Study and analysis of the wiredrawing of CuZn37 wires via numerical simulations and slab method

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Abstract: Improving efficiency and productivity of industrial manufacturing activities is crucial in today's global economy and the advanced engineering methods they have proven to be an effective solution to better understand the operation of the processes. The technological problem in wiredrawing is conditioned by multiple factors such as drawing die geometry, tribological system, process speed and the state of the metal to be drawn, among others. A wire rod of CuZn37 alloy brass with Ø8 mm is obtained by continuous casting process from electrolytic materials. The structural state of the initial wire rod and the draft sequence conditions the deformations and residual stresses accumulated in its cross section, affecting the sequential process and final quality. The present work proposes a complete analytical-numerical study aided to the better understanding of the problem for the design of a process proposal for an adequate continuous wiredrawing sequence for the production of Ø2 mm brass wire. An industrial sequence without intermediate annealing was evaluated by the analytical-numerical procedure allowing to better understand the technological problems involved. This methodology has allowed to check that it is not possible to achieve such a high degree of reduction ratio above of r=0.70÷0.75, without applying intermediate annealing heat treatment.

Keywords: Wiredrawing, Finite element method, Slab method, CuZn37 brass, Metal forming.

1. Introduction
Brass wire processed by wiredrawing is commonly used to manufacture different application products being specifically produced for its use in the electro discharge machining (EDM) cutting process [1].

For the manufacture of brass alloy wire, the continuous wiredrawing industrial process is divided in two phases: rod breakdown (coarse reduction) and finishing (fine reduction). The finishing wiredrawing machines are designed for high production range 2 millimetres in diameter down (multiwire wiredrawing lines), while the coarse sequence (rod breakdown) reduces the rod from 8-9 millimetres in diameter obtained by continuous upcasting [2,3] to a dimension suitable for processing by finishing [4]. In both types of process, it should be started from a heat-treated material, beginning from optimal metallographic and tensional conditions for a maximum possible plastic deformability [5].

The industrial rod breakdown of CuZn37 must achieve diameters around 2 millimetres preferably in a single sequence, without intermediate anneals with to save energy, time, and money. This objective is sometimes frustrated because of unwanted breakages in the last stages of the industrial process, case in which is necessary to apply intermediate annealing treatment to reach the desired reduction.
In the wiredrawing process, the elongation in the \( \text{“i”} \) step should be rolled up and accumulated in the subsequent pulling capstan. The wire slides backward over the capstan due to its rotational speed, maintaining a minimum back-pull tension in the wire just before the entrance to the next \( \text{“i+1”} \) die to avoid the instabilities that may cause the breakage of the wire [6]. The % elongation per step determines the design of the drawing sequence by a sliding winch system that usually works around 20%. On the other hand, is essential to know the force and power required in each of the process passes.

The analytical modelling of the steady state in the material-tool system, based on plane strain axisymmetric condition and constant friction as simplifying hypotheses, estimates the drawing force \( F_{\text{draw}} \) in a single pass [7,8] and it can be applied in a multi-step wiredrawing process [9]. Besides, the shape factor (\( \Delta \)) defines the relationship between the reduction and the cone semiangle in the die as shown in equation (2). A delta factor larger than 3 increases the likelihood of cup-cone fractures so, according to industrial practice, \( \Delta \) should be between 1.5 and 3. Low values of \( \Delta \) implies worst friction conditions while higher values increases accumulated stresses and surface hardening encouraging the void formation and centre bursting defect into the wire [10]. On the other hand, numerical simulation by finite element method (FEM) offers the possibility of a realistic simulation of the process and allow to see and analyse the behaviour of the meshed structure of the wire during its deformation [11,12]. Furthermore, consulted works such as the one developed by Verma et al. [13] have shown the potential of the finite element method (FEM) for the analysis of the single and multi-step wiredrawing.

The present work is focused on the problems shown in the rod breakdown industrial process of brass, proposing a viable alternative to achieve the desired semi-finished product avoiding wire breakages.

2. Materials and Methods
From among variety of brass alloys, CuZn37 is a common brass that can be cold worked by drawing, although its ductility is lower than other alloys with lower zinc content. The chemical composition of this alloy is shown in the table 1 [14].

| Cu (%) | Al (%) | Fe (%) | Ni (%) | Pb (%) | Sn (%) | Zn (%) | Others | Density (g/cm\(^3\)) |
|-------|-------|-------|-------|-------|-------|-------|--------|-----------------|
| 62-64 | 0.05  | <0.1  | <0.3  | <0.1  | <0.1  | Rest   | <0.1   | 8.4             |

The industrial process under study presents breakage problems just after reaching a cumulative reduction rate of approximately \( r = 0.80 \). Thus, in a first phase of the work, a detailed study of the sequence has been simulated through FEM simulation in order to identify the causes of this problem. All the technological and design data of the referenced wiredrawing sequence are shown in the table 2.

| Step (i) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 |
|---------|---|---|---|---|---|---|---|---|---|---|----|----|----|
| Output diameter, \( d_i \) (mm) | 8.00 | 6.70 | 5.75 | 5.04 | 4.49 | 4.00 | 3.57 | 3.18 | 2.86 | 2.57 | 2.34 | 2.15 | 2.00 |
| Die semiangle, \( \alpha \) (°) | -- | 19 | 18 | 17 | 16 | 16 | 16 | 15 | 15 | 15 | 15 | 14 | 14 |
| Calibre length, \( L_c \) (mm) | -- | 1.34 | 1.26 | 1.14 | 1.12 | 1.00 | 0.89 | 0.79 | 0.715 | 0.64 | 0.58 | 0.53 | 0.50 |
| Delta shape factor, \( \Delta \) | -- | 3.68 | 4.05 | 4.44 | 4.78 | 4.78 | 4.85 | 4.85 | 4.89 | 4.85 | 5.53 | 5.72 | 6.69 |

So, by the appropriate annealing treatment [15] of CuZn37 rod after the upcast process, the more optimal mechanical properties can be obtained [16,17]. This condition offers the best performance of
the alloy for its cold plastic deformation. In this sense, the alloy has been defined by the Ludwik-Hollomon behaviour [17], expressed in equation (1).

The values of $K$ and $n$ defines the coefficient of resistance to plastic deformation and coefficient of hardening by deformation of the metal, respectively [18]. The values assumed for these hardening coefficients and those set for the elastic and breaking limits of the alloy were defined after consulting in the bibliography [16-19] and correspond to the optimum and best attainable condition of stability-grain size-deformability that can be achieved in this alloy.

\[ \sigma_y(i) = \sigma_y(i-1) + K \cdot \varepsilon_i^n \] (1)

The yield strength limit of the deformed metal, $\sigma_y(i)$ increases as a function of the value of this limit just in the previous state/step $(i-1)$ of the process, the degree of deformation reached $\varepsilon_i$ and the hardening behaviour as a function of $K$ and $n$. The starting material is defined in table 3.

### Table 3. Optimum mechanical properties of CuZn$_{37}$ rod (upcast and annealed) [14,18,19].

| Diameter (mm) | Tensile stress, $\sigma_{\text{max}}$ (MPa) | Yield stress, $\sigma_y$ (MPa) | $K$ | $n$ |
|---------------|-----------------------------------------|---------------------------|-----|-----|
| 8             | 343                                     | 137                       | 710 | 0.46|

Usually, the design of the multi-pass sequence is conditioned to a particular value of % elongation per pass. In this case, the consecutive reductions have been calculated under the condition of a constant delta $\Delta$ (equation 2), thus from this equation (3) the value of output diameter can be calculated, and $r$ is the reduction rate applied in the wiredrawing pass “i” and expressed in the equation (4).

\[ \Delta = \sin \alpha \cdot \frac{(d_0+d_f)}{(d_0-d_f)} \] (2); \quad \[ d_f(i) = \frac{d_0(i)(\Delta-\sin \alpha(i))}{(\Delta+\sin \alpha(i))} \] (3); \quad \[ r = 1 - \frac{A_f}{A_0} \] (4)

An optimal value of delta for most commercially known die designs is close to $\Delta$=3, under normal process conditions. To prevent vacuum defects and central bursting in the wire, a $\Delta$=2.8 has been set, minimizing negative effects caused by friction in the interface. The new alternative has been designed with the aid of PullWorks software application [9]. The process conditions are shown in table 4.

### Table 4. Process conditions for the alternative multi-step wiredrawing process.

| Input diameter, $d_0$ (mm) | 8.00 |
|----------------------------|------|
| Output diameter, $d_f$ (mm) | 2.00 |
| Recommended die angle, 2$\alpha$ (°) | 16 |
| Recommended calibration length, $L_c$ (mm) | 0.35$d_f$ |
| Production velocity (m/min) | 20 |
| Friction coefficient, $\mu$ | 0.15 |

Some works [20,21] defined the Coulomb friction as a proper friction model in wiredrawing and Santana Martinez et al. [11] empirically determined it for pure copper using polycrystalline diamond (PCD) dies with $\alpha = 7^\circ$ to $9^\circ$, obtaining the lower values between $\mu = 0.12$ and $\mu = 0.21$ with a wiredrawing velocity $v = 14$ to 18 m/s and mineral oil lubrication. According to the consulted works, the $\mu$ friction coefficient between steel and brass in dry conditions is between $\mu = 0.25$ and $\mu = 0.4$ and $\mu = 0.10$÷0.15 when using proper lubrication [19,20]. So, the use of PCD insert dies was considered in this study (e.g., figure 1) and $\mu = 0.15$ has been set in the FEM simulations, considering brass-PCD and optimum lubrication.

FEM was implemented by Deform2D [22] to perform simulations of all the passes in both: the industrial sequence tried without success in the manufacturing plant and the proposed alternative. Since in a cold forming process, the metal does not reach recrystallization temperature and in order to simplify...
the problem, room, and constant temperature (20 °C) has been assumed. This fact has also made possible to compare the results obtained by both models. The simulations All the conditions implemented in the FEM simulations are shown in the Table 5.

Table 5. The assumed conditions in FEM simulations of deformations.

| Process simplification | 2D, Axisymetric |
|------------------------|-----------------|
| Problem type           | Lagrangian incremental |
| Temperature            | Isothermal, 20°C |
| Die material           | Perfect rigid |
| Rod material           | Perfect plastic, CuZn37 |
| Dimensions of Initial rod/part | Ø8 mm x 20 mm length |
| Mesh type              | 2D, Quadratic |
| Number of initial nodes | 561 |
| Number of initial elements | 560 |
| Remeshing criteria     | Interference ≥ 0.2 mm |
| Solver matrix type/Iteration method | Skyline/ Newton-Raphson |

Figure 1. Progression of the $\sigma_{\text{draw}}$ in the multi-step sequence with 12 consecutive passes.

Figure 2. Progression of the unwanted deformation vs. accumulated reduction ratio in 12 passes.

3. Results and discussion
As has been observed in the simulations of the industrial sequence, the multi-stage schedule clearly shows a critical point just after the die number six. As it has been measured, at this point, the drawn wire
accumulates a certain degree of unwanted deformation, which is reflected in a slightly smaller diameter $d_f^{(FEM)}$ and a higher percentage elongation $\Delta l^{(FEM)}(\%)$ compared with the expected/calculated values. The unwanted plastic deformation is increased after $r=0.80$, as is shown in the figure 2. This effect is also reflected in the progression in the value of the drawing stress observed in the simulations. The progression of the $\sigma_{\text{draw}}$ in the multi-pass industrial sequence in shown in the figure 1.

The CuZn37 drawn wire was intended to get in an industrial rod breakdown machine model M85, from Niehoff (Maschinenfabrik Niehoff GmbH & Co., Schwabach, Germany). This machine can mount a maximum of twelve consecutive passes, capable of producing up to 38 m/s of wire at the outlet, must work in a percentage elongation range between 55 and 25% [4].

After several attempts in which breakage occurred, the die supplier Premier Wire Die (Premier Wire Die Inc., Fort Wayne, IN, EE.UU.) recommended dies with $\alpha = 8^\circ$ and $L_c = 0.35 \cdot d_i$, and provided us information of the breaking limit $\sigma_{\text{max}}$ values (see table 6). As it has been evidenced, an intermediate annealing must be applied for a reduction above $r = 0.80$. The new alternative has been designed with constant $\alpha(i)$, $L_c(i)$ and $\Delta$ for a more stable process. Figure 3 shows the results in PullWorks and figure 4 the progression of $\sigma_{\text{draw}}$ in the alternative proposal. The process data is summarized in table 6.

Figure 3. Alternative 14 pass schedule design with intermediate annealing in PullWorks software.
Figure 4. Progression of $\sigma_{\text{draw}}$ in the alternative process with intermediate annealing.

Table 6. Alternative process: rod breakdown→intermediate annealing→complementary wiredrawing.

| Step (i) | 0 | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9 | 10 | 11 | 12 | 13 | 14 |
|----------|---|---|---|---|---|---|---|---|---|---|----|----|----|----|----|
| Annealed | YES | NO | NO | NO | NO | NO | YES | NO | NO | NO | NO | NO | NO | NO | NO |
| Output diameter, $d_f$ (mm) | 8.00 | 7.24 | 6.55 | 5.93 | 5.37 | 4.86 | 4.40 | 3.98 | 3.60 | 3.26 | 2.95 | 2.67 | 2.42 | 2.19 | 2.00 |
| Accum. reduction rate, $\Delta r$ | -- | 0.181 | 0.330 | 0.451 | 0.549 | 0.631 | 0.698 | 0.752 | 0.798 | 0.834 | 0.864 | 0.889 | 0.908 | 0.925 | 0.938 |
| Output diameter $^{c}$, $d_{f,\text{FEM}}$ (mm) | -- | 7.19 | 6.46 | 5.78 | 5.31 | 4.80 | 4.35 | 3.93 | 3.54 | 3.20 | 2.90 | 2.60 | 2.35 | 2.12 | 1.93 |
| Elongation, $\Delta l$ (%) | 0.00 | 22.10 | 22.18 | 22.00 | 21.94 | 22.09 | 22.00 | 22.22 | 22.23 | 21.95 | 22.12 | 22.07 | 21.73 | 22.11 | 19.90 |
| Elongation $^{c}$, $\Delta l_{\text{FEM}}$ (%) | 0.00 | 20.51 | 23.45 | 21.00 | 22.03 | 22.43 | 22.24 | 24.04 | 24.19 | 22.63 | 24.81 | 26.72 | 23.20 | 25.65 | 20.37 |
| Accum. area reduction, $\Delta A\%$ | -- | 18.10 | 32.96 | 45.05 | 54.94 | 63.09 | 69.75 | 75.25 | 79.75 | 83.39 | 86.40 | 88.86 | 90.85 | 92.51 | 93.75 |
| Accum. unit strain, $\Delta \varepsilon$ | -- | 0.20 | 0.40 | 0.60 | 0.80 | 1.00 | 1.20 | 1.40 | 1.60 | 1.80 | 2.00 | 2.19 | 2.39 | 2.59 | 2.77 |
| velocity, $v$ (m/s) | -- | 1.53 | 1.87 | 2.28 | 2.78 | 3.39 | 4.13 | 5.05 | 6.17 | 7.53 | 9.19 | 11.22 | 13.66 | 16.68 | 20.00 |
| Yield stress $^{a}$, $\sigma_y$ (MPa) | 137 | 475 | 603 | 698 | 777 | 846 | 908 | 476 | 604 | 698 | 778 | 847 | 908 | 965 | 1012 |
| Mean Yield stress, $\bar{\sigma}_{\text{my}}$ (MPa) | 137 | 306 | 454 | 576 | 676 | 761 | 835 | 306 | 455 | 576 | 677 | 762 | 835 | 900 | 956 |
| Breaking stress $^{b}$, $\sigma_{\text{max}}$ (MPa) | 343 | 435 | 530 | 635 | 705 | 750 | 777 | 435 | 530 | 635 | 705 | 750 | 777 | 820 | 850 |
| Drawing stress $^{c}$, $\sigma_{\text{draw}}$ (MPa) | 0 | 259 | 355 | 398 | 506 | 653 | 670 | 271 | 279 | 289 | 363 | 482 | 590 | 468 | 573 |

$^{a}$ calculated by the Ludwik-Hollomon equation (1).

$^{b}$ estimated from the experimental data supplied by Premier Wire Die company.

$^{c}$ obtained in the FEM simulations.

Observing the progression in the response variables that condition the feasibility of the new alternative process, drawing stress $\sigma_{\text{draw}}$ behaves below/parallel the mechanical limits and the percentage elongation $\Delta l$ (%) observed in FEM is close with respect to the theoretically expected values. The new process is adequate and safe to work, without risk of breakage, by a first phase for reduction from 8 millimeter diameter wire rod up to a wire of 4.40 millimeters in diameter. After a suitable annealing treatment, the desired final diameter of 2 millimeters would be achieved in a second phase.
Figure 5 shows that the analytical method offers $F_{\text{draw}}$ values generally lower than those from the FEM. This fact is due to the slab method only implementing the effect of the homogeneous deformation and friction while the FEM simulations considers other dynamic terms as the influence of velocity and the inhomogeneous strain distribution in the wire. As shown in the figure 5, the drawing force $F_{\text{draw}}$ curve only corresponds better to FEM for the lower reductions of the proposed sequence, in line with what was concluded in previous works [8].

![Graphical comparative of the progression of the $F_{\text{draw}}$, slab method vs. FEM.](image)

**Figure 5.** Graphical comparative of the progression of the $F_{\text{draw}}$, slab method vs. FEM.

4. Conclusions

The industrial experience and the applied FEM simulations have allowed to conclude that, in the case of CuZn37 alloy and beginning from upcasted and optimally treated wire rod with 8 millimetre diameter, it is not possible to carry out rod breakdown process in a single continuous wire-drawing sequence without intermediate annealing. The results of the response variables measured in the numerical simulations have evidenced the instability of the sequential process initially undertaken in the present work. This instability is based on the observations made on the drawing stress $\sigma_{\text{draw}}$ and percentage elongation $\Delta l$ (%), in each one of the wire-drawing passes. This fact implies the recommendation to apply an intermediate annealing treatment before continuing above $r=0.70\div0.75$.

Definitively, PullWorks software resulted as a friendly and helpful solution for the design of the proposed alternative process that has been properly analysed in detail using the complement that constitutes the FEM software.

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References

[1] Amorim F L, Torres R D, Laurindo C A H and Reolon L W 2019 Performance and surface integrity of wire electrical discharge machining of thin Ti6Al4V plate using coated and uncoated wires Materials Research 22 (3) pp 4–9

[2] Knych T, Piotr U and Marzena P 2011 The Continuous Casting Technology of the Aluminum Rod Assigned for the Wire for Electrical Purposes Materials Science Forum 690 (January) pp 87–90

[3] Härkki K and Miettinen J 1999 Mathematical modeling of copper and brass upcasting. Metallurgical and Materials Transactions B: Process Metallurgy and Materials Processing


[4] Maschinenfabrik Niehoff GmbH Rod breakdown lines (https://www.niehoff-gmbh.info/en/products/rod-breakdown-lines) accessed 12 January 2021

[5] Ozgowicz W, Kalinowska-Ozgowicz E and Grzegorczyk B 2010 The microstructure and mechanical properties of the alloy CuZn30 after recrystallization annealing Journal of Achievements of Materials and Manufacturing Engineering 40 (1) pp 15–24

[6] Valverg H 2010 Applied Metal Forming including FEM Analysis (New York: Cambridge University Press)

[7] Dixit U S and Dixit P M 1995 An analysis of the steady-state wire drawing of strain-hardening materials Journal of Materials Processing Technology 47 (3–4) pp 201–229

[8] Rubio E M, Camacho A M, Sevilla L and Sebastián M A 2005 Calculation of the forward tension in drawing processes Journal of Materials Processing Technology 162–163 pp 551–557

[9] Rodriguez-Alabanda O, Romero P E, Guerrero-Vaca G and Sevilla L 2018 Software implementation of a new analytical methodology applied to the multi-stage wire drawing process: the case study of the copper wire manufacturing line optimization International Journal of Advanced Manufacturing Technology 96 pp 2077–2089

[10] Davis E A and Dokos S J 1944 Theory of wire drawing. Transactions of ASME Journal of Applied Mechanics 11 pp 193–198

[11] Santana Martínez G A, Qian W L, Kabayama L K and Prisco U 2020 Effect of Process Parameters in Copper - Wire Drawing Metals 10 (1) p 105

[12] Rodríguez-Alabanda O, Molero E, Tintelecan M, Guerrero-Vaca G, Romero P E and Martínez-Santana G A 2020 Fine Electrolytic Tough Pitch Copper Multistage Wire-drawing Pass Schedule Design by Analytical and numerical methods Proc. 14th Int. Conf. INTER-ENG 2020 Interdisciplinarity in Engineering (Târgu Mureș, Romania) 63 (12) pp 1–11

[13] Verma S and Rao P S 2019 Multistage wire drawing process analysis and optimization of process parameters. International Journal of Technical Innovation in Modern Engineering & Science 5 (01) pp 173–183

[14] UNE EN 12165 2018 Cobre y aleaciones de cobre. Semiproductos para forja, Asociación Española de Normalización, Madrid (Spain)

[15] Ataya S and Seleman M E 2012 Microstructure stability of CuZn37 brass. 14th Int. Mat. Symp. IMSP 2012 (Denizli, Turkey) 14 pp 1–8

[16] Copper Development Association Wrought Materials-Copper-Zinc alloys (https://copperalliance.org.uk/knowledge-base/resource-library/wrought-complex-copper-zinc-alloys-composition-properties-standards-and-uses/) accessed 10 January 2021

[17] Hollomon H 1945 Tensile Deformation. Metals Technology, American Institute of mining and metallurgical engineers XII (I) pp 1–22

[18] Tempelman E, Shercliff H and Eyben B N van 2014 Manufacturing and Design: Understanding the Principles of How Things Are Made (Elsevier Ltd., London,UK)

[19] Liu Y F, Li J, Zhang Z M, Hu X H and Zhang W J 2015 Experimental comparison of five friction models on the same test-bed of the micro stick-slip motion system Mechanical Sciences 6 (1) pp 15–28

[20] Avitzur B 1983 Handbook of Metal Forming (New York: John Wiley & Sons Inc.)

[21] Senhadji S, Belarifi F and Robbe-Valloire F 2016 Experimental investigation of friction coefficient and wear rate of brass and bronze under lubrication conditions Tribology in Industry 38 (1) pp 102–107

[22] Scientific Forming Technologies Corporation Deform Product Brochure (https://www.deform.com/products/deform-3d/) accessed 27 December 2020