A PRELIMINARY STUDY ON DEVELOPING A MATERIAL MODEL BASED ON A MIXTURE OF CLAY AND CERAMIC FLOUR INTENDED FOR THE EXTRUSION OF BANDS FOR CERAMIC ROOF TILES TO ESTABLISH A NUMERICAL MODEL FOR THE LOAD ON FORMING TOOLS

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Abstract

The article concerns preliminary research involving the development of a flow model for a material consisting of a mixture of clay (70 %), quartz sand (10 %) and ceramic flour (20 %) in an upsetting test in order to determine the course of plasticizing stress as a function of actual strain. This material constitutes the mass for the production of ceramic roof tiles and, at the beginning of the process, it is pressed through forming tools, then cut to the appropriate size, stamped and dried. It is difficult to find information in the literature on the subject of numerical modelling of the process of extruding a strip of clay, especially in terms of the operation of forming tools, which wear out mainly as a result of intense friction of the pressed material, causing abrasive and tribological wear of the tools. Therefore, first, the authors conducted upsetting tests to determine the flow characteristics, and then attempted to develop a material model for the clay mixture. The results of the conducted R&D work, after many verifications and modifications, allowed for the construction of a model based on the Hansel-Spittel formula along with the identification of the parameters and coefficients appearing in the equation. The final stage of the work was the development of a numerical model for the preliminary analysis of the formation of the squeezed band.

Keywords: ceramic roof tiles; band extrusion; clay flow curves; material modelling

1. INTRODUCTION

At present, the main direction of development in the area of the construction and performance of machines is optimization and increase of the operation time of machine elements, especially in respect of their resistance to abrasive wear [1, 2]. Problems resulting from excessive work of machine parts negatively affect their durability and reliability, and thus also the whole production and technological processes. Such a situation also takes place in the ceramic industry on the production lines of ceramic roof tiles, where selected machine elements, including tools used for clay band extrusion, are in direct contact with the processed material, whose main components are: clay, quartz sand and milled crushed brick [3]. The most intensive abrasive wear takes place during the extrusion of the mass through the forming tool set, where the mass is previously mixed, homogenized, vented and shaped [4]. This process is currently carried out in horizontal band extruders, which consist of: a double shaft mixer and a pug mill [5]. The production mass processed by these machines has wettability at the level of 20-25 % and it is compressed in the pug mill's head under the pressure of 3-10 MPa. A product of this stage of production is an extruded band, which is formed by a set of two special tools (so-called bits), which are especially exposed to intensive abrasive wear and work temperature increase [6, 7]. In order to analyze and optimize production processes of this type, with a special consideration of the operation conditions and loads of the tools (bits), it is necessary to conduct a lot of research and scientific studies, which, at the same time, in the case of such processes, are difficult to realize. Due to the fact that, for these production processes, analytic and experimental studies are difficult to conduct as well as time-consuming and expensive, we should take advantage in this area of numerical modelling and other IT techniques. It should be emphasized that the subject literature does not provide a lot of information on numerical modelling of the process of clay band extrusion, especially in terms of the forming tools‘ operation. A big difficulty in this aspect is mostly constituted by the model of the extruded clay band material in order to properly model the technological process. It is possible to find studies which provide the characteristics for clay [8], however, in the case of a roof tile mass, its composition is crucial, which will surely decide about the properties. For the determination of the material characteristics for a clay mixture, we can use compression tests (upsetting) in an axisymmetric deformation state, which results from the specificity of such a material as well as the facility in performing such tests. First, however, we should properly prepare the samples as a clay mass with additions dries relatively fast, which significantly affects the preparation of samples in the form of cylinders as well as the physical changes and the properties of the material. Another challenge in the case of modelling a process of clay band extrusion is the introduction of the data from the performed compression tests in a tabular form or the selection of the optimal mathematical model, which will best represent the characteristics of such a material. In the case of the development of such a model, it is important to identify the parameters and coefficients present in the model. The key step is the selection of the appropriate computational package based on the proper constitutive models and the elaboration of a numerical model in order to perform a preliminary analysis of the extruded band formation. The last and most important stage of the research works will be verification of the obtained numerical simulation results [9]. The presented series of R&D works is necessary for the construction of a proper numerical model of a technological process connected with the extrusion of a clay band assigned for ceramic roof tiles at further production stages. It should be emphasized that the realization of all the tests is difficult and burdened with uncertainty, especially in terms of their correctness. What is more, such an approach cannot be universal but individual for every process and dedicated to a specific industrial application.

The aim of the article is to prepare the samples for the extrusion tests as well as to realize compression tests and determine the charascteristics, and, on this basis, to propose a mathermatical description of the material model in such a way so that a proper numerical model of the process can by ultimately built and preiminary numerical simulations can be carried out.

2. DESCRIPTION OF THE PROCESS OF BAND EXTRUSION FOR CERAMIC ROOF TILES

Within the perfomed studies, tool steel NC11LV used for forming tools in the production of ceramic roof tiles was verified. The basic task of these tools is providing the shape and thickness to the band, which, at the following stage, is cut into a specific dimension and then transported to a punch press, where the final shape of the tile is formed (**Figure1a**). The forming tools, as shown in Figure 1b, are mounted at the end of a pug mill, which, depending on the capacity, extrudes the mass under the pressure of 2 – 10 MPa, the effect of which are high pressures operating on the tool, which lead to intensive abrasive wear [6, 10].

a) b)

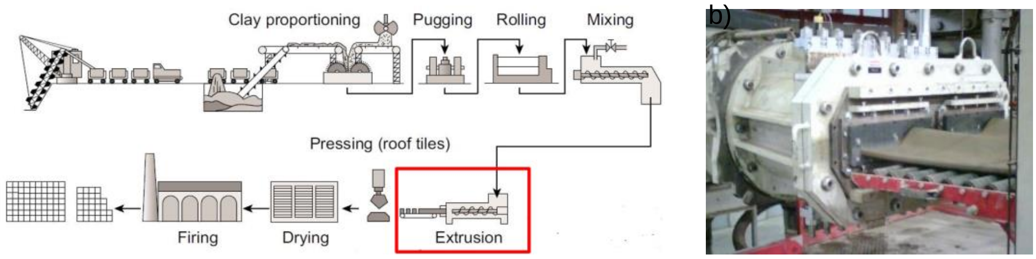


Figure 1 View of: a) a flowchart of a roof tile manufacturing plant [11], b) the pressure head with a forming tool

A particular attention should be paid to tools that directly contact the pressed clay mass and form the shape of the strip, because the degree and type of their wear mainly affects the quality of the final product, i.e. ceramic roof tiles. Of course, the geometry of the tools differs depending on the range of the produced roof tiles, which also affects the operational aspect.

3. METHODOLOGY AND TEST DESCRIPTION

The tests were divided into three stages:

- Preparation of samples for plastometric compression tests and determination of flow characteristics,
- Selection of a proper mathematical model and identification of its parameters,
- Development and construction of a numerical model of the band extrusion process with preliminary results.

4. RESULTS AND DISCUSSION

4.1. Material characteristics

In the first place, proper samples for plastometric tests were prepared. The test material was collected from a huge clay mass with additions (a few tens of tons) present in the production hall. In the case of a material of this type, the preparation of samples constitutes a certain technological problem. Due to the rapid drying of small portions of such a mass and difficulties in the preparation of cylindrical samples, a decision was made to form cylinders on a special laboratorial semi-industrial press (**Figure 2a**).

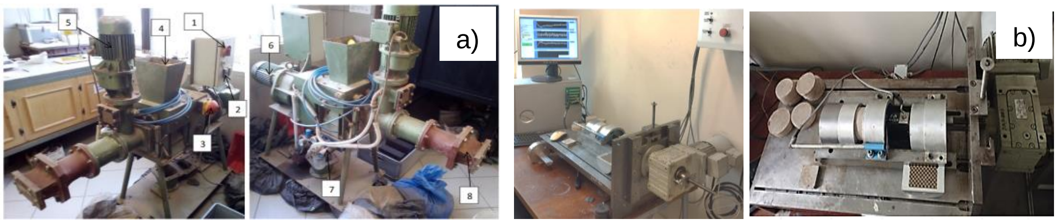


Figure 2 Photographs of: a) the semi-industrial press for the preparation of cylindrical samples for compression: 1-main switch-key, 2-control panel; 3-emergency switch; 4-loading chamber; 5-drive; 6-worm drive; 7-vacuum pump; 8-extruder die, b) laboratory press for physical modelling and compression tests.

A laboratorial pug mill type VP0 is assigned for processing and quality control of appropriately prepared plastic masses. The material is loaded manually through the loading chamber, vented and next extruded in the form of a shaped band through an extruder die. In turn, the laboratory press is built of a main board (table top), to which various tools and instruments are attached. The drive device is a motoreducer by Lenze, consisting of a bevel gear with helical teeth and a three-phase motor with the power of 1.3 kW and the torque at the output of 18 Nm. The motoreducer is attached to the engine plate, mounted in guides, which can be regulated in the vertical plane of the table, allowing for the adjustment of the punch position in order to realize the particular processes for different sample shapes and dimensions. By means of a nut-screw system, the rotational motion of the motoreducer's roller is changed into a rectilinear motion of the screw, which is connected with the punch of the press. The control of the motoreducer is realized with the use of an inventer. The maximal value of the forming force equals 7 kN. The model material flow curves were determined in an upsetting test performed on cylindrical samples with the height of 60 mm and diameter of 60 mm. The test was realized until the occurrence of a crack on the cylinder's side surface. The applied lubricant was industrial grade petroleum jelly, which was placed in special openings made in the front surfaces of the samples. During the test, no barrel was formed on the cylinder's side surface, which would point to a very low friction coefficient, and so, its effect on the yield stress was omitted. For the given material and test conditions, the experiment was repeated 3 times. Next, for the analysis, the average course of stress was selected. The basic tests were performed at the temperature of 22°C and the deformation rate of $0.1 s^{-1}$. Tests were also conducted for other conditions in order to determine the sensitivity of the model materials to temperature and deformation rate. **Figure 3** shows the determined courses from the compression tests recalculated into material characteristics in the form of yield stress-deformation flow curves. As we can notice, the determined curves resemble the characteristics of warm-deformed metallic materials. We can also see an effect of the deformation rate on the yield stress level as, togerther with a deformation rate increase, the stress increases as well. For the initial rate of 0.3m/s, the yield stress value places itself at the level of 0.28 MPa, and the deformation reaches 0.85. In turn, for the highest deformation rate of 3m/s, the stress is at the level of 0.34 MPa, and the deformation is slightly over 0.8. During the tests, cracking of the samples resembling shearing could be observed, especially for higher deformation rates.

a) b)

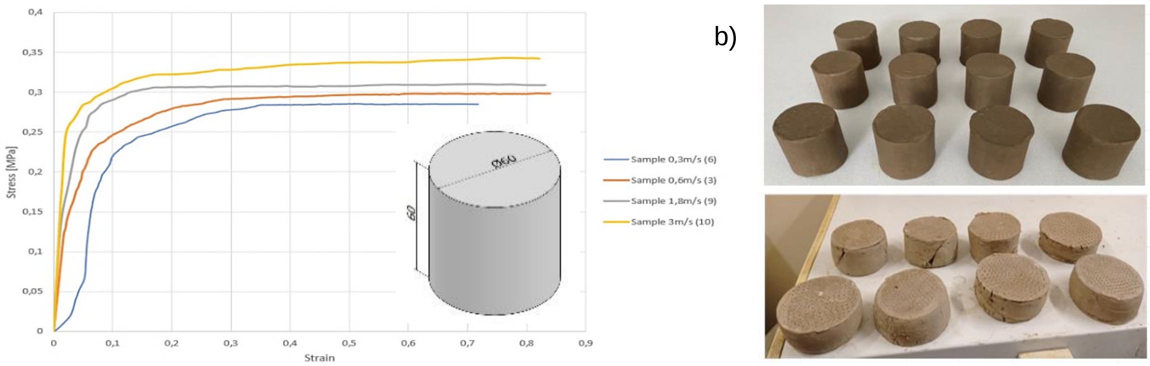


Figure 3 View of: a) the stress-strain curves of the material for the production of ceramic tiles, b) a photograph of the samples before and after deformation

It should be noted that such cracking, as well as the fact that the clay mass is partially compressible, can affect the results obtained in the upsetting test. Also the highest rate for which an upsetting test could be conducted equalled 4m/s, however, the sample got damaged very quickly, which can be the cause of errors in further analyses. In the case of an industrial process, the measured extrusion rate equals 0.26m/s.

4.2. Material model

Due to the presented upsetting test results as well as the specificity of the clay mass with additions, in order to verify the obtained flow curves, a rheological model was introduced into the Abaqus program in a tabular form after the procedure of reverse analysis. To that end, a direct task model in the finite element method was developed. The evolution of the yield stress value with the increasing deformation was obtained based on minimization of the objective function during the successive iterations of the upsetting simulation. The objective function was defined as a mean-square error between the calculated and measured results of the force and displacement during upsetting. During the reverse analysis, the effect of the deformation rate on the work-hardening characteristics was considered. On this basis, it was assumed that a good description of such curves would be provided by the Hansel-Spittel model:

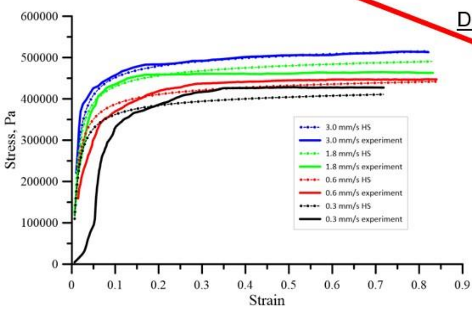
$$\sigma_f = Ae^{m1T}\varepsilon^{m2}e^{\frac{m4}{\varepsilon}}(1+\varepsilon)^{m3} \tag{1}$$

where:

- ε - total deformation;
- $\dot{\varepsilon}$ - deformation rate tensor;
- T - temperature;
- A, m1, m2, m3, m4 - model coefficients dependent on the material.

Next, during the tests, the particualr coefficients in the equation were identified and determined (**Figure 4**). Currently, further tests are being conducted with the aim to specify and verify the coefficients in the equation.

$$\sigma = A\exp(m_1 T)\,\varepsilon^{m_2}\exp\left(\frac{m_4}{\varepsilon}\right)\dot{\varepsilon}^{m_3}$$



Defined constant

A	2.18E+02
m1	0.322746222
m2	0.030083048
m3	0.095892041
m4	-0.00772939

Figure 4 View of: a) the flow curve results based on the reverse analysis, b) the HS equation with the preliminarily identified coefficients

We should also remember that the data from the experiment did not consider different temperatures, and so, the temperature effect on the stress can be the cause of certain discrepancies.

4.3. Development of a numerical model and preliminary simulation results

A commercial program Abaqus and a constitutive Drucker-Prager model (DP) were selected for the simulations. A constitutive model DP is usually used for simulations of materials such as granular soils, which demonstrate plasticity dependent on the pressure, which means that the material hardens with a pressure increase. This model can also describe the behaviour of materials in which the yield stress during compression is much higher than the yield stress during tension. Next, the construction of a numerical model of the band extrusion process began (**Figure 5**). The initial-boundary conditions were assumed according to the present technology.

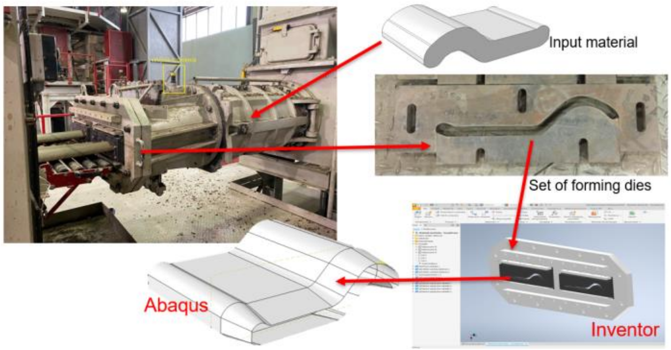


Figure 5 Preparation of a numerical model for the extrusion of a clay band assigned for ceramic roof tiles

After the implementation into the numerical program of the partially simplified geometry of the tools and the charge in the form of solids (CAD models) developed in the Inventor program, it was discreticized. The band sample was preliminarily divided into about 86 000 Lagranian-type elements and the tools – into over 880 000 Eulerian-type elements (**Figure 6a**). The preliminary numerical simulation results have been presented in **Figure 6b**. The elaborated numerical model for the extrusion process of a clay band with additions is one of the first attempts to approach an issue of this type related to the modelling of an industrial process of extruding a clay band, which, in consequence, as the final product, will constitute a ceramic roof tile.

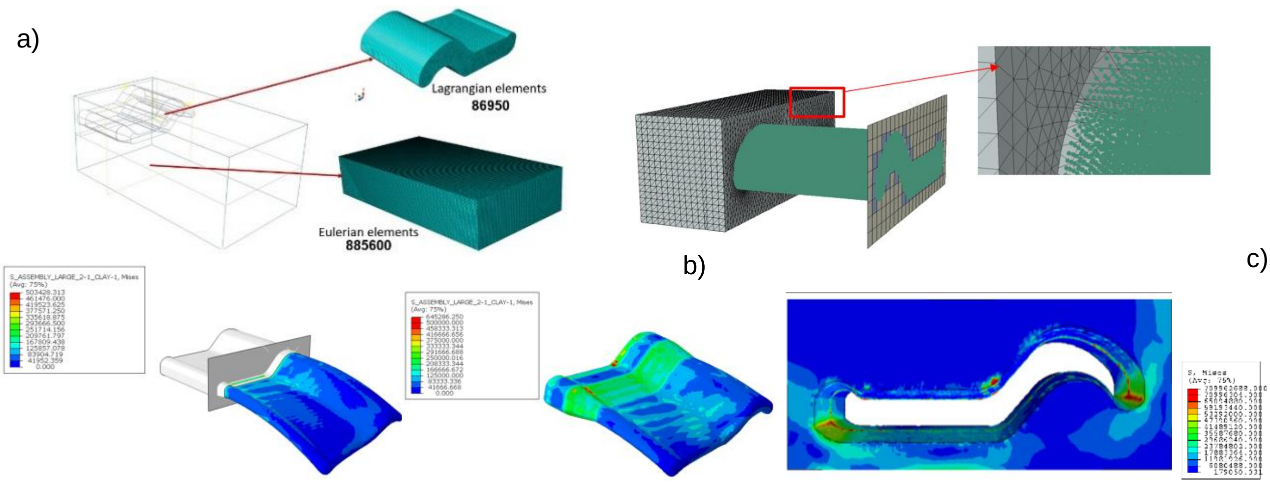


Figure 6 View of: a) a simplified geometry with discretization of solids into elements, b) preliminary simulation results – distributions of reduced stresses for the extruded band, c) stresses in the eye of the forming tools

Nevertheless, it seems that the numerical simulation results point to properly conducted research works as both the shape of the extruded band and the preliminary results with the stress distributions in the formed mass and on the tools seem to be acceptable. At present, tests are being conducted on a material model for which new coefficients in the Hansel-Spittel equation have been determined and the element mesh for both geometries is even more densified.

5. CONCLUSIONS

The article presents the results of preliminary research studies including the development of a proper model of material flow consisting of a mixture of clay and other additions through an upsetting test in order to determine the flow curves. Next, for such results, a reverse analysis was carried out. Due to the specificity of such a material, a mathematical model based on an HS equation was constructed. The material model with a simplified geometry was implemented into the Abaqus computational package, in which a numerical model of the band extrusion process was elaborated with the assumption of the initial-boundary conditions from the industrial process. Currently, both the numerical model itself and the plastometric test results are at the stage of intensive verification studies as many results and assumptions during the research can be burdened with error. For this reason, it is necessary to verify both the material model itself and the numerical model based on the industrial process. It is initially planned to verify the results by comparing the forces from numerical modelling in relation to the band jacking forces in real conditions. It should be clearly emphasized that the constructed numerical model is one of the first attempts at approaching an issue of this type related to the modelling of an industrial process of clay band extrusion as neither the available literature nor other studies include such information. The proposed approach to the analysis and optimization will certainly bring measurable economic benefits for the production process as well as stimulate the development of science in this field.

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