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Effect of volume change on the time required for complete cooling of samples for physical modelling: Commercial plasticine

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ABSTRACT

This article presents the results of experimental studies on the influence of the geometric parameters of a model material on the kinetics of thermo-mechanical processes under physical modelling conditions. Commercial PRIMO plasticine was used as the model material, which, due to its rheological stability and strong temperature dependence of mechanical properties, constitutes an adequate model material used in plastic forming research. The main objective of the study was a quantitative evaluation of the cooling dynamics of cylindrical specimens with varied dimensions D/H = 1 (10–50 mm) and the determination of the effect of volume changes on the values of the average flow stress. As part of the research, static upsetting tests were carried out on an Instron 3369 universal testing machine, applying a constant deformation rate and friction minimisation. The results demonstrated the existence of a strong, nonlinear correlation between specimen volume and the time required to achieve full temperature homogenisation. It was observed that in the initial cooling stage, a rapid increase in flow stress occurs, resulting from intensive heat dissipation. With increasing cooling time, the rate of change decreases, asymptotically approaching an equilibrium state in which mechanical properties stabilise independently of specimen size. A key achievement of this work is the formulation of a predictive mathematical model in the form of a second-degree polynomial function describing the relationship between optimal cooling time and specimen diameter. The high coefficient of determination confirms the reliability of the model in laboratory test optimisation. Empirical data showed that for the specimens with a diameter of 50 mm, the time required for temperature stabilisation exceeds 35 hours, emphasising the importance of the scale effect in the interpretation of physical modelling results. The developed tool allows elimination of errors resulting from thermal inhomogeneity of the material, which directly translates into improved accuracy of physical simulations of forging, rolling, and extrusion processes.

Keywords: model material, physical modelling, plasticine, synthetic wax.

INTRODUCTION

Modern materials industry and manufacturing technologies are subject to increasing requirements in terms of energy efficiency, reduction of production costs, and shortening of the implementation time of new technological solutions. This applies particularly to hot metal forming processes such as rolling, forging, and extrusion, the design of which requires consideration of coupled mechanical, thermal, and tribological phenomena as well as nonlinear material characteristics [1].

Traditional methods of designing metal forming processes, based on empirical technological trials conducted under industrial conditions, are associated with high tooling costs, significant energy consumption, and waste generation. For this reason, they are gradually being replaced by simulation methods, among which mathematical, numerical, and physical modelling play a key role. Numerical methods, such as the finite element method, boundary element method, and finite volume method, have gained particular importance in the analysis of metal forming processes, enabling detailed analysis of stress,

strain, and temperature fields under conditions of complex tool kinematics [2–5]. Despite the dynamic development of numerical methods, their effectiveness remains strongly dependent on the correctness of the adopted material models and boundary conditions. In the case of processes characterised by complex material flow states and large plastic deformations, such as cross-wedge rolling, significant computational uncertainties may occur resulting from discretisation and local solution instabilities [6,7].

A method complementary to numerical simulations is physical modelling, consisting in reproducing the actual technological process on a laboratory scale while maintaining criteria of geometric, kinematic, and dynamic similarity [8]. In the context of hot metal forming processes, similarity of the flow curves of the model material to the rheological characteristics of the real material is of key importance [9,10].

The literature emphasises that correct determination of flow curves of model materials constitutes the basis for reliable physical modelling of metal forming processes. Particular attention is paid to the influence of temperature and deformation history on flow stress values, which should be determined under conditions as close as possible to real technological processes. The plastometric procedures proposed in research studies enable quantitative evaluation of the mechanical properties of model materials and their application in the analyses of forging, rolling, and extrusion processes [34]. An advantage of physical modelling is the possibility of direct observation of material flow, analysis of strain distribution, and identification of potential internal and surface defects, which is often impossible under industrial conditions [11,12].

The materials used in physical modelling are divided into metallic and non-metallic [13]. Low-melting metals such as lead or tin exhibit favourable rheological similarity to steel under hot deformation conditions; however, their toxicity and environmental issues limit their application range [14]. For this reason, non-metallic materials are increasingly used, particularly wax mixtures, polymers, and commercial plasticine [15,16].

Commercial plasticine, being a mixture of mineral and organic components, is characterised by strong temperature dependence of rheological properties, low cost, and easy availability. Studies have shown that in the temperature range of 0–20 °C plasticine behaves as a viscoplastic material, and its flow curves show high qualitative and quantitative similarity to carbon steels deformed at temperatures of 900–1200 °C [10,18–29]. This enables not only analysis of flow kinematics, but also estimation of force parameters of real processes using appropriate similarity coefficients.

At the same time, plasticine, as a material with an organic matrix, is particularly sensitive to preparation conditions and the thermal state of specimens. Structural inhomogeneities, presence of gas inclusions, and temperature gradients may lead to significant discrepancies in mechanical test results [30]. Numerous material homogenisation procedures have been described in the literature, whose common objective is to ensure repeatable rheological properties of specimens [31–33]. A much less frequently analysed issue, however, is the influence of specimen geometry and volume on the kinetics of the cooling process and the time required to achieve a uniform thermal state.

Studies on physical modelling indicate that the geometric scale effect can significantly influence the interpretation of experimental results, particularly in the case of thermo-mechanically coupled processes. Changing specimen dimensions leads not only to differences in heat exchange time, but also to modification of local material flow conditions. The literature emphasises the necessity of considering these effects at the laboratory experiment planning stage to avoid errors resulting from thermal inhomogeneity of the model material [35].

Despite the wide application of physical modelling in metal forming research, the issue of cooling kinetics of model materials and its dependence on specimen geometry is only fragmentarily addressed in the literature. In laboratory practice, arbitrary seasoning or cooling times are often adopted without unambiguous verification of achieving full thermal homogenisation within the specimen volume. This may lead to significant discrepancies in rheological test results and incorrect interpretation of force parameters of the modelled processes.

Therefore, the aim of this study was a quantitative determination of the influence of the diameter of cylindrical specimens made of commercial PRIMO plasticine on the time required to achieve a stable mechanical state at a temperature of 0 °C, and the development of an empirical model enabling determination of the optimal cooling time under laboratory testing conditions.

MATERIAL AND METHODS

In the physical modelling studies, a commercial model material-PRIMO plasticine in a black-coloured version-was used. This material was selected due to the stability of its rheological properties and their pronounced temperature dependence, which enables analysis of thermomechanical phenomena analogous to those occurring during real metal forming processes. Of particular importance is the ability of the material to reproduce changes in flow behaviour as a function of temperature and time, which is crucial when analysing cooling stages after deformation is completed.

The mechanical and plastic properties of the model material, including flow curves, the range of plastic strains, and behaviour under uniaxial and multiaxial loading, have been extensively characterised in the literature and were used as a reference basis for planning the present study [23–28]. This ensured an appropriate level of rheological similarity between the model material and real metallic materials subjected to plastic forming, while the maintaining conditions that allow observation and recording of thermal phenomena on a laboratory scale.

The main objective of the conducted research was to analyse the influence of changes in the volume of the model material on the course of the heat exchange process and the time required for cooling until a uniform temperature throughout the cross-section was achieved. Particular emphasis was placed on determining the relationship between specimen volume and the intensity of heat conduction within the material, as well as the efficiency of heat dissipation to the surroundings.

The analysis of the cooling process accounted for both heat conduction mechanisms within the model material and boundary conditions related to convection and thermal radiation at the material–environment interface. The obtained results enabled evaluation of the influence of the volume-to-cooling-surface ratio on the temperature stabilisation time of the material, which is directly relevant to the correct interpretation of physical modelling results of plastic forming processes. In an industrial context, this issue corresponds to real technological processes, such as bulk forging, rolling, and extrusion, in which changes in the dimensions of the deformed billet significantly affect thermal phenomena and final product properties.

Laboratory physical modelling studies were conducted to quantitatively analyse the influence of changes in the volume of the model material on the course and duration of its cooling process. The scope of work included assessment of the relationship between specimen geometry and heat exchange dynamics under controlled conditions, taking into account long-term thermal exposure. The model material used was commercial PRIMO plasticine in black, based on synthetic waxes with additions of mineral materials, oils, and colouring pigments. This material is characterised by stable rheological properties as well as a pronounced dependence of mechanical and thermal behaviour on temperature, enabling its application in physical modelling studies of phenomena occurring during plastic forming.

Cylindrical specimens with varied volumes were prepared by changing diameter and height while maintaining an approximately constant height-to-diameter ratio (H/D ≈ 1). The following geometric variants were prepared: ϕ10 × 10 mm, ϕ15 × 15 mm, ϕ20 × 20 mm, ϕ25 × 25 mm, ϕ27 × 27 mm, ϕ30 × 30 mm, ϕ40 × 40 mm, and ϕ50 × 50 mm. Three specimens were prepared for each variant to assess repeatability and reduce experimental scatter.

Specimen preparation included preliminary manual processing of the model material, forming rods of specified diameters, and cutting specimens to appropriate heights, followed by seasoning at room temperature for 24 hours to allow relaxation of internal stresses and ensure uniform temperature distribution prior to testing.

Specimen cooling was carried out in a controlled laboratory refrigerator with forced air circulation at a temperature of 0 °C. The temperature inside the chamber was monitored using digital thermometers with probes placed in the immediate vicinity of the specimens. Cooling times were determined based on a previously developed test plan, including short, medium, and long durations to capture the thermal stabilisation phase. This ensured that specimen surface temperature was stable and uniform, and that the influence of heating during mounting in the Instron machine and initial plasticine deformation was minimised.

The uniformity of the thermal state within the specimen was assessed indirectly by observing stabilisation of flow stress values in static compression tests. It was assumed that the absence of further significant changes in flow stress in subsequent tests indicated attainment of

thermo-mechanical equilibrium throughout the specimen volume.

Cylindrical specimens were placed on a grid-type shelf to ensure free airflow around the entire surface and uniform heat transfer, over a wide range of cooling times from 1 to 2340 minutes. This allowed analysis of both short-term and long-term heat exchange processes and assessment of the influence of specimen volume on cooling kinetics across different time intervals.

In parallel with thermal studies, mechanical property tests of the model material were performed using an Instron 3369 universal testing machine equipped with flat platens for static compression tests. The tests were conducted in accordance with the guidelines of standard PN-57/H-04320, which specifies the procedures for upsetting cylindrical specimens, particularly regarding specimen geometry and loading conditions. Compression tests were performed after completion of the specified cooling time, under conditions close to 0 °C.

A constant crosshead speed of 50 mm/min was applied, corresponding to quasi-static conditions, enabling recording of stable force–displacement curves. The specimens were positioned axially between two flat polytetrafluoroethylene (PTFE) inserts, with additional application of PTFE lubricant to reduce friction at the specimen–tool interface.

Upsetting was carried out until a 50% reduction in specimen height relative to the initial value was achieved, ensuring a representative range of plastic deformation required to determine flow curves of the model material while maintaining deformation stability. Compressive force and tool displacement were recorded and subsequently converted into true stress and true strain values, taking into account current specimen dimensions during deformation. The obtained data enabled further analysis of the influence of thermal conditions and specimen volume changes on the mechanical behaviour characteristics of the model material.

Table 1. Strain rates as a function of specimen size

Diameter d [mm]	Strain rate $\dot{\varepsilon}$ [1/s]
10	0.0833
15	0.0555
20	0.0417
25	0.0333
27	0.0309
30	0.0278
40	0.0208
50	0.0167

With the application of a constant crosshead speed of 50 mm/min, different strain rates were obtained for individual specimens. The average strain rate values for each specimen are presented in Table 1. The cooling process was continued until a uniform temperature across the entire specimen cross-section was achieved, which constituted the criterion for completion of cooling. For this purpose, a wide and irregular range of cooling times, expressed in minutes, was selected, covering both very short and long stages-from 1 to 2340 minutes.

Short cooling times (1–30 min) allowed registration of intensive heat dissipation and rapid temperature changes characteristic of the initial phase of the process, in which the largest temperature gradients between the core and surface of the specimen occur. Medium cooling times (60–360 min) enabled analysis of gradual decay of these gradients and progressive temperature equalisation across the specimen cross-section. Long cooling times (above 360 min, up to 2340 min) were selected to confirm attainment of thermal equilibrium, understood as uniform temperature throughout the material cross-section.

The use of irregular time intervals, with a higher density of measurement points during the initial cooling phase and gradual reduction in later stages, is justified by the decreasing dynamics of the cooling process. This approach allows precise identification of the moment of temperature gradient disappearance and unambiguous determination of the time required for complete temperature equalization within the specimen volume.

All experiments were conducted at a temperature of 0 °C, ensuring repeatable conditions and precise comparison of specimens with different volumes. It should be emphasised that the results apply to this specific temperature state, and generalisation of the model to other temperatures requires further investigation.

RESULTS

The laboratory test results obtained in the form of flow curve characteristics of the model material-PRIMO plasticine-were subjected to detailed quantitative analysis. On the basis of the

recorded data, the relationship between changes in maximum averaged flow stress values and the specimen cooling time from ambient temperature to 0 °C was developed.

During the conducted tests, no cracking or other specimen damage was observed, confirming adequate plasticity of the material at 0 °C.

Figure 1 presents an example flow curve obtained during axial deformation of a cylindrical specimen with a diameter of 27 mm and height of 27 mm, previously cooled for 30 minutes. The interval indicated in the graph formed the basis for determining the average maximum flow stress value, which was subsequently used in further stages of result development.

Analysis of changes in flow stress of commercial plasticine as a function of cooling time indicates a significant dependence of the mechanical properties of the material on thermal conditions. The observed flow stress values show a clear inverse relationship with specimen temperature. Table 2 presents average stress values as a function of billet size and specimen cooling time.

Figure 2 shows the evolution of average maximum flow stress as a function of cooling time for specimens of different diameters. The presented values represent arithmetic means of three repetitions performed under identical experimental conditions. The absence of further increase in flow stress values with increasing cooling time was adopted as the criterion for attainment of a stable state corresponding to full thermo-mechanical homogenisation of the material.

For all analysed cases, a qualitatively similar course of the curves is observed. In the initial cooling phase (short times), a rapid increase in flow stress values occurs, indicating intensive material stiffening processes associated with rapid decay of thermal effects and equalisation of internal stresses. In this time range, the dynamics of changes are the highest, and differences between individual specimens are clearly pronounced.

As cooling time increases, the rate of flow stress increase gradually decreases, and the curves assume an asymptotic character. This indicates gradual attainment of mechanical equilibrium, in which further cooling does not cause significant changes in the analysed parameter. For the longest cooling times, flow stress values stabilise at similar levels regardless of specimen dimensions.

At the same time, the influence of specimen geometry on the cooling process is evident. Smaller specimens are characterised by faster increases in flow stress and earlier attainment of a quasi-stationary state. For specimens of larger volume, the process proceeds more slowly, which

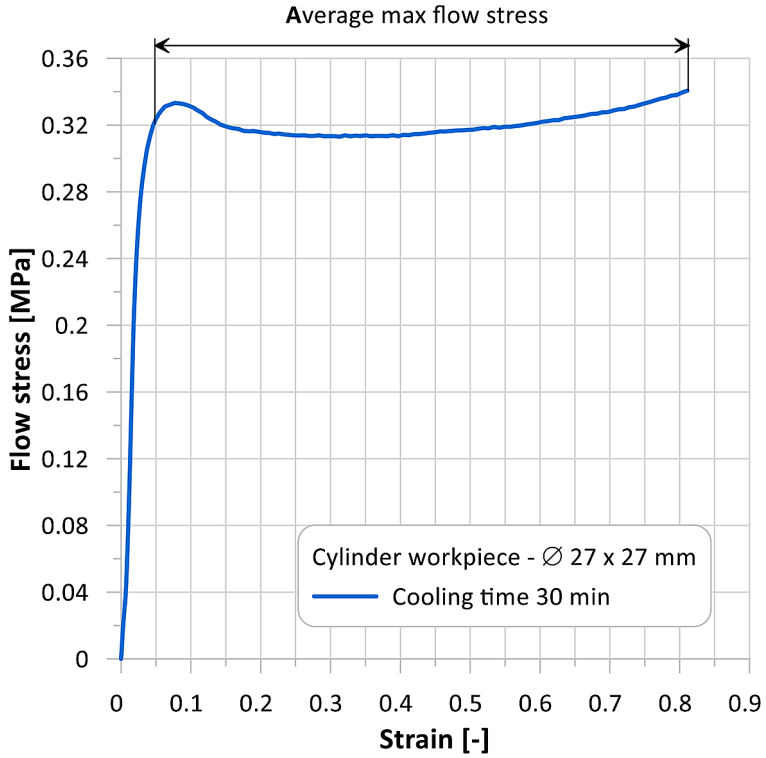

Figure 1. Example flow curve obtained for a 30-minute cooling time test

Table 2. Average stress values depending on billet size and cooling time

Time [min]	∅10 [mm]	∅15 [mm]	∅20 [mm]	∅25 [mm]	∅27 [mm]	∅30 [mm]	∅40 [mm]	∅50 [mm]
1	0.22	0.20	0.18	0.17	0.16	0.15	0.13	0.11
5	0.32	0.29	0.25	0.23	0.21	0.16	0.13	0.11
10	0.41	0.33	0.30	0.25	0.26	0.20	0.17	0.15
15	0.43	0.35	0.32	0.27	0.29	0.22	0.18	0.16
20	0.45	0.38	0.34	0.29	0.29	0.24	0.20	0.18
25	0.47	0.39	0.36	0.31	0.29	0.26	0.22	0.20
30	0.49	0.41	0.37	0.32	0.32	0.27	0.23	0.21
60	0.54	0.43	0.40	0.35	0.34	0.30	0.26	0.24
90	0.61	0.46	0.43	0.38	0.34	0.33	0.29	0.26
120	0.62	0.48	0.45	0.40	0.34	0.33	0.31	0.28
150	0.62	0.49	0.46	0.41	0.36	0.34	0.32	0.29
180	0.62	0.50	0.47	0.42	0.37	0.35	0.33	0.30
210	0.62	0.52	0.48	0.43	0.37	0.36	0.34	0.31
240	0.62	0.55	0.49	0.44	0.38	0.37	0.35	0.32
270	0.62	0.55	0.50	0.45	0.39	0.38	0.36	0.33
300	0.62	0.55	0.51	0.45	0.39	0.38	0.37	0.33
330	0.62	0.55	0.51	0.46	0.40	0.39	0.37	0.34
360	0.62	0.55	0.51	0.46	0.41	0.39	0.37	0.34
420	0.62	0.55	0.51	0.46	0.42	0.40	0.38	0.34
480	0.62	0.55	0.51	0.47	0.43	0.41	0.38	0.35
540	0.62	0.55	0.51	0.47	0.44	0.42	0.38	0.36
600	0.62	0.55	0.51	0.47	0.45	0.42	0.39	0.36
660	0.62	0.55	0.51	0.47	0.46	0.43	0.39	0.36
720	0.62	0.55	0.51	0.47	0.46	0.43	0.39	0.37
900	0.62	0.55	0.51	0.47	0.46	0.44	0.40	0.37
1080	0.62	0.55	0.51	0.47	0.46	0.44	0.40	0.37
1260	0.62	0.55	0.51	0.47	0.46	0.44	0.40	0.37
1440	0.62	0.55	0.51	0.47	0.46	0.44	0.40	0.38
1620	0.62	0.55	0.51	0.47	0.46	0.44	0.41	0.38
1800	0.62	0.55	0.51	0.47	0.46	0.44	0.41	0.38
1980	0.62	0.55	0.51	0.47	0.46	0.44	0.41	0.38
2160	0.62	0.55	0.51	0.47	0.46	0.44	0.41	0.38
2340	0.62	0.55	0.51	0.47	0.46	0.44	0.41	0.38

can be associated with a longer time required for structural state equalisation throughout the material volume. This effect indicates the significant role of geometric scale in plasticine cooling processes under reduced temperature conditions.

The presented results confirm that cooling time and specimen volume significantly influence flow stress values of the model material. The character of the obtained curves indicates domination of rheological and cooling-related processes leading to gradual material stiffening and stabilisation of its mechanical properties at 0 °C. The optimal cooling time was defined as the time required to achieve a quasi-stationary state, in which further extension of cooling did not cause significant changes in average flow stress values in the specimens.

Figure 3 illustrates the dependence of optimal cooling time, defined as the moment of attaining constant flow stress values, on the diameter of the cylindrical specimen. The visible sharp increase in cooling time for diameters above 30 mm indicates significant practical limitations in conducting model tests for specimens of large dimensions.

Although the present study does not include direct comparison with heat conduction models

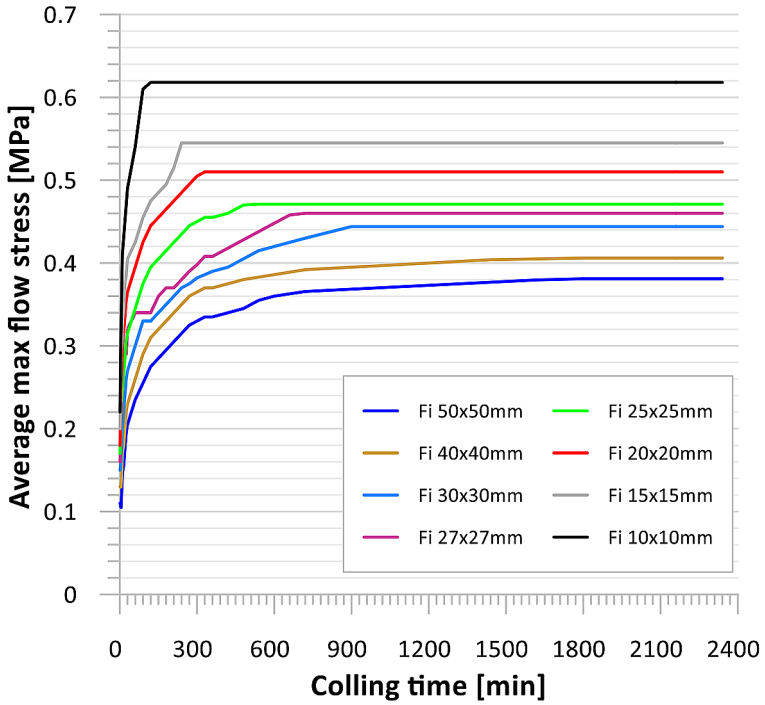

Figure 2. Evolution of average maximum flow stress of the model material

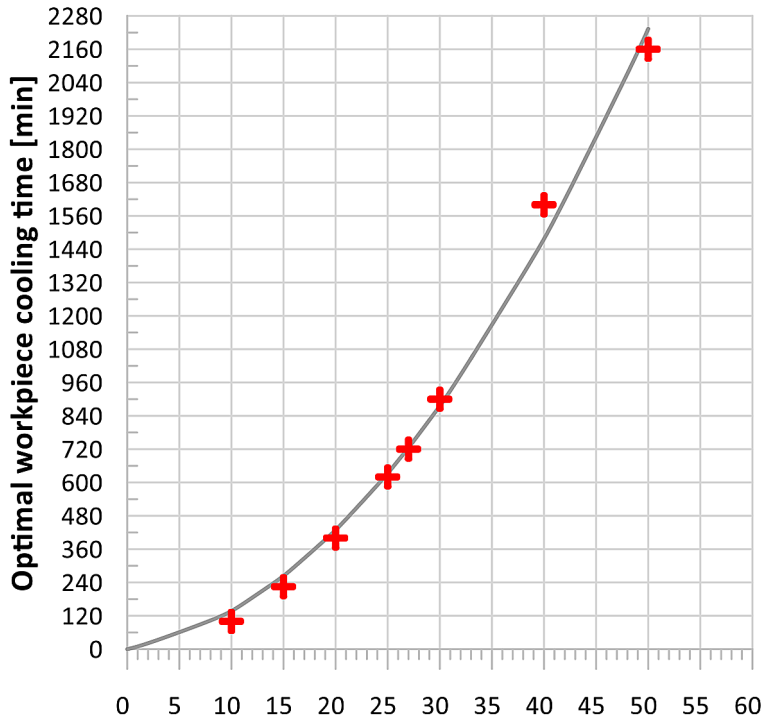

Figure 3. Optimal cooling time of the model material

or numerical thermal simulations, the observed trends are consistent with the expectations derived from basic heat transfer principles. Future studies are planned to compare experimental data with theoretical models, which will further verify the correctness of the developed polynomial model.

Detailed interpretation of the graph shows that for specimens with smaller dimensions, in the diameter range of 10–20 mm, the increase in cooling time is relatively mild, rising from approximately 110 to 400 minutes. However, above the threshold of 30 mm, a sharp change

in process dynamics is observed; for a specimen with a diameter of 50 mm, the required cooling time exceeds 2100 minutes, corresponding to nearly 35 hours of continuous processing. The very high degree of fit of the theoretical model to empirical data suggests high repeatability of boundary conditions and correctness of the adopted measurement methodology.

Analysis of the collected experimental data enabled precise formulation of a mathematical model describing the dependence (1) of optimal cooling time on specimen diameter. On the basis of the distribution of empirical points, a trend line in the form of a second-degree polynomial was determined, described by the equation:

$$t = 0.7739d^2 + 5.946d \quad (1)$$

where: d represents specimen diameter [mm], and t corresponds to cooling time [min].

The determined second-degree polynomial model describes the dependence of optimal cooling time on specimen diameter in the range of 10–50 mm. It should be noted that application of the model outside this range may lead to inaccurate predictions and is not recommended.

The obtained polynomial relationship is qualitatively consistent with cooling time scaling trends reported in the literature on physical modelling and heat transfer in bodies of varying dimensions. Published studies indicate that increasing specimen volume leads to nonlinear extension of the time required to reach thermal equilibrium, resulting from thermal energy accumulation in the material mass and limited heat dissipation intensity.

It should be emphasised that the model proposed in this study is empirical in nature and was developed directly based on laboratory test results, making it a particularly useful practical tool for organising model experiments, without the ambition to provide a universal description of thermal phenomena. Verification of the developed model's accuracy showed a very high degree of fit to real data, confirmed by a coefficient of determination of $R^2 = 0.9929$.

This value, close to unity, indicates that the proposed equation explains 99.29% of the variability in measurement results, which under technical and industrial conditions is considered evidence of model precision and reliability. Such high correlation minimises the prediction error risk.

CONCLUSIONS

The conducted experimental studies on physical modelling of plastic forming processes using black PRIMO plasticine enabled a comprehensive analysis of the influence of specimen geometric parameters on the kinetics of thermo-mechanical phenomena. The selected model material, due to its temperature-dependent rheological properties, allows faithful reproduction of changes in metal flow behaviour. The study focused on cooling cylindrical specimens of different diameters under controlled thermal conditions, enabling determination of relationships between billet dimensions and heat dissipation efficiency.

Analysis of mechanical characteristics showed that in the initial cooling phase a rapid increase in flow stress occurs, associated with intensive thermal energy dissipation and development of temperature gradients between the specimen core and surface. Over time, the process stabilises and the material reaches a state of structural and thermal equilibrium. A clear dependence between specimen volume and the time required to reach a quasi-stationary state was observed – smaller specimens achieve it faster, while larger ones require extended cooling.

Quantitative studies showed that cooling time for the specimens with diameters of 10–20 mm increases moderately from approximately 110 to 400 minutes, whereas the specimens above 30 mm exhibit a sharp increase, e.g. a 50 mm diameter specimen requires as much as 2100 minutes (over 35 hours). An empirical mathematical model in the form of a second-degree polynomial was developed, enabling prediction of optimal cooling time for the specimens with diameters of 10–50 mm, with a high coefficient of determination ($R^2 = 0.9929$). The model enables rational experiment planning and minimises the risk of insufficient cooling and underestimation of flow stress by as much as 15–20% in larger specimens.

In summary, the results emphasise the significant influence of specimen geometry on heat exchange dynamics and rheological properties of the model material. The developed model not only optimises cooling time but also increases repeatability and reliability of model studies used in analysis of industrial processes such as forging, rolling, and extrusion. The extended cooling time of larger specimens primarily results from limited thermal conductivity and a higher volume-to-surface ratio, causing slower temperature

equalisation. Future studies will extend the analysis to different cooling temperatures to better reproduce industrial conditions and assess the universality of the developed model.

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