Design and fabrication of prototype of extrusion equipment for research and teaching purposes

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Abstract: In Engineering Schools, metal forming teaching laboratories are not always equipped with all the suitable equipment to show the students how metal forming operations are performed in industrial facilities, due mainly to space and/or economical limitations. In this work, a proposal of design and fabrication of prototype of extrusion equipment is presented, mainly for teaching purposes, but also, for research activities in extrusion processes. To reach the aim, the components of the prototype are integrated in a universal testing machine Hoytom HM-100kN. This kind of equipment is available in any Engineering School, which makes the proposal accessible to any lecturer interested in metal forming teaching. The final design of the prototype was made taking into account the possibility of using standardized components to facilitate both installation and maintenance tasks. It is also important to emphasize the modular nature of the design to allow its adaptation to different applications and case studies. The prototype presented has demonstrated to be able to produce long profiles by cold extrusion, not only with plasticine (typically used in physical modelling) but with a metallic material, as tin. This prototype could be used as an example of extrusion equipment to be reproducible in metal forming laboratories of other universities.

Keywords: Metal forming, Extrusion, Prototype, Laboratory, Teaching.

1. Introduction

Direct extrusion is a metal forming process in which a metallic billet is forced by compression to flow through a die to produce a long profile with a defined cross-sectional shape [1]. In Engineering Schools, metal forming teaching laboratories are not always equipped with all the suitable equipment to show the students how metal forming operations are performed in industrial facilities, due mainly to space and/or economical limitations. Often, competences and skills related to laboratory practice have to be acquired through physical or numerical simulation [2,3].

In this work, a proposal of design and fabrication of prototype of extrusion equipment is presented, mainly for teaching purposes, but also, for research activities in extrusion processes [4]. Although some similar experiences have been done in this field mainly with plasticine (typically used in physical modelling), there are few proposals with metallic materials [5,6]; anyway, this kind of experiences are not really well reported in the literature, as it is difficult to find works with this teaching approach because most of the works about extrusion are strictly scientific articles [7–11]. To reach the aim, the components of the prototype are integrated in a universal testing machine. This kind of equipment is available in any Engineering School, which makes the proposal accessible to any lecturer interested in metal forming teaching.
The novelty of the proposal compared to previous works found in the literature is that the prototype is be able to produce long profiles by cold extrusion, not only with plasticine but with a metallic material; and that the final design of the prototype was made taking into account the possibility of using standardized components to facilitate both installation and maintenance tasks. It is also important to emphasize the modular nature of the design to allow its adaptation to different applications and case studies.

The structure of the paper is divided into different sections, starting with a contextualization and background of the work; next the main methodological aspects regarding the experimental procedure are presented, with especial emphasis in the description of the components of the designed equipment followed by the details about the fabrication of the samples by sand casting and machining to make them ready for the extrusion process; cold extrusion conditions are also specified and an analytical expression to estimate the required load depending on the material properties and other technological factors is also included. Finally, tin extrudates fabricated by the extrusion prototype under different lubrication conditions are presented along with the forces registered, which is also an interesting approach for teaching purposes because it allows to show the influence of important process parameters in the extrusion forces required. The work ends presenting the main conclusions and future work to go on with this teaching innovation line.

2. Methodology

2.1. Experimental procedure
The equipment where the prototype will be installed is located at the "Metal forming and materials testing laboratory" of the Department of Manufacturing Engineering of the UNED, and consists of a universal testing machine Hoytom HM-100 kN with control software Howin 32 RS (figure 1a) and a Bongshin load cell model DSCK (figure 1b).
This kind of equipment is typically designed to characterise the mechanical behaviour of materials by tensile, compression or flexural testing. It will have to be adapted by means of the necessary tooling to carry out the extrusion processes. Concretely, the compression working area will be used. This machine has a maximum force of 100 kN but is recommended not to overcome 90 kN to avoid damaging its components.

2.1.1. Components of the equipment. The final design of the prototype was made taking into account the possibility of using standardised components to facilitate both installation and maintenance tasks. Emphasis was also placed on the modular nature of the design to allow it to be adapted to different applications and case studies.

Finally, after analysing the commercial materials available, adapting them to the preliminary design and optimising this design to facilitate its manufacture, the final design chosen is presented in figure 2. Figure 2(a) shows the final configuration of the prototype integrated in the universal testing machine along with some components of the tooling system (figure 2(b)).

![Figure 2. (a) Extrusion prototype installed in the universal testing machine Hoytom HM-100kN. (b) Main components of the tooling system: die, container and auxiliary tooling to host the die.](image)

The design is integrated by the following components:

- **Punch**: this is the part attached to the mobile crosshead of the universal machine, which will transmit the force to the billet to perform its extrusion.
- **Die**: part responsible of the geometric change (transverse section reduction) by plastic deformation of the billet. Extrusion dies can have very complex designs, depending on the profile to be extruded and the operating conditions. The extrusion prototype allows to use dies of different geometries.
- **Container and auxiliary tooling to host the die**: a set of two parts that will house the die and the billet to be extruded. The lower part contains the die, and the upper part (container) hosts the initial billet.
- **Auxiliary support and housing structure for the extruded part**: set of parts attached to the fixed crossbeam of the universal machine that support the die and the container and gives the extruder...
sufficient travel to allow the extruded part to exit. This distance is achieved thanks to 8 standardised threaded shafts that separate the two other parts of the structure: the part jointed to the universal machine (bottom) and the part that supports the container and the die (top).

2.1.2. Preparation of the samples. Tin has been selected as the metal to be extruded. The disadvantage of tin is that it is not a metal used for this type of application; usually it is alloyed with other metals, used in soft solder, coatings, etc. Therefore, this metal is usually sold in the form of wire coil, small spheres, ingots, etc. But it is not usually sold as cylindrical bars. However, because tin has a low melting point (231.9 °C), it is possible to achieve the cylindrical shape by a sand-casting process carried out in our machine shop (figure 3). Tin ingots are heated to melting temperature in a furnace (figure 3(a)); once the metal is molten, it is poured into a cylindrical sand mould (figure 3(b) and (c)), which is about 100 mm long and has a diameter depending on the diameter required for the extrusion process.

![Figure 3. (a) Tin ingots and Carbolite furnace. (b) Casting of the melted tin in the sand mold (c) Tin billet after solidification inside the mold. (d) Initial billet after turning to achieve final dimensions.](image)

Finally, it is necessary to machine these bars both to adjust the length and the diameter to the initial dimensions required of the billet (and also to improve the surface finish). A Pinacho Mod. L-1/200 lathe is used to carry out these operations. This process has the disadvantage that the tin is too soft for the clamping system and, as can be seen in figure 3(d), this causes marks from the clamps at one end of the specimens.

2.1.3. Extrusion conditions. Six test pieces have been manufactured with the aim of analysing the influence of two factors, the ram velocity and the type of lubricant. The idea is that through these
experimental tests the correct operation of the prototype will be checked. The test conditions were as follows:

- **Ram velocities, \( v \):**
  - \( v_1 = 55.0 \text{ mm/s} \)
  - \( v_2 = 27.5 \text{ mm/s} \)

- **Type of lubricant:**
  - Dry conditions: no lubricant
  - Graphite powder
  - Molybdenum disulphide (MoS\(_2\))

Combining the two ram velocities with each type of lubrication, we have a total of 6 tests, numbered in the order in which they were carried out (see table 1).

| Number of tests | Ram velocity, \( \nu \) (mm/s) | Lubricant          |
|-----------------|-------------------------------|--------------------|
| 1               | 27.5                          | Dry                |
| 2               | 55.0                          | Dry                |
| 3               | 27.5                          | Graphite powder    |
| 4               | 55.0                          | Graphite powder    |
| 5               | 27.5                          | MoS\(_2\)          |
| 6               | 55.0                          | MoS\(_2\)          |

**Figure 4.** Extrudates obtained by the extrusion prototype: Dry conditions (left), Graphite powder (center), Molybdenum disulphide MoS\(_2\) (right).
2.2. Analytical estimation

Analytical calculations based in Johnson’s semiempirical model presented in equation (1) and (2) were also accomplished to estimate the required load depending on the material properties and other technological factors that include the geometrical and friction conditions with a clear influence on the forming capacity of the prototype and its limitations:

\[ F = A_0 \cdot \bar{Y} \cdot \left( \epsilon_x + \frac{2L}{D_0} \right) \]  

\[ \epsilon_x = a + b \cdot \ln r_x \]  

where \( A_0 \) is the initial area of the billet, \( L \) is the contact length of the container, \( D_0 \) is the initial diameter of the billet and \( \bar{Y} \) is the average flow stress; \( r_x \) is the extrusion ratio \( (A_0/A) \) and \( a \) and \( b \) are constants obtained by semi-empirical methods whose values are typically 0.8 and 1.2, respectively.

3. Results and discussion

Tin extrudates fabricated by the extrusion prototype presented in this work under conditions indicated in table 1 are shown in figure 4.

The graph in figure 5 shows the results of forces required of the six experimental tests carried out.

![Figure 5. Extrusion forces for the 6 samples tested in the extrusion prototype.](image)

In this graph we can see at a glance a clear difference between the tests with and without lubricant. And in all of them the maximum force required for the process is very similar and is in the range of 75-85 kN. It can be seen how in the processes without lubrication the maximum force is reached almost instantaneously, while in the lubricated processes this force is obtained more gradually, although the maximum value is very similar in both cases.

In the table 2 we can see the total extruded length \( (L_{\text{total}}) \) and the maximum force \( (F_{\text{max}}) \) for each of the tests; along with the numbering corresponding to the order in which the tests were carried out, which corresponds to the extrudates shown in figure 4.

Along with all the graphs, the line that estimate the theoretical force necessary for the extrusion process according to the semi-empirical Johnson’s equation is also presented -equations (1) and (2)-. We can observe how this theoretical force is very close to the forces obtained experimentally, being an upper limit. Taking into account the particularities of the design explained above, it can be said that it is quite close to the experimental model. Therefore, it is confirmed that Johnson’s model is very useful to
estimate the required forces prior to the design of this kind of extrusion prototypes, and especially, considering other metallic materials with higher mechanical strength.

Table 2. Results after performing the extrusion test in the prototype.

| Number of tests | Ram velocity, $v$ (mm/s) | Lubricant             | $L_{\text{total}}$ (mm) | $F_{\text{max}}$ (kN) |
|-----------------|--------------------------|-----------------------|--------------------------|------------------------|
| 1               | 27.5                     | Dry                   | 41.44                    | 82.66                  |
| 2               | 55.0                     | Dry                   | 41.51                    | 82.47                  |
| 3               | 27.5                     | Graphite powder       | 49.95                    | 83.30                  |
| 4               | 55.0                     | Graphite powder       | 52.00                    | 82.17                  |
| 5               | 27.5                     | MoS$_2$               | 39.65                    | 76.99                  |
| 6               | 55.0                     | MoS$_2$               | 38.79                    | 82.09                  |

4. Conclusions and future work

The main objective of this work was to fabricate a functional extruder on a laboratory scale to extrude, if possible, metallic materials, designing "ad hoc" tooling for its integration in a universal testing machine. In view of the results of the tests carried out with tin, it can be considered that this objective has been completely achieved.

The first step was to find an extruder design that would allow us to extrude parts of sufficient length to overcome the transient zones and to achieve an extrusion process in permanent regime. In addition, this design had to be versatile enough in order to favoring the adaptation to other variants of extrusion processes in a simple way; and be made up of commercially available or easily manufactured elements. This has been achieved to a large extent, since all the non-commercial elements have been manufactured in the UNED facilities with the available machinery. And both the commercial and manufactured elements are easily replaceable, either for maintenance or for other elements to carry out other types of extrusion processes.

The manufacture of the prototype was the main objective, but it has been also proven the possibility to use this prototype to teach students the real performance of this kind of metal forming process at laboratory scale; but also the influence of important process parameters such as friction and geometrical conditions (initial dimensions of the billet, extrusion ratio applied, for example) in the extrusion forces required.

At the same time, a procedure based in sand casting to produce the initial billets has been performed, which is a very interesting approach to design a practice that combines casting and metal forming for bachelor studies in Engineering.

The prototype presented has demonstrated to be able to produce long profiles by cold extrusion, not only with plasticine (typically used in physical modelling) but with a metallic material, as tin. This prototype could be used as an example of extrusion equipment to be reproducible in metal forming laboratories of other universities.

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References

[1] Groover M P 2010 *Fundamentals of Modern Manufacturing. Materials, Processes, and Systems* (New York: John Wiley & Sons)

[2] Amigo F J and Camacho A M 2017 Reduction of induced central damage in cold extrusion of dual-phase steel DP800 using double-pass dies *Metals (Basel)* 7 p 335
[3] García-Domínguez A, Claver J, Camacho A M and Sebastián M A 2015 Comparative analysis of extrusion processes by finite element analysis Procedia Engineering 100 pp 74–83

[4] Pérez Rosco A 2019 Prototipo de extrusora a escala de laboratorio con fines docentes e investigadores: diseño y desarrollo experimental, modelización por elementos finitos y análisis de parámetros de extrusión Master’s Thesis. Departamento de Ingeniería de Construcción y Fabricación. Universidad Nacional de Educación a Distancia

[5] Pacheco Ruffián G 2017 Diseño y construcción de una extrusora lateral y obtención de fuerzas Bachelor’s Thesis. Departamento de Ingeniería Mecánica y Fabricación. Universidad de Sevilla

[6] Garófalo Méndez D M and Hidalgo León M G 2011 Diseño y construcción de prototipo de extrusión directa para producir perfiles de plomo artesanal Bachelor’s Thesis. Facultad de Ingeniería en Mecánica y Ciencias de la Producción. Escuela Superior Politécnica del Litoral

[7] Qamar S Z, Pervez T and Chekotu J C 2018 Die defects and die corrections in metal extrusion Metals (Basel) 8 p 380

[8] Marin M M, Camacho A M and Pérez J A 2017 Influence of the temperature on AA6061 aluminum alloy in a hot extrusion process Procedia Manufacturing 13 pp 327-334

[9] Fernández D, Rodríguez-Prieto A and Camacho A M 2020 Effect of process parameters and definition of favorable conditions in multi-material extrusion of bimetallic AZ31B-Ti6Al4V billets Applied Sciences 10 p 8048

[10] Zhang Y, Song K, Zhang S and Wang Y 2021 Hardness and failure assessment of a hot extrusion punch during service Engineering Failure Analysis 125 p 105382

[11] Bohluli H, Khalili K and Seyedkashi S M H 2021 An investigation on twist extrusion followed by forward extrusion in production of aluminum–copper bimetallic bar CIRP Journal of Manufacturing Science and Technology 33 pp 52–62