Evaluation of the possibility of deep drawing of aluminium cylindrical drawpieces from sheets at different relative rolling reductions

T Milek
Kielce University of Technology, Faculty of Mechatronics and Mechanical Engineering, Al. Tysiąclecia Państwa Polskiego 7, 25-314 Kielce, Poland
tmatm@tu.kielce.pl

Abstract. In the paper, experimental results of research into a multi deep drawing process of cylindrical drawpieces are discussed. The investigations aimed to evaluate the possibility of deep drawing of aluminium cylindrical drawpieces from sheets and analysis of experimentally obtained changes of forces at different relative rolling reductions. For the purpose of research, EN AW-1050A aluminium blanks with constant diameter and different thicknesses were examined. The material was prepared by longitudinal rolling with different relative rolling reductions ($z = 10\div50\%$) and blanking process. Before deep drawing, some specimens were heat-treated to increase their plasticity. The material was annealed at 300-440ºC for a period of 0.3 h. A special stand was utilised during the research. The experimental results on forces and displacements were recorded and processed using a computer stand with Test&Motion software. Selected parameters of the deep drawing process, including forces and limit deformations in four drawing steps, were determined. The results may be used as boundary conditions to perform an in-depth numerical analysis of the deep drawing process of aluminium cups without inter-annealing of material in the course of the production.

1. Introduction
Production engineering principally aims to ensure the appropriate quality of the finished product. That involves, not only achieving dimensional accuracy but also the elimination of material defects that might occur in the technological process. Under manufacturing conditions, the deep drawing process may result in folding and cracking of metal sheets.

Information regarding, among others, the selection of minimum drawing and redrawing coefficients, number of drawing operations, application conditions, and pressure pad unit pressures, as well as the relationships for calculating pressing forces when drawing and redrawing, are important in terms of engineering cylindrical drawpiece drawing process technology. The source literature provides most of these parameters for the single drawing of drawpieces made of low-carbon steel sheet [1, 2]. Within all drawing processes (single drawing and redrawing), the pressing force necessary to induce deformation is not applied directly onto the deformation zone but to the punch instead, which transfers it onto the web of a cylindrical drawpiece, from where it is then transferred onto the material deformation zone through the walls [3].

Numerous studies of the process of cold-drawing cylindrical drawpiece made of aluminium and its alloys have been conducted over recent years. They included both experiments, as well as FEM-based
computer simulations [4-9]. The impact of punch radii and a die profile on the drawing force and deformability of aluminium sheet was studied [4]. Using both, a numerical simulation (LS-DYNA3D), as well as an experiment, optimisation of selected process parameters for the deep drawing mechanical process of two 2B06 aluminium alloy components of a Chinese aircraft was suggested [5]. The conical die drawing results for cylindrical drawpieces made of aluminium alloys (AA 1200) were discussed [6]. The numerical and experimental analysis of the AA 6014 aluminium drawpiece drawing process was conducted [7]. Furthermore, technological progress in the field of sheet metal forming was presented [8]. Besides, among others, a control algorithm, which enabled to determine the quality of kitchen sink-like drawpieces after drawing was proposed [9].

The main direction for the rational engineering or improvement of the drawing process is aimed at increasing the drawpiece height and decreasing the number of operations, owing to a lowered number of tensile stresses that can be achieved, among others, through improving the strength of metal within the dangerous cross-section and decreasing the tangential compressive stress in the deformable collar or increasing its stability to prevent fold formation. Within the cold drawing process, metals are subject to hardening (relative rolling reduction), resulting in increased deformation resistance and improved strength-related properties ($R_m$, $R_s$) and decreased metal plasticity ($A$, $Z$). The metal strain hardening degree within the deep drawing process is a complex and insufficiently studied issue, which depends, among others, on such factors as metal susceptibility to hardening, deformation degree, which can be characterised by the drawing coefficients and subsequent redrawings, material pressing force, corner radius of a die and punch draw radius, and the value of the clearance between the punch and die [10, 11].

The research paper reviews the results of experiments involving the drawing of axisymmetric drawpieces without a collar, with a maximum permissible slenderness, made of EN-AW-1050A aluminium in the course of four operations (drawing and three redrawings). They were aimed at evaluating the possibility of producing drawpieces with maximum deformation degrees in individual operations, without the need for inter-operational annealing, and the comparative analysis of drawing forces in the punch displacement functions at various sheet relative rolling reduction degree, concerning material in starting condition and after recrystallisation (soft state).

2. Methodology

The material for the experimental tests of a multi-operational drawing of cylindrical drawpieces were EN AW-1050A aluminium discs with a diameter of 66 mm ($D_3$) and thicknesses of $s_0 = 1$ mm and from $s_1 = 0.9$ to $s_2 = 0.5$ mm, in 0.1 mm increments (which corresponded to relative material thicknesses of $s_0/D_3 = 0.015$ and $s_1/D_3 = 0.014$; 0.012; 0.011; 0.009 and 0.008, respectively). In order to achieve them, first the $s_0 = 1$ mm thick, 72 mm wide and 300 mm long sheets were rolled with a varied relative rolling reduction degree ($z = 10\%$; 20%; 30%; 40% and 50%). The relative rolling reduction $z$ was calculated according to the following formula [1, 3, 10]:

$$z = \frac{s_0 - s_1}{s_0} \times 100\%$$

(1)

where: $s_0$ – initial thickness of sheet before deformation, $s_1$ – thickness of sheet after deformation.

Longitudinal cold rolling was conducted using a DUO-100 laboratory roll stand, designed for rolling non-ferrous metals. Next, discs were punched using a punching die installed on a ZD100 hydraulic press with a pressing force of 1 MN. The press, after modification by LABORTECH (Czech Republic), satisfied the class 1 metrological requirements. Some of the samples were annealed in a muffle furnace (by CZYLOK) intended for material heat treatment at temperatures of 300-440°C for a period of 0.3h. The short holding time was determined by the low cross-section of the material. The source literature [12] indicates that cold rolling hardens an aluminium sheet. Through the application of an appropriate relative rolling reduction degree after the last annealing, its mechanical properties can be impacted. High softness and drawability of aluminium sheet are obtained after annealing finished sheets at a temperature
of 300-350°C. Particularly fine grain with good drawability is obtained after annealing at a temperature of 450-500°C, whereas care shall be taken for the heated aluminium to quickly pass the critical temperatures of 260-350°C [12]. The last stage involved a multi-operational process of drawing cylindrical drawpieces without a collar, which consisted of the following elements:

- The laboratory press-tool with four sets of exchangeable dies and punches of various sizes. Figure 1 shows the diagrams of main instrumentation elements, while Table 1 includes the most important dimensions of punches and dies used within the experiments for single drawing and three redrawings (where \(d_s\) is the punch diameter, \(d_m\) – die diameter, \(r_s\) – punch radius, and \(r_m\) – die radius);
- LabTest5.20SP1 universal testing machine, with an electric drive and a 20 kN pressing force, manufactured by LABORTECH. It was calibrated and satisfied the metrological requirements for class 0.5;
- The computer test bench with specialised Test&Motion (LABORTECH) software for measuring forces and displacements.

![Figure 1](image)

**Figure 1.** Diagrams of main parts of tools used in an experiment for single drawing and redrawing processes [13]: a) tooling for single drawing (where: 1 – die, 2 – punch, 3 – blank-holder, 4 – drawpiece); b) tooling for redrawing (where: 1 – die, 2 – punch, 3 – pilot sleeve, 4 – drawpiece).

|                | Single drawing | First redrawing | Second redrawing | Third redrawing |
|----------------|----------------|-----------------|------------------|-----------------|
| \(d_s\)       | 35.5           | 26.5            | 21.5             | 17.5            |
| \(d_m\)       | 38             | 29              | 24               | 20              |
| \(r_s\)       | 5              | 3               | 3                | 3               |
| \(r_m\)       | 5              | 3               | 3                | 3               |

A blank holder was used in the course of the single drawing (element 3 in figure 1a) because the literature-based condition of \(s_0(s_1)/D_e \leq 0.02\) [1,2] was satisfied. The blank holder prevents the formation of folds and cracks in the material. The redrawing operations did not require the use of a blank holder, because according to the source literature [1,2] there was no such a need since the \(s_0(s_1) > 0.015\ \) was satisfied. The tests assumed the following drawing coefficients: for single drawing - \(m_1 = 0.57\) and for redrawing - \(m_2 = 0.76; m_3 = 0.82; m_4 = 0.83\). These coefficients were close to the limit value stated by the source literature [1, 2], which were determined depending on \(s_0(s_1) 100/D_e\). The total drawing coefficient \((m_n)\) for individual operations was determined via the formula (2) [1-3]:

\[
m_{1,n} = \frac{d_n}{d_{n-1}}
\]

where: \(d_n\) – post-operation drawpiece diameter measured at half of the wall thickness; (mm),
\(d_{n-1}\) – pre-operation material diameter (blank or drawpiece).
Calculated values of \( m_1, m_2, m_3, m_4 \) included the drawpiece diameters, which were measured after drawing, and not accordingly to the dimensions of the tool’s working parts because their dimensions and clearances between the punch and die were constant for subsequent operations, at varying disc thicknesses. The potential occurrence of longitudinal wall cracking at the drawpiece edge was also verified, due to the loss of the material’s elastic properties. According to [1, 2], to avoid the occurrence of such cracking and the need to anneal a drawpiece, the following condition should be satisfied prior to a subsequent operation:

\[
\varepsilon_c = 1 - \frac{d_n}{D_k} = 1 - m_1 \cdot m_2 \ldots m_n < \varepsilon_{\text{cdep}}
\]  

The permissible total deformation \( \varepsilon_{\text{cdep}} \) for aluminium is 0.6–0.8 [1, 2]. Basing on given \( m_1, m_2, m_3, m_4 \) coefficients adopted in the course of drawing and calculating \( \varepsilon_c \) after subsequent operations, it was concluded that there was no need for recrystallising inter-operational annealing since \( \varepsilon_c \) amounted to 0.7 after four drawing operations (\( \varepsilon_{c1} = 0.43; \varepsilon_{c2} = 0.57; \varepsilon_{c3} = 0.64 \) and \( \varepsilon_{c4} = 0.70 \), respectively for successive operation).

The cylindrical no-collar drawpieces obtained in the fourth and final operation (third redrawing) measured 19 mm in diameter and 2.54–2.80 in slenderness (depending on sheet thickness). EN AW-1050A aluminium was selected as the test material owing to its good plastic properties and the wide application of this material and its alloys within the industry [5, 8].

3. Experimental results and analysis
The mechanical properties of the material, defined as tensile strength \( R_m \) and elongation \( A \), were determined using a static tensile test in accordance with [14], on a LabTest5.20SP1 universal testing machine. The samples were cut out in the directions transverse relative to the sheet metal rolling direction. The results for the starting material were \( R_m = 126 \) MPa and \( A = 18.3\% \) [13]. Increasing relative rolling reduction degree \( z \) entailed an increase in the tensile strength \( R_m \) (figure 2) and a decrease in the elongation \( A \) (figure 3) of aluminium specimens. The obtained results in terms of aluminium test samples’ mechanical property changes indicated increased strain hardening of the material after cold rolling.

![Figure 2. Impact of the relative rolling reduction degree \( z \) on the tensile strength \( R_m \) of EN-AW 1050A aluminium samples.](image1.png)

![Figure 3. Impact of elongation \( A \) on the relative rolling reduction degree \( z \) of EN-AW 1050A aluminium samples.](image2.png)
Figure 4. Changes of the drawing forces (P) in the punch displacement function (h) for drawpieces made of EN-AW 1050A starting material at s₀=1mm (a) and rolled with relative rolling reduction degrees of b) z = 10%; 0.9 mm thick, c) z = 20%; 0.8 mm thick, d) z = 30%, 0.7 mm thick, e) z = 40% 0.6 mm thick, f) z = 50%, 0.5 mm thick.
The tests provided force changes over a four-operation drawing of cylindrical aluminium drawpieces without a collar, made of EN-AW 1050A aluminium, for various sheet metal relative rolling reduction degrees, of \( z = 10\%; 20\%; 30\%; 40\%, \) and \( 50\% \), respectively (figure 4).

The force waveforms in the punch displacement function for individual operations were remarkably similar in nature, regardless of the sheet relative rolling reduction degrees. The studies proved that, in the course of drawing, pressing forces changed depending on the punch path \( h \) (or drawpiece height) for successive drawing operations (figure 4). The punch path \( h_i \) at which the drawing forces obtained maximum value relative to the total path \( h \) in the course of drawing was \( h_i/h = 0.3 \div 0.45 \) for the single drawing operation; \( h_i/h = 0.5 \div 0.6 \) for the first and second redrawing; and \( h_i/h = 0.7 \div 0.8 \) for the third redrawing. This analysis confirmed the conclusions from previous studies regarding the changes of forces in a multi-operation drawing of cylindrical drawpieces without DCO1 steel, Cu-ETP copper, CuZn37 brass EN-AW1050A aluminium collar, for the relative rolling reduction degrees of \( z = 0\%; 12\% \) and \( 24\% \) [11].

Regardless of the studied sheet relative rolling reduction degree, the maximum drawpiece drawing forces (i.e. for drawing and three redrawing processes) decreased (figure 4 a-f). That was caused by the adopted draw coefficients increasing in subsequent operations (i.e. decreasing successive deformation degrees). In industrial conditions, when engineering such a drawpiece forming process, the most commonly adopted principle is that in the case of individual transitions, deformation degrees decrease gradually, due to material strain hardening increasing as drawing signs of progress [1-3, 10].

It is assumed that an increasing relative rolling reduction degree is accompanied by a decreasing thickness of the disc intended for drawing. This is why the graphs (figure 4 a-f) state that the maximum drawing forces decreased in analogous operations together with the relative rolling reduction degree, despite the material strain hardening phenomenon.

The second stage of the research involved forming drawpieces made of soft state blanks, i.e. after rolling at various relative rolling reduction degrees, the EN-AW 1050A sheet was subject to annealing prior to drawing, at temperatures of \( 300^\circ C \) and \( 440^\circ C \), respectively. Experimental tests have shown that when using soft-state aluminium blanks, it is not always possible to draw drawpieces in four operations (drawing and three subsequent redrawings), at coefficients close to limit values. Especially the blanks annealed at a higher temperature \( (440^\circ C) \) often experienced drawpiece cracking within the critical cross-section (at the radius of the cylindrical part-web transition). Annealing resulted in increased material plasticity but also decreasing metal strength in the dangerous section.

Figure 5 lists drawing force changes for drawpieces drawn from \( s_0 = 1 \) mm thick, EN-AW 1050A sheet discs, annealed prior to drawing at temperatures of \( 300^\circ C \) and \( 440^\circ C \), respectively. The chosen force changes were for the first drawing of drawpieces from annealed and starting material blanks and then compared in the form of a graph in figure 6.

The maximum drawing force for drawpieces made of a soft sheet \( (8.95 \) kN at \( 440^\circ C \) and \( 10.41 \) kN at \( 300^\circ C \)) shown in figure 6 were lower by \( 20\% \) and \( 8\% \), respectively, than the highest drawing force for the starting material blank \( (11.27 \) kN). In the case of samples formed from EN-AW 1050A sheet rolled with a relative rolling reduction degree of \( z = 50\% \) and \( s_1 = 0.5 \) mm soft state material, the differences between the maximum forces in the first operation were rather similar (figure 7) to the aforementioned \( s_0 = 1 \) mm thick test specimens. The maximum drawing force for soft-state sheet metal drawpieces \( (4.75 \) kN at \( 440^\circ C \)) was approx. \( 25\% \) lower than the highest drawing force for a starting material disc \( (6.35 \) kN). Whereas the highest forces for the first drawing operation involving a soft-state blank at \( 300^\circ C \) and starting material differed slightly (by less than \( 6\% \)). When it comes to the nature of changes in the punch displacement function for individual operation at various sheet metal relative rolling reduction degree (figure 4) and for a soft-state material (figure 5 and figure 7), it was remarkably similar.
Figure 5. Drawing force \( (P) \) changes in the punch displacement function \( (h) \) for drawpieces drawn from \( s_0 = 1 \text{mm thick}, \text{EN-AW 1050A} \) sheet annealed prior to drawing at temperatures of a) \( 300^\circ \text{C} \) and b) \( 440^\circ \text{C} \).

Figure 6. Comparison of drawing force \( (P) \) changes in the punch displacement \( (h) \) function for drawpieces made of \( s_0 = 1 \text{mm thick EN-AW 1050A} \) sheet metal blank in starting state, without annealing (curve 1) and annealed at temperatures of \( 300^\circ \text{C} \) (curve 2) and \( 440^\circ \text{C} \) (curve 3), respectively.

Figure 7. Drawing force \( (P) \) changes in the punch displacement \( (h) \) function for drawpieces made of \( 0.5 \text{ mm thick EN-AW 1050A} \) sheet discs rolled with a relative rolling reduction degree of \( z = 50\% \), annealed prior to drawing at temperatures of a) \( 300^\circ \text{C} \) and b) \( 440^\circ \text{C} \).
4. Conclusions
Based on the conducted experiments involving the drawing and redrawing of cylindrical drawpieces of EN-AW 1050A aluminium, obtained at various relative rolling reduction degrees (z = 10-50%) and in a soft state, it was concluded that:

1. There was a possibility for drawing drawpieces of a hardened sheet in four operations, without inter-operational annealing, for assumed draw coefficients similar to minimum limit values stipulated in source literature. This was confirmed by the conducted experiment for both low and high relative rolling reduction degrees.

2. Annealing blank after a relative rolling reduction, especially at 440°C, did not guarantee to obtain repeatable drawpieces in four operations, at the maximum deformation degrees assumed during the tests.

3. The obtained drawing forces in the punch displacement function for individual operation (drawing and three redrawings) and relative rolling reduction degrees are similar in nature. The differences in the maximum values arise primarily from the increasing strain hardening of the material (increasing value) and lowering material thickness (decreasing value).

The results can be used as boundary conditions to perform an in-depth numerical analysis of the deep drawing process of aluminium cups without inter-annealing of material in the course of the production.

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