Arch. Metall. Mater. **69** (2024), 4, 1293-1302

DOI: https://doi.org/10.24425/amm.2024.151392

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PHYSICAL MODELLING OF CROSS-WEDGE ROLLING OF BALL STUDS

The publication presents and reviews the results of a physical modelling study of the Cross Wedge Rolling process of ball-studs. The ball-studs was formed in a double system from C45 steel at 1050°C, while the physical modelling process was performed on a scale of 1:2.5 using Primo plasticine as the model material, which was formed at 5°C. For the real tests, steel tools were used, while for the model tests the tools were made of ABS plastic. The experimental tests were followed by measurements of the individual stud steps. The geometrical analysis of the specimens showed that the model material allowed the shape of the forging obtained in the rolling process to be accurately modelled. Based on the physical modelling studies of the Cross Wedge Rolling process of ball-studs, it was concluded that the ball-studs rolling process can be modelled using PRIMO plasticine. Based on the analysis of the physical modelling results obtained, it was concluded that physical modelling allows the Cross Wedge Rolling process to be modelled with a high convergence of the results obtained in real and physical tests.

Keywords: Plasticine; PRIMO; CRW; Cross wedge-rolling; Ball studs

1. Introduction

Cross Wedge Rolling is one of the most popular basic methods for forming products with axisymmetric geometries. The Cross Wedge Rolling process is characterised by tools in the form of rolls or flat plates, which have a wedge-shaped forming blank on their surface [1].

Cross Wedge Rolling allows the forming of axisymmetric products with a high surface quality and high accuracy of shape of the formed component. Products obtained by Cross Wedge Rolling process can be used as forgings in subsequent forming processes or as the final product for subsequent machining.

Cross Wedge Rolling with roll tools and Cross Wedge Rolling with flat tools are the most commonly used rolling methods. In the case of roll-rolling with roll-shaped tools, the tools are characterised by the alignment of the roll rotation axes in one plane, where the rolls, rotating in the same direction, shape the product. In contrast, in the post-roll rolling process with flat wedge tools, the tools perform a linear motion relative to each other, where the lower tool may remain stationary or move at the same speed as the upper tool. The direction of movement of the tools is the same while the direction of return is opposite [2].

Limitations of Cross Wedge Rolling processes include uncontrolled sliding of the shaped material between the wedge tools, narrowing of the stepped steps and the formation of axial cracks in the workpiece [3-9].

Metal forming processes can be studied in the laboratory as well as by computer; FEM simulation methods are very often used for computer studies. The design of metal forming processes is a difficult and time-consuming issue. Difficulties limiting the optimisation of metal forming processes are: complex experimental investigations, which are often possible to carry out under industrial conditions; high tooling production costs, which generate high costs if the designer makes a mistake. Therefore, methods are sought that facilitate the design of metal forming technology by eliminating testing in an industrial environment with real materials. Methods of modelling and simulation of metal forming processes allow testing of metal forming processes under laboratory conditions, without the need for industrial machinery and equipment [5,10-14].

FEM simulation consists of replacing a real element with a discrete model, which is then used for numerical calculations. Numerical methods are characterised by their ease of testing. However, the computational accuracy depends on the correct assumption of the boundary conditions of the process under investigation and on the software capabilities of the software, e.g. in many programmes there are problems with the simulation of the separation process of shaped elements.

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Physical modelling, on the other hand, has a number of advantages, including lower testing costs, shorter testing times, the ability to observe the process as it unfolds and the ability to perform tests under laboratory conditions. Despite the advantages, physical modelling also has several disadvantages, such as contact stresses that are difficult to estimate, time-consuming preparation of specimens for testing and difficulties in measuring the resulting products due to the softness of the modelling materials [4,6,9,15].

Physical modelling is one of the simulation methods used in metal forming. It is a method that facilitates the analysis of material flow, stress distribution and metal forming processes. Physical modelling consists of replacing the real material with a model material that maintains predefined similarity criteria: similarity of material flow curves, similarity of friction conditions, similarity of tool shape, similarity of shaping kinematics and similarity of thermal processes [6,8,16-20].

Modelling materials are divided into two groups: materials for modelling shaped parts and materials used to make modelling tools (steel, non-ferrous metals, glass, plastics, wood, gypsum, etc.). Tools used for modelling billets can be divided into two subgroups: metallic modelling materials (aluminium, lead, sodium, etc.) and non-metallic modelling materials (resins, natural waxes, synthetic waxes, cellulose, plasticine, etc.) [8,21,22].

Analysing the available literature, it was observed that physical modelling simulations are most often used to model extrusion and forging processes, while longitudinal and skew rolling processes are analysed to a much lesser extent.

The first physical modelling studies of forging processes were used as early as the 1920s, where the precursors of physical modelling studies were Massey and Holquist [23,24]. From 1980 onwards, more and more research results on simulation physical modelling of forging processes have been published. In 1986, Boer [25] investigated the physical modelling of the forging process of a turbine blade by modelling the real material, a nickel alloy, with FIMO plasticine. Subsequently, in the following years, individual research teams investigated physical modelling of forging processes – research team Takemaus (1996) [26], Vazquez (1996) [27], Yuli (2000) [28], Fujikawa (2000) [29], Zhan (2001) [30], Assempour, Razi (2002) [31], Gronostajski (2008) [32], Hosseini Ara (2018) [33].

Studies on physical modelling of extrusion processes have been conducted by, among others: Ravn (2001) [34] , Sofouglu (2004) [35], Kazanowski (2004) [36] and Zhou (2018) [37], Hawryluk (2019) [38].

Cross Wedge Rolling processes were modelled in the 1960s by Awano and Danno [39]. Only in recent years have the problems of modelling this process been taken up by Komorii, Zhou, Wójcik and Pater, among others. Komori [40] and Zhou [41] analysed the significance of the Mannesman effect, while Wójcik and Pater analysed Cross Wedge Rolling processes of products such as balls and stepped shafts [39,42,43].

This paper undertakes an analysis of the physical modelling of the Cross Wedge Rolling process of ball-stud in a dual system. The results obtained from the physical modelling process were validated against those obtained from the real Cross Wedge Rolling process. Cross Wedge Rolling of ball-stud was described in their works by Tomczak, Pater, Bulzak [44-47]. The processes of shaping studs under hot, hot and cold forming conditions with various rolling methods were numerically and laboratory analysed.

2. Aims and methodology

The paper presents a physical modelling process for Cross Wedge Rolling of a ball stud, which was then verified in a real laboratory testing process. The main objective of the research was to analyse the possibility of using physical modelling as one of the simulation methods for the Cross Wedge Rolling process. The surface quality and shape geometry of the products obtained, as well as the qualitative and quantitative similarity of the shaping force, were adopted as the main comparative parameters.

The axially symmetrical ball-stud type element shown in Fig. 1 was used for the tests.

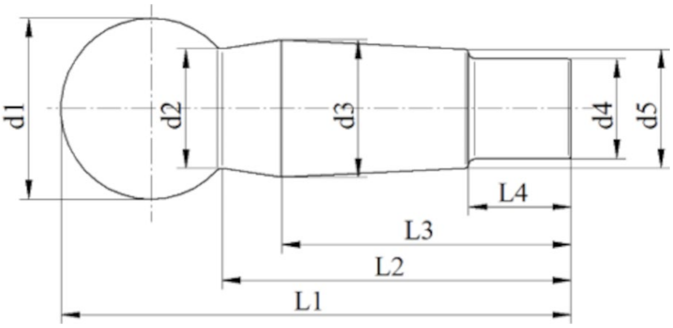

Fig. 1. Geometrical diagram of the product specimen analysed

In order to stabilise the process, process symmetry was introduced by using a dual configuration of the test product (spherical parts facing each other coaxially).

Model tests were carried out on a specially designed laboratory stand, which was built on the basis of the chain-drawing machine shown in Fig. 2.

Fig. 2. Model cross-wedge rolling machine: 1 – data acquisition device, 2 – AXIS force measurement sensor, 3 – physical modelling module, 4 – chain drawing machine

An additional module was designed and constructed to simulate the real machine (Fig. 3) on a scale of 1:2.5. The stand allows the linear speed of the tools to be modified (from 0 to 150 mm/s) and was equipped with a force measurement sensor (AXIS FC1K) shaping with a maximum measurement range of 1 kN.

The real Cross Wedge Rolling machine used for the lab tests is shown in Fig. 3. The rolling machine has a constant tool speed of 300 mm/sec, and is equipped with a forming cylinder pressure sensor to analyse the variation of the forming force of the rolling process

Fig. 3. Real cross wedge rolling machine, scale 1:1

For the physical modelling of the Cross Wedge Rolling process of an axisymmetric ball-stud type product, white and black commercial plasticine from the model product manufacturer PRIMO was used. The model material used was to model C45 steel formed hot at 1050°C.

The plasticine used is a commercial model material produced on the basis of synthetic waxes with additional materials such as clays, oils and colour pigments. The model tools, on the other hand, were produced using the FDM 3D printing method. The material used to manufacture the tools is ABS plastic.

In the previous stages of research, the plastometric and strength properties of the model material, a white and black commercial plasticine from the manufacturer PRIMO, were analysed; in addition, the friction conditions between the model material and the 3D-printed ABS tools and the value of the Cockroft-Latham fracture criterion function were investigated. In the next stages, preliminary studies were carried out to model the formation of the Mannesmann effect.

3. Materials

For the physical modelling of Cross Wedge Rolling, a modelling material based on synthetic waxes – PRIMO commercial plasticine – was used. A modelling material in two colours, white and black, was selected to model hot-rolled steel. The plasticine used in the study was supplied in the form of billets weighing approximately 0.5 kg.

PRIMO Plasticine is a modelling material in which the main ingredient is synthetic wax, while the additional substances, the fillers, are natural clays, oils and colour pigments.

The selected model material was initially tested by plastometric testing. In the course of the research, flow curves were determined for the model materials, the coefficient and friction factor between the model material and the ABS tools were determined, as well as the fracture criterion limits by the Cockroft-Latham criterion. The procedures of the research carried out are presented in the articles.

Physical modelling by using commercial plasticine makes it possible to replace the material of real tools (made of steel) with a model material.

The model material used in the physical tests presented in this paper is non-metallic ABS plastic, which is characterised by high hardness and high resistance to mechanical damage. The model tools were made by 3D printing using FDM technology, which consists of applying layers of molten ABS material, forming the shape of the tool's target geometry.

In order to correctly carry out tests on the selected model material and physical modelling simulations of Cross Wedge Rolling, it was necessary to prepare a procedure for preparing commercial plasticine for model tests. The procedure for preparing the material was developed on the basis of existing methods for preparing plasticine. The author's procedure modified the sample preparation methods developed by Chijiiwa, Segawa, Huang, Shih, Miraseidi, Wong, Sofuoglu and Świątkowski [7,8,47-55].

The most commonly used method of preparing plasticine samples consists of 3 stages: the first stage is the manual processing of the received billets of model material to remove air bubbles, the second stage is the shaping of batches with the appropriate shape, and the third stage is storage for 24 hours at the target test temperature. This method was used in their research by Chijiiwa [10,25], Huang [27], Segawa [26], among others.

Another equally frequently used method is one based on 4 stages, where stage one is a heating process to a temperature of about 40-50°C, stage two consists of repeated kneading, stage three is the making of samples, and in stage four the prepared samples are cooled to room temperature for a period of 24 hours. This method was used by Shih [53] and Mirsaeidi [54], among others.

Another method is a modified first method, which has been used by Wong [30], among others: the first stage is the manual processing of the received billets of model material to remove air bubbles, the second stage is the shaping of batches with the appropriate shape, the third stage is the removal of residual air bubbles by applying vacuum for a period of 24 hours, and in the last stage the samples are stored for 24 hours at the target temperature of testing.

The last method of preparing plasticine samples is based on two stages of heating the material. The sample preparation process used by Sofuoglu [7,13,31] was based on this method: stage one – heating to a temperature of about 40-50°C for a period of 1.5-2 hours, stage two – repeated kneading, stage three – making samples, stage four – heating to a temperature of about 50°C for a period of 24 hours, stage five – cooling to room temperature for a period of 24 hours.

The custom procedure was based on three main stages. The first stage in the preparation of the model material is its manual processing, which consists of multiple processing of the plasticine, preheated to approximately 35°C. This stage allows air pockets, which adversely affect the quality of the material samples, to be eliminated. Air pockets in the form of cavities inside the billet received from the manufacturer are formed during the plasticine production step.

The second stage of the customised sample preparation procedure is the process of forming samples with the target geometry. In this stage, the previously prepared model material is subjected to extrusion or rolling processes to prepare material of homogeneous quality throughout the volume of the billets. The material is then split or shaped according to the shape needed (discs, strips, bars).

The third stage consists of a 24-hour process of cooling the prepared billets to the target temperature for physical testing. A period of 24 hours allows a uniform temperature to be achieved across the billet or sample.

Preliminary plastometric tests were carried out on commercial plasticine PRIMO white and black. Plastometric tests were carried out using the static compression method on cylindrical samples. Based on the results obtained, a constitutive equation was developed to describe the flow curves of the tested materials. The model material was described by Eq. (1):

$$\sigma_p = C\cdot\varepsilon^{(n_1+b_1\cdot T)}\cdot\exp(n_2\cdot\varepsilon)\cdot\dot{\varepsilon}^{(m+b_2\cdot T)}\cdot\exp(a\cdot T) \qquad (1)$$

where: ε – strain [-], $\dot{\varepsilon}$ – strain rate [1/s], T – temperature [°C], C, n_1, n_2, m, a, b_1, b_2 – constant coefficients [-].

TABLE 1

Summary of the coefficients of the functions described by Eq. (1)

	Coefficients						
	C [-]	**n_1 [-]**	**n_2 [-]**	**m [-]**	**a [-]**	**b_1 [-]**	**b_2 [-]**
White plasticine	0,5061	–0,0661	–0,0614	0,2299	–0,0617	0	–0,0017
Black plasticine	0,6952	–0,0582	–0,0327	0,2521	–0,0729	0	–0,0027

Comparing the graphs obtained from the plastometric tests of the model material and the flow curves of C45 steel (Fig. 4), it was observed that the flow curves of PRIMO white and black plasticine show a very high qualitative similarity. This similarity justifies the possibility of using plasticine as a modelling material for hot-formed C45 steel.

In the next stage of preliminary research, strength tests were carried out on the commercial plasticine used as a model material. The tests were carried out using the static tensile method for cylindrical-primary specimens made in accordance with the standard. On the basis of the tests performed, the values of absolute elongation ΔL, relative Ap, relative uniform Ar and relative material constriction Z were determined. Tests on the model materials were carried out at 5°C for three different tensile speeds: 5, 50 and 500 mm/min, the results are shown in TABLE 2.

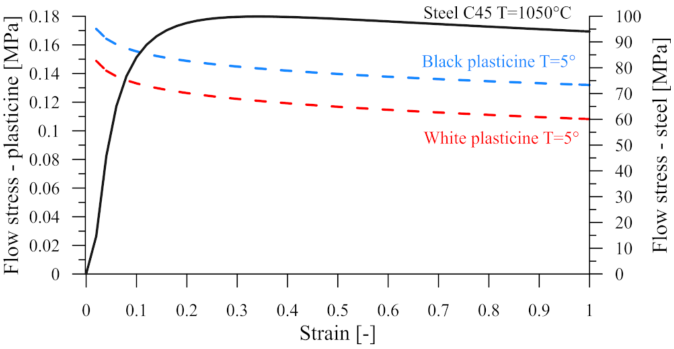

Fig. 4. Graph comparing flow curves of model materials and steel

TABLE 2

Plastic property values of commercial plasticine

Tensile speed [mm/min]	**White plasticine**				**Black plasticine**			
	ΔL [mm]	**A_p [%]**	**A_r [%]**	**Z [%]**	**ΔL [mm]**	**A_p [%]**	**A_r [%]**	**Z [%]**
5	30,60	61,20	27,10	81,51	27,77	55,54	33,03	87,96
50	20,37	40,74	11,51	78,56	17,23	34,46	23,46	76,28
500	18,67	37,34	4,12	73,99	11,63	23,26	18,15	66,01

Next, based on the obtained values of forces as a function of displacement, calculations of the strength Rm of the model materials – PRIMO white and black plasticine – were carried out. Fig. 5 shows a plot of the change in strength of the model materials as a function of change in strain rate. It was observed that the strength of the model materials is sensitive to its change. As the strain rate increases, the strength of the material increases. For the strength tests, three specimen strain rates of 5, 50 and 500 mm/min were used. The use of a constant forming speed makes the strain rate variable and dependent on the instantaneous height of the specimen. Thus, the strain rate representing the measurement at a given forming speed was taken as the arithmetic mean value, determined according to the formula:

$$\dot{\varepsilon} = \frac{1}{n}\sum_{i=1}^{n}\frac{v}{h_i} \qquad (2)$$

where: v – linear speed of the swelling tool [mm/min], h_i – instantaneous sample height [mm].

The next step was to determine the friction coefficient between the model material and the ABS tools. A method based on the Amontons-Coulomb hypothesis was used to determine the coefficient of friction.

Before deciding on this method, tests were attempted using other methods: cone forming anvil swaging, ring swaging and cylinder swaging. The conical anvil method was eliminated due to the problematic nature of the tooling, i.e. at the angles of the cones used, the 3D printed ABS tools had a conical surface that did not match the similarity requirements of the tools used in

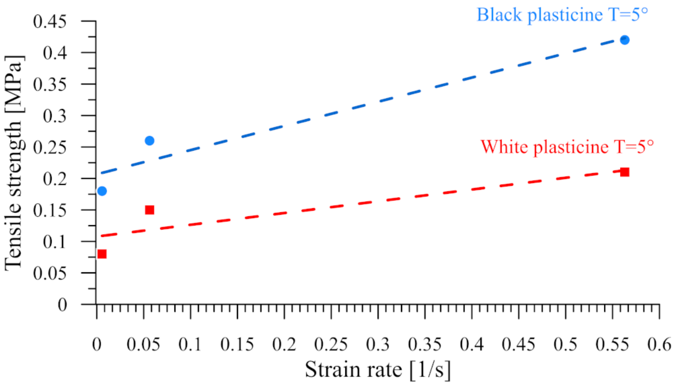

Fig. 5. Tensile strength of model materials – commercial plasticine

physical testing, and it proved problematic to remove material from the tools without deforming the specimen. The cylinder and ring swaging method was also eliminated due to the large deformation of the deformed specimen when removing them from the tools to take their measurements. Therefore, the best method was the Amontons-Coulomb law method, which consisted of sliding a loaded disc-shaped specimen over a flat surface while the pulling force was recorded.

Based on the results obtained, dynamic and static friction coefficient calculations were carried out. The values of the friction coefficients were calculated using the formula:

$$f = \mu \cdot N \tag{3}$$

where: μ – coefficient of friction [-], N – contact force [N].

It was determined from the tests that the best representation of the coefficient of friction of hot steel was achieved using Teflon oil for the model tests. Based on the results, the values of the coefficients and friction factors were determined and are presented in TABLE 3, where the results are compared with the coefficients obtained from the literature for hot-formed steel. It was observed that a model material of the PRIMO commercial plasticine type, shaped with tools printed from ABS plastic, reproduced very well the friction conditions of hot-formed steel with tools made from steel.

The observed difference between the values of coefficients/friction factors between white and black plasticine is due to the chemical composition of 'PRIMO' commercial plasticine. The colour additive of the commercial plasticine significantly influences the values of friction coefficients/factors. The level of plasticising stress for black plasticine is higher than that of white plasticine. At the same time, the coefficient/factor of friction between the material and the tools is lower than for white plasticine. The value of the plasticising stress also influences the adhesion of the material to the tools; despite the use of lubrication, the material adheres more deformational, while black plasticine with its lower adhesion character better retains the lubricating film of the lubricants used.

The final stage of preliminary research was to identify similarities in the formation of the Mannesmann effect. The Mannesmann effect is a phenomenon which consists in the formation of cracks and fissures within a shaped product. The defects usually have the shape of longitudinal axial cracks. The factors that influence the formation of the Mannesmann effect are: cyclically varying compressive and tensile stresses; progressive destruction of material cohesion as a result of low-cycle fatigue; a high level of non-metallic inclusions in the formed material. A customised method for determining the critical value of the damage function, based on rotational compression of a disc in a channel, was used for the study. The method used makes it possible to determine the crack moment resulting from the Mannesmann effect during the compression process.

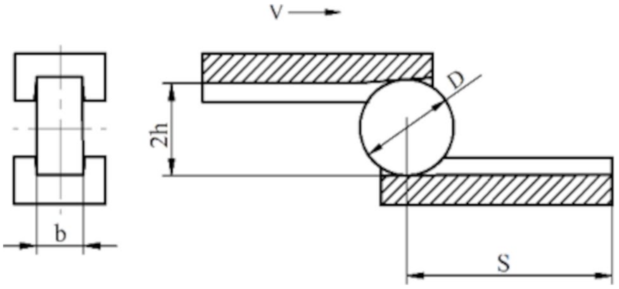

Fig. 6. Diagram of the method rule for rotary compression in a channel

In the test method used, the disc to be shaped is inserted into the shaping channel at a distance S from the end of the lower tool. The upper tool then moves to form the disc from an initial diameter D to a final diameter 2 h. During forming, the bottom tool remains stationary. The lateral walls of the shaping channel prevent axial elongation of the material, so that the specimen is constantly subjected to varying compressive and tensile stresses that favour the formation of axial cracks.

Rotational compression tests were carried out for model materials and hot-formed steel. Model tests on commercial plasticine were carried out at 0, 5, 10, 12,5, 15 and 20°C, while tests on C45 steel were carried out for five temperatures of 950, 1000, 1050, 1100 and 1150°C. Based on the results of the physical tests carried out and the real compression of the specimens in the channel, the limits of the forming distance and the corresponding number of specimen rotations, beyond which internal cracks formed, were determined. Based on the

TABLE 3

Values of coefficients and friction factors

Material	**White plasticine PRIMO**	**Black plasticine PRIMO**	**Steel [5]**			
Lubricant	**PTFE**	**PTFE**	**Without lubricant**	**NaCl salt water solution**	**Soap**	**Graphite in water**
μ	0,42	0,37	Adhesion	0,4	0,3	0,2
m	0,84	0,74	1	0,7	0,5	0,4

results of the experimental tests, the graph shown in Fig. 7 was drawn up, which shows the correlation between the limit value of the number of rotations and the forming temperature. From the graph it is possible to read the forming temperature of the model materials reflecting the cracking of the steel at the selected forming temperatures of the real materials.

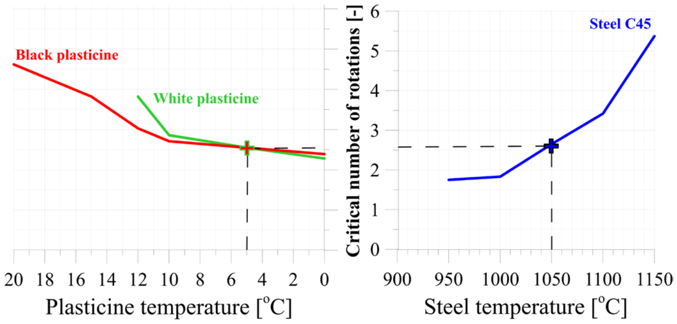

Fig. 7. Graph of the change in the critical value of the limit number of rotations

As a result of the real and model tests carried out, the possibility of using PRIMO white and black commercial plasticine as model materials for physical modelling of the Mannesmann phenomenon by the channel compression method was validated. The results obtained make it possible to determine the process conditions for physical modelling of cross-rolling processes in which cracks resulting from the Mannesmann effect can occur.

4. Methods and results

A ball-stud forging was used for model and real Cross Wedge Rolling tests. The forged stud is made of C45 grade steel rolled at 1050°C. The physical modelling process, on the other hand, was carried out on a scale of 1:2.5 using white and black PRIMO plasticine shaped at 5°C as the modelling material. The temperature for the physical modelling tests was chosen on the basis of an analysis of the graph of the change in the limit number of rotations (Fig. 7), created during tests of the Mannesmann phenomenon obtained from experimental rotary compression tests in the channel of model and real materials. The real tools are shown in Fig. 8, while the model tools (3D ABS printing) are shown in Fig. 9.

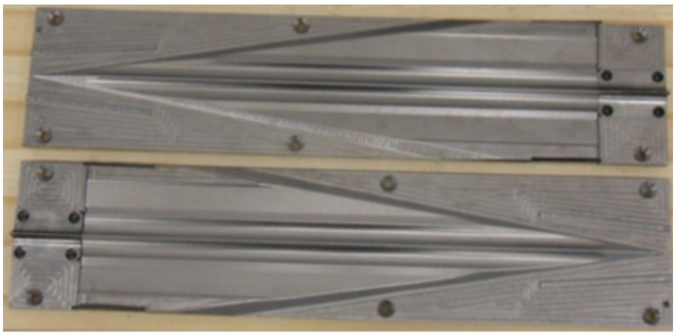

Fig. 8. Real tools used to roll ball-studs

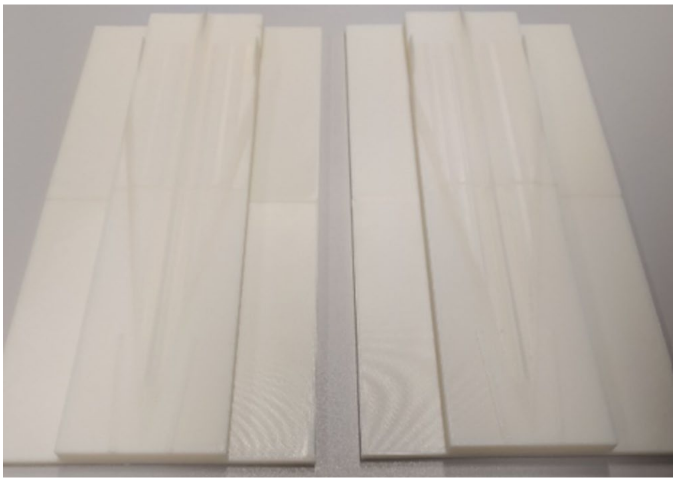

Fig. 9. Model tools used for physical modelling

A billet (made of C45 steel), 28 mm in diameter and 100 mm in length, was adopted for the tests in which hot-formed steel forgings were shaped. The billet used for physical modelling was a bar with a diameter of 11.2 mm and a length of 40 mm. The billet dimensions were scaled up by a value of 2.5. The modelling billet was made according to the author's procedure and finally cooled to a forming temperature of 5°C. Testing was carried out in triplicate for each of the variants analysed, making a total of nine trials. Figs. 10 and 11 show the ball-stud forgings obtained in model and real tests.

Fig. 10. Ball-studs forging produced by a real process

Fig. 11. Ball-stud models (1:2.5) produced during physical modelling

In the next stage of the research, the diameters and lengths of the individual parts of the studs were measured according to the diagram shown in Fig. 1. The values of the measurement results are presented in the form of TABLE 4, in which the average values of the individual forging dimensions are listed.

The analysis of the shape of the samples obtained showed that the model material allows the shape of the forging obtained

TABLE 4

Mean values of geometric shape dimensions based on Fig. 12

Typ	d1 [mm]	D2 [mm]	D3 [mm]	D4 [mm]	D5 [mm]	L1 [mm]	L2 [mm]	L3 [mm]	L4 [mm]
Nominal	29	19	22	16	19	82	56,2	46,6	16,6
White plasticine									
Model	11,34	7,75	8,85	6,27	7,23	32,68	22,66	18,84	6,50
1:1	28,35	19,36	22,11	15,68	18,08	81,70	56,65	47,09	16,25
Black plasticine									
Model	11,25	7,80	8,90	6,28	7,23	32,52	22,58	18,74	6,52
1:1	28,13	19,49	22,24	15,69	18,08	81,30	56,46	46,84	16,30
Steel C45 1050°C									
C45	28,5	18,9	21,3	16,5	18,4	80,9	56,1	46,3	16,1

in the rolling process to be modelled in detail. The dimensions of the forgings obtained from the PRIMO white and black plasticine differ by about 1.9% from the dimensions of the forging obtained in the real process and by about 2% relative to the nominal dimensions. On the surface of the forgings obtained, no significant differences were observed between the model forgings and the real ones. Lines were observed around the perimeter of the conical surface of the forging obtained; these lines are the imprint of the filament path created in the 3D printing process of the tool.

Then, based on the force waveforms recorded during the model tests and the real tests, force diagrams were drawn up as a function of the wedge tool displacement. Fig. 12 shows the plots of the shaping forces for the physical modelling and real tests.

Analysing the obtained diagrams of the forming force curves, a qualitative similarity of the force distribution was observed. All the curves obtained for the individual test variants are characterised by four stages in which the shaping force increases. The first shaping force increase occurs when the shaping tool is plunged into the workpiece material. The second and third areas of force increase occur when the target outline of the rolled forging is shaped, then the force value decreases during calibration. In the last stage of the shaping force value change, the side waste is cut off. It was observed that the maximum forming force for C45 steel at 1050°C reached a value of 47.6 kN. When rolling PRIMO white plasticine, a maximum force of 29.5 N was reached, while for PRIMO black plasticine the maximum value is equal to 43.5 N.

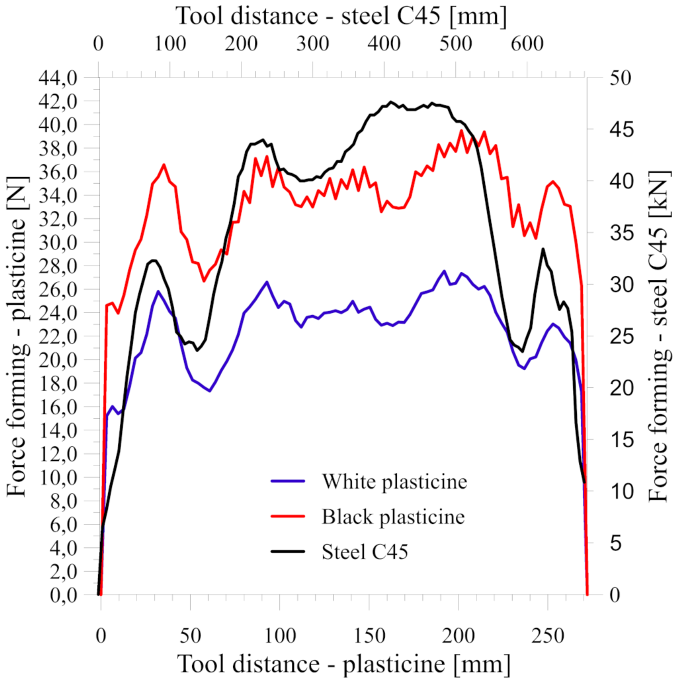

Fig. 12. Forming force diagram during cross wedge rolling of ball-studs

Next, estimates of the value of the real forming force were calculated. The estimation calculations were based on the force values obtained from the physical modelling of the rolling of PRIMO white and black plasticine studs, formed at 5°C. Estimation calculations were carried out using relation (4).

$$F = \lambda F' s^2 \tag{4}$$

where: F' – maximum forming force from model tests [N]; λ – similarity coefficient of plasticity of the model material [-], s – tool scale [-].

To determine estimates of the forming force, it was necessary to determine the similarity coefficient calculated from relation (5).

$$\lambda = \frac{\int_0^1 \sigma_{F\ steel}\, d\varepsilon}{\int_0^1 \sigma_{F\ plast}\, d\varepsilon} \tag{5}$$

where: $\sigma_{F\,steel}$ – plasticising stress of steel [MPa], $\sigma_{F\,plast}$ – plasticising stress of plasticine [MPa].

From the calculations, the similarity coefficient was determined to be 159 for PRIMO black plasticine and 215 for PRIMO white plasticine.

After calculating the estimated forming force values, a graph was drawn comparing the estimated forces with the values obtained in the real process (Fig. 13). Analysing the force curves obtained, it was observed that the maximum estimated forming force for PRIMO white plasticine reached a value of approximately 37 kN, while that for PRIMO black plasticine reached 39.2 kN. The obtained estimated force values are lower than the real value by approximately 27% for PRIMO white plasticine and 18% for PRIMO black plasticine.

A physical modelling study of the ball-studs rolling process concluded that the hot-rolling process of ball-studs can be modelled with PRIMO plasticine used as a model material.

Black PRIMO plasticine was found to be a better modelling material for determining the maximum force of the ball stud forming process, despite the fact that white PRIMO plasticine slightly better modelled the forming process in the first and second rolling stages.

On the basis of studies of selected Cross Wedge Rolling processes (shaping of drive shaft, balls and ball-stud), analysis of the physical modelling results obtained, it was found that physical modelling allows the Cross Wedge Rolling process to be modelled with a high convergence of results (force parameters, shape, defects and quality) obtained in real and physical tests.

5. Conclusions

This paper presents research into the physical modelling of Cross Wedge Rolling using PRIMO commercial plasticine as a modelling material for hot-formed steel. Physical modelling is a simulation method that facilitates the analysis of runs and phenomena occurring during metal forming. The method has a number of advantages, the most important of which include: performing experimental and preliminary studies under laboratory conditions without the need for an industrial environment, reducing the cost of preliminary studies and the possibility of observing shaping during the process.

The theoretical and experimental studies have confirmed that physical modelling using commercial plasticine can be used to analyse the material's flow kinematics and predict the force parameters and constraints occurring during Cross Wedge Rolling of ball-studs.

On the results of the physical modelling and real studies, the following conclusions were concluded:

- Physical modelling using PRIMO commercial plasticine makes it possible to determine estimates of the forming forces occurring during hot forming of steel,
- The material that best modelled the force values turned out to be PRIMO black plasticine – the value of the maximum estimated force was about 18% lower than the actual force, while white plasticine differed by 27%,
- In the case of modelling with PRIMO commercial plasticine, a qualitative similarity in force distribution was observed,
- Physical modelling makes it possible to achieve a high level of conformity of the shapes and dimensions of forgings with respect to those obtained by hot-rolling real steel products.
- The model materials used allow the cross-wedge rolling process to be accurately modelled. The forgings obtained from white plasticine differ from those obtained by the actual process by approximately 1.9%. while forgings made from black plasticine differ by approx. 2%,
- PRIMO black plasticine proved to be a better modelling material for determining the maximum value of the forming course of the pins, despite the fact that white plasticine slightly better modelled the forming course in the first and second rolling stages.

REFERENCES

[1] Ł. Wójcik, Z. Pater, Physical simulation of the Mannesmann effect in the rolling process. Archives of Metallurgy and Materials **64** (4), 1369-1375 (2019).
DOI: https://doi.org/10.24425/amm.2019.130103

[2] G.V. Andreev, L.V. Guzjavicus, E.M. Makusok, V.J. Scukin, Vybor geometričeskich parametrov klinovogo instrumenta. Abrazivnaja Obrabotka i Obrabotka Metallov Rezaniem i Davlenem, 73-76 (1975).

[3] Ł. Wójcik, Z. Pater, T. Bulzak, J. Tomczak, Physical Modeling of Cross Wedge Rolling Limitations. Materials **13** (4), (2020).
DOI: https://doi.org/10.3390/ma13040867

[4] M. Arentoft, Z. Gronostajski, A. Niechajowicz, T. Wanheim, Physical and mathematical modelling of extrusion processes. Journal of Materials Processing Technology **106** (1-3), 2-7 (2000).
DOI: https://doi.org/10.1016/S0924-0136(00)00629-4

[5] L. Kowalczyk, Wydawnictwo instytutu technologii eksploatacji, Modelowanie fizykalne procesów obróbki plastycznej. Radom (1995).

[6] V. Mandic, M. Stefanovic, Physical modeling and FEM simulation of the hot bulk forming processes. Journal for Technology of Plasticity **27** (1-2), 41-53 (2002).

[7] H. Sofuoglu, J. Rasty, Flow behavior of Plasticine used in physical modeling of metal forming processes. Tribology International **33** (8), 523-529 (2000).
DOI: https://doi.org/10.1016/S0301-679X(00)00092-X

[8] K. Świątkowski, Analiza badań modelowych z użyciem materiałów woskowych. Obróbka Plastyczna Metali (5), 5-4 (1994).

[9] T. Wanheim, Trends in physical simulation of metal working processes. Proceedings of the the 4th Cairo University Conference on Mechanical Design and Production Cairo University, 27-28 (1988).

[10] A. Auer, PWN, Modelowanie analogowe procesów o stałych rozłożonych. Warszawa (1976).

[11] Z. Gabryszewski, J. Gronostajski, PWN, Mechanika procesów obróbki plastycznej. Warszawa (1991).

[12] J. Hawryluk, WNT, Maszyna cyfrowa narzędziem człowieka współczesnego. Warszawa (1974).

[13] G.L. Himicz, M.B. Caljuk, Optimizacja reżimow chołodnoj sztampowski.

[14] O.C. Zienkiewicz, Arkady, Metoda elementów skończonych. Warszawa (1974).

[15] V. Vazquez, T. Altan, New concepts in die design – physical and computer modeling applications. Journal of Materials Processing Technology **98** (2), 212-223 (2000).
DOI: https://doi.org/10.1016/S0924-0136(99)00202-2

[16] K. Chijiiwa, Y. Hatamura, N. Hasegawa, Chracteristics of plasticine used in the simulation of slab in rolling and Continous Casting. Transations ISIj **21**, 178-186 (1981).
DOI: https://doi.org/10.2355/tetsutohagane1955.66.5_496

[17] U.M. Ascher, S.J. Ruuth, R.J. Spiteri, Implicit-explicit Runge-Kutta methods for time-dependent partial differential equations. Applied Numerical Mathematics **25** (2-3), 151-167 (1997).

[18] A. Auer, PWN, Modelowanie analogowe procesów o stałych rozłożonych. Warszawa (1976).

[19] H. Sofuoglu, Texas Tech University, Physical modeling of extrusion process. Texas (1990).

[20] K. Świątkowski, R. Cacko, Investigations of new wax-based model materials simulating metal working process. Journal of Materials Processing Technology **72** (2), 267-271 (1997). DOI: https://doi.org/10.1016/S0924-0136(97)00179-9

[21] P.F. Bariani, G. . Berti, L.D'Angelo, R. Meneg, Physical Simulation Using Model Material for the Investigation of Hot-Forging Operations. Advanced Manufacturing Systems and Technology **372**, 347-354 (1996). DOI: https://doi.org/10.1007/978-3-7091-2678-3_4

[22] E. Hossain, C. Ketata, Experimental study of physical and mechanical properties of natural and synthetic waxes using uniaxial compreesive strenth test. Proceedings of the Third International Conference on Modeling, Simulation and Applied Optimization **1-5** (2009).

[23] H.F. Massey, The Flow of Metal During Forging. Proceedings of the Manchester Association of Engineers, 1-3 (1921).

[24] J.L. Holmquist, Investigation of the piercing processes by means of model wax billets. Iron Steel Engineering **29**, 56-65 (1952).

[25] C.R. Boer, N. Rebelo, H. Rydstad, G. Schroder, Springer, Process modeling of metal forming and thermomechanical treatment. Berlin (1986).

[26] T. Takemasu, V. Vazquez, B. Painter, T. Altan, Investigation of Metal Flow and Preform Optimization in Flashless Forging of a Connecting Rod. Journal of Materials Processing Technology **59**, 95-105 (1996). DOI: https://doi.org/10.1016/0924-0136(96)02290-X

[27] V. Vazquez, K. Sweeney, D. Wallace, C. Wolff, M. Ober, T Altan, Tooling and Process Design to Cold Forge a Cross Groove Inner Race for a Constant Velocity Joint – Physical Modeling and FEM Process Simulation. Journal of Materials Processing Technology **59**, 144-157 (1996). DOI: https://doi.org/10.1016/0924-0136(96)02295-9

[28] L. Yuli, D. Kun, Z. Mei, Y. He, Z. Fuwei, Physical modeling of blade forging. Journal of Materials Processing Technology **99**, 141-144 (2000). DOI: https://doi.org/10.1016/S0924-0136(99)00406-9

[29] S. Fujikawa, Application of CAE for Hot-Forging of Automotive Components. Journal of Materials Processing Technology **98**, 176-188 (2000). DOI: https://doi.org/10.1016/S0924-0136(99)00196-X

[30] M. Zhan, Y. Liu, Y. He, Physical Modeling of the Forging of a Blade witha Damper Platform Using Plasticine. Journal of Materials Processing Technology **117**, 62-65 (2001).

[31] A. Assempour, S. Razi, Determination of Load and Strain-Stress Distributions in Hot Closed Die Forging Using the Plasticine Modeling Technique. International Journal of Engineering-Transactions B: Applications **2** (15), 167-172 (2002).

[32] Z. Gronostajski, M. Hawryluk, The main aspects of precision forging. Archives of Civil and Mechanical Engineering **2** (8), 39-55 (2008). DOI: https://doi.org/10.1016/S1644-9665(12)60192-7

[33] R. Hoseini-Ara, P. Yavari, A new criterion for preform design of H – shaped hot die forging based on shape complexity. International Journal Material **11**, 233-238 (2018).

[34] B.G. Ravn, C.B. Andersen, T. Wanheim, Pressure contours on forming dies. Part 1. Simulation using physical modeling technique. Journal of Materials Processing Technology **115**, 212-219 (2015). DOI: https://doi.org/10.1016/S0924-0136(01)00808-1

[35] H. Sofuoglu, H. Gedikli, Physical and numerical analysis of three dimensional extrusion process. Computational Materials Science **31**, 113-124 (2004).

[36] P. Kazanowski M.E. Epler, W.Z. Misiołek, Bi-metal rod extrusion-process and product optimization. Material Science and Engineering A **369**, 170-180 (2004). DOI: https://doi.org/10.1016/j.msea.2003.11.002

[37] W. Zhou, J. Lin, T.A. Dean, L. Wang, Feasibility studies of a novel extrusion process for curved profiles: Experimentation and modeling. International Journal of Machine Tools and Manufacture **126**, 27-43 (2018). DOI: https://doi.org/10.1016/j.ijmachtools.2017.12.001

[38] M. Hawryluk, D. Wilk-Kołodziejczyk, K. Regulski, M. Głowacki, Development of an approximation model of selected properties of model materials used for simulations of bulk metal plastic forming processes using induction of decision trees. Archives of Metallurgy and Materials **64**, 1073-1085 (2019). DOI: https://doi.org/10.3934/matersci.2022020; DOI: https://doi.org/10.24425/amm.2019.129497

[39] T. Awano, A. Danno, Metal flow on rolled shafts – a study of hot hot rolling of stepped shafts part 1. Sosei to Kako (5), 258-295 (1968).

[40] K. Komori, Simulation of Mannesmann piercing process by the three-dimensional rigid-plastic finite-element method. International Journal of Mechanical Sciences **12** (47), 1838-1853 (2005). DOI: https://doi.org/10.1016/j.ijmecsci.2005.07.009

[41] X. Zhou, Z. Shao, C. Zhang, F. Sun, W. Zhou, L. Hua, J. Jiang, L. Wang, The study of central cracking mechanism and criterion in cross wedge rolling. International Journal of Machine Tools and Manufacture **159**, 103647 (2020). DOI: https://doi.org/10.1016/j.ijmachtools.2020.103647

[42] Ł. Wójcik, Z. Pater, T. Bulzak, J. Tomczak, K. Lis, A Comparative Analysis of the Physical Modelling of Two Methods of Balls Separation. Materials **14** (23), 1-20 (2021). DOI: https://doi.org/10.3390/ma14237126

[43] Ł. Wójcik, Z. Pater, Physical analysis of cross-wedge rolling process of a stepped shaft. Advances in Science and Technology Research Journal **11** (4), 60-67 (2017). DOI: https://doi.org/10.12913/22998624/75966

[44] Z. Pater, J. Tomczak, Ł. Wójcik, T. Bulzak, Physical modelling of the ball-rolling processes. Metals **9** (1), 1-14 (2019). DOI: https://doi.org/10.3390/met9010035

[45] T. Bulzak, Z. Pater, J. Tomczak, K. Majerski, Hot and warm cross-wedge rolling of ball pins – Comparative analysis. Journal of Manufacturing Processes **50**, 90-101 (2020). DOI: https://doi.org/10.1016/j.jmapro.2019.12.001

[46] J. Tomczak, T. Bulzak, Z. Pater, Theoretical and experimental analysis of rotary compression of ball pins hollow forgings.

Advances in Science and Technology Research Journal **10** (32), 109-117 (2016).
DOI: https://doi.org/10.12913/22998624/65129

[47] Z. Pater, J. Tomczak, T. Bulzak, S. Martyniuk, A helical wedge rolling process for producing a ball pin. Procedia Manufacturing **27**, 27-32 (2018). DOI: https://doi.org/10.1016/j.promfg.2018.12.039

[48] K. Chijiiwa, Y. Hatamura, T. Suzuki, Experimental method of stress simulation of rolling and continuously cast slab by plasticine. Transaction ISiJ **21**, 502-511 (1981).
DOI: https://doi.org/10.2355/tetsutoh gane1955.66.8_1103

[49] H. Sofuoglu, J. Rasty, Three-Dimensional Analysis of Extrusion Process by Utilizing the Physical Modeling Technique, Journal of Energy Resources Technology. Transactions of the ASME **115** (1), 32-40 (1993). DOI: https://doi.org/10.1115/1.2905967

[50] K. Świątkowski, Badania porównawcze własności materiałów modelowych uzyskiwanych różnymi metodami. Rudy i Metale Nieżelazne **50** (8), 448-451 (2005).

[51] A. Segawa, K. Kawanami, Rolling-deformation characteristics of clad materials determined by model experiment and numerical simulation: experimental rolling tests using plasticine. Journal of Materials Processing Technology **47** (3-4), 375-384 (1995).
DOI: https://doi.org/10.1016/0924-0136(95)85010-4

[52] Z. Huang, M. Lucas, M. Adams, Modelling wall boundary conditions in an elasto-viscoplastic material forming process. Journal of Materials Processing Technology **107** (1-3), 267-275 (2000).
DOI: https://doi.org/10.1016/S0924-0136(00)00705-6

[53] C.-K. Shih, C. Hung, Experimental and numerical analyses on three-roll planetary rolling process. Journal of Materials Processing Technology **142** (3), 702-709 (2003).
DOI: https://doi.org/10.1016/S0924-0136(03)00810-0

[54] M. Mirsaeidi, F. Reza Biglari, K. Nikbin, E. Moazami Goudarzi, S. Bagherzadeh, Optimum forging preform shape design by interpolation of boundary nodes. Proceedings of the World Congress on Engineering **2** (1-3), (2009).

[55] S.F. Wong, P. Hodgson, C.J. Chong, P.F. Thomson, Physical modelling with application to metal working, especially to hot rolling. Journal of Materials Processing Technology **62** (1-3), 260-274 (1996). DOI: https://doi.org/10.1016/0924-0136(95)02219-8