black material.

Tab. 4 shows the limit values of the Cockroft-Latham integral for C45 steel. The data in this Fig. shows that C values vary with temperature.

The limit value of the Cockrofta-Latham integral (C) for the entire temperature range (900°C-1200°C) of the hot forming of C45 steel is C_{gr}=0.756±0.125.

Tab. 4. Limit values of Cockrofta-Latham determined for C45 steel

Temp.	No.	Limit values of Cockrofta-Latham determined	
		Attempt	Average
900˚C	1	0.778	0.849
	2	0.917	
	3	0.853	
1000˚C	1	0.572	0.682
	2	0.645	
	3	0.829	
1100˚C	1	0.864	0.765
	2	0.870	
	3	0.563	
1200˚C	1	0.673	0.726
	2	0.664	
	3	0.842	

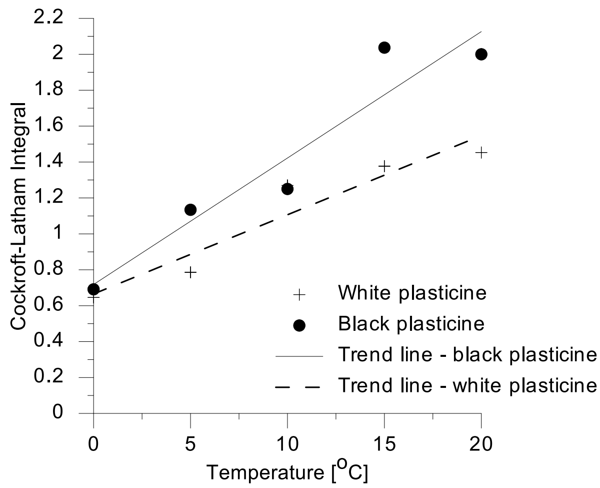

Fig. 14. Limit value of the Cockroft-Latham integral for model materials (commercial plasticine), depending on the temperature

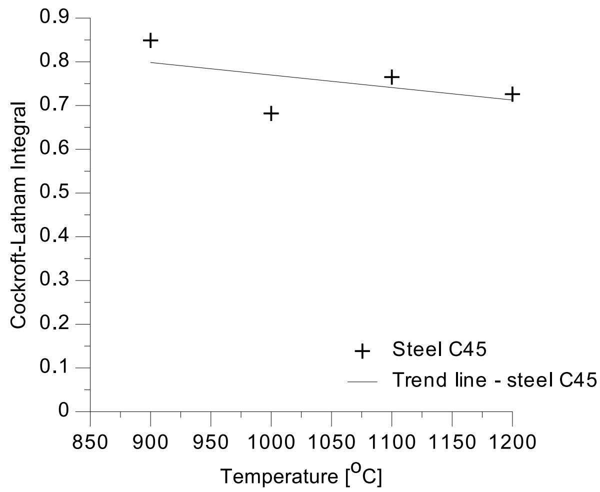

Fig. 15. Limit value of the Cockroft-Latham integral for C45 steel, depending on the temperature

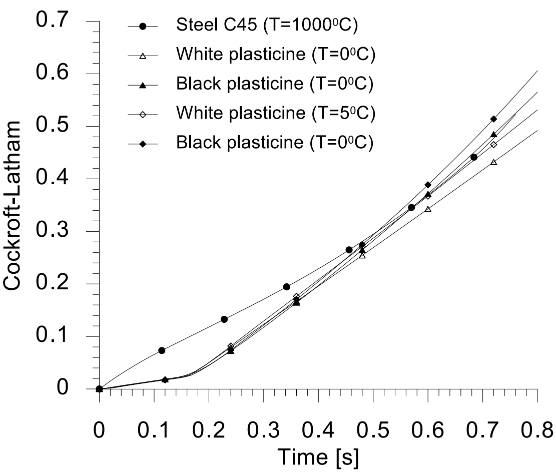

Fig. 16. Change of the Cockroft-Latham integral when elongating samples

Figs 14 and 15 show the average values of the Limits of Cockroft-Latham (C) as a function of temperature. The C trend line for individual materials was also determined on these charts.

The resulting trend lines are described by the following equations:

Black plasticine:

$$\mathrm{C} = 0.718 + 0.07T \quad (3)$$

White plasticine:

$$C = 0.665 + 0.44T \quad (4)$$

where: C– limit value of the Cockroft-Latham integral, T– sample temperature [°C].

Fig. 16 shows the change in the value of the Cockroft-Latham integral for samples with the most approximate integral values between the material model and the hot-shaped C45 steel

4. SUMMARY

The paper presents the methodology and results of research aimed at determining the limit value of the Cockroft-Latham integral (C) for the model material (commercial plasticine - two colors) and for hot-formed C45 steel.

The used research method is based on experiments and numerical stretching process. The use of cylindrically shaped samples with constriction allowed to initiate the crack in a predicTab. place.

The limit values of the C-L integral for model materials increase linearly with the temperature increase, while for C45 units, the C values decrease slightly as the temperature rises.

The results of laboratory and numerical tests of the model material and steel of the C45 grade, hot-worked, were compared with each other.

Similarly, the results of the limit value of the Cockroft-Latham integral for heat treated C45 steel at 900°C-1200°C with white plasticine worked in the temperature range of 0°C to 5°C and with black plasticine molded at 0°C were observed. The C values for C45 steel in this temperature range oscillate between 0.849÷0.726. The limit value of the Cockroft-Latham integral for white plasticine processed in the temperature range of 0°C-5°C is 0.850÷0.646 and for black plasticine at 0°C it is equal 0.691.

The conducted research allowed to conclude that it is possible to use white plasticine with a temperature of 0°C-5°C and black at 0°C as a model material for physical examination of hot forming of C45 steel in the field of material cracking modeling.

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