Effect of the blank-holding load on the drawing force in the deep-drawing process of cylindrical and square cups
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Abstract. In this study, the influence of the blank-holding force (BHF) on the drawing force (DF) in the deep-drawing process of cylindrical and square cups has been investigated experimentally. For this purpose, different constant and variable BHFAs have been applied to AA6016-T4 aluminum alloy and DC04 steel sheets during the forming process. It has been observed that an increased constant BHF leads to an increase of DF. On the other hand, the variable BHF approach, in which the BHF decreases in six steps throughout the punch stroke, reduces the DF.

Introduction
In the deep-drawing process a lower drawing force (DF) is always desirable in order to have minimum energy consumption. There are many factors that affect DF, such as the friction between blank and tools, the lubrication conditions, the tool geometry, the punch–die clearance, and the blank-holding force (BHF). Among these factors, BHF plays a key role. BHF has the role to prevent the wrinkling. A higher BHF, however, leads to an increase of the friction force between the blank holder and the blank in the flange area, which implicitly leads to the increase of DF, and, in extreme cases, it may lead to tearing. On the other hand, a lower BHF will cause wrinkling. Therefore, it is important to know the effect of BHF on DF as well the conditions in which the DF can be reduced by adjusting BHF [1]. Studies conducted by other researchers show that BHF can be a temporal variable [2] or temporal and spatial variable [3], i.e. variable in time as well as along the contour of the blank [4]. Moreover, the BHF variation can be defined before starting the forming process or it can be adjusted during the process, depending on the available equipment. Most systems which use the spatial variable BHF are integrated into the tool and are thus independent of the press: Wei [5] uses a dual layer blank holder in which a pattern of small pins can be inserted. Yagami [6] presents a segmented blank holder in which a pattern of small pins can be inserted. Kitayama [7] classify the strategies for finding the BHF evolution in two categories: those based on a closed-loop type algorithm and those based on a response surface methodology. Tommerup [8] presents a die with flexible blank holder which is used for drawing rectangular parts. Under the influence of a hydraulic pressure applied on the flexible blank holder in four places, this element is locally deformed and allows the application of a pressure in specific areas of the blank. BHF is adjusted using a feedback control system [9]. In order to reduce the friction force between the blank and blank holder, a pulsed force can be superimposed over the BHF. Iwamatsu [10] has analyzed such effect on the formability of titanium alloys.

In this paper, the effect of constant and time variable BHF is investigated in the deep-drawing process of cylindrical and square cups. The experiments on AA6016-T4 aluminum alloy and DC04 steel sheets are performed using an Erichsen universal sheet metal testing machine, which allows setting of constant as well as variable BHFAs.
Tested materials and experimental procedures

**Materials.** Two sorts of metallic sheets have been chosen to perform the study in this paper: an AA6016-T4 aluminum alloy, with the nominal thickness 1 mm and a low carbon steel sheet of grade DC04 with the nominal thickness 0.85 mm. The mechanical parameters of these materials have been determined by tensile tests using a Zwick/Roell machine, model Z150. Table 1 shows the mechanical properties obtained from the tensile tests [11].

<table>
<thead>
<tr>
<th>Material</th>
<th>$R_{p0.2}$ [MPa]</th>
<th>$R_m$[MPa]</th>
<th>$E$[GPa]</th>
<th>$r$ [-]</th>
<th>$n$ [-]</th>
<th>$K$[MPa]</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA6016-T4</td>
<td>158.070</td>
<td>264.809</td>
<td>64.880</td>
<td>0.552</td>
<td>0.239</td>
<td>479.714</td>
</tr>
<tr>
<td>DC04</td>
<td>196.241</td>
<td>309.210</td>
<td>170.920</td>
<td>1.954</td>
<td>0.209</td>
<td>526.759</td>
</tr>
</tbody>
</table>

**Experimental equipment.** The deep-drawing of cylindrical and square cups have been carried out using an Erichsen universal sheet metal testing machine, Model 142-20. The machine is equipped with various die sets that can be changed to perform different tests. The machine software called “MES” has been used both for process control and for the acquisition of the following data: drawing force, blank-holding force and punch stroke. The geometry and dimensions of the tools used in the deep-drawing experiments are shown in Figures 1 and 2.

![Fig. 1. Tool geometry and dimensions for deep-drawing of cylindrical cups](image1)

![Fig. 2. Tool geometry and dimensions for deep-drawing of square cups](image2)

For the deep-drawing of cylindrical cups (Fig. 1) the tool dimensions are the same for both AA6016-T4 aluminum alloy and DC04 steel sheets except the diameter of the drawing die ($D_d$), which is adapted to the thickness of the metallic sheet. For this, two drawing dies have been used. For the aluminum alloy sheet, with the nominal thickness of 1 mm, a drawing die with the diameter $D_d = 52.82$ mm has been used, which provides a clearance of 1.41 mm between punch and die. In
the case of the DC04 steel sheet with the nominal thickness of 0.85 mm, the die diameter is $D_d = 52.38$ mm. As a result, the punch-die clearance is 1.19 mm.

In the case of the tools used for the deep-drawing of square cups (Fig. 2), the dimensions are also the same for the two sorts of metallic sheets, except for the die edge length ($A_d$) and die corner radius ($r_d$). By adopting two different die edge lengths, a clearance of 1.45 mm for the AA6016-T4 aluminum alloy and 1.20 mm for the DC04 sheet material are provided between the die and punch. In order to ensure these punch-die clearance values, two drawing dies with appropriate dimensions have been used.

**Procedure.** In order to study the influence of the blank-holding force on the punch force, two kinds of BHF were considered: constant and time variable (Table 2). Two reference values of the constant BHF have been used for each material, both for cylindrical and square cups. Table 2 also lists the initial values of the time variable BHF. Starting from these initial values, BHF is decreased in six increments throughout the punch stroke, as discussed in the results section for each particular case. The die and sheet have been lubricated with graphite grease. The testing speed has been set to 30 mm/min in all cases.

### Table 2. Experimental plan for studying the effect of the blank-holding force (BHF) on the drawing force (DF)

<table>
<thead>
<tr>
<th>Material</th>
<th>BHF [kN] - Cylindrical cups</th>
<th>BHF [kN] - Square cups</th>
</tr>
</thead>
<tbody>
<tr>
<td>AA6016-T4</td>
<td>10 (constant)</td>
<td>6 (constant)</td>
</tr>
<tr>
<td></td>
<td>13 (constant)</td>
<td>9 (constant)</td>
</tr>
<tr>
<td></td>
<td>13 (variable)</td>
<td>9 (variable)</td>
</tr>
<tr>
<td>DC04</td>
<td>13 (constant)</td>
<td>10 (constant)</td>
</tr>
<tr>
<td></td>
<td>19 (constant)</td>
<td>13 (constant)</td>
</tr>
<tr>
<td></td>
<td>13 (variable)</td>
<td>19 (variable)</td>
</tr>
</tbody>
</table>

**Experimental results**

**Cylindrical deep-drawn cups.** The results of the deep-drawing experiments of cylindrical cups for the AA6016-T4 aluminum alloy are shown in Figure 3.

Figure 3.a shows the evolution of DF as a function of punch stroke for two values of constant BHF: 10 kN and 13 kN. The constant BHF used in these experiments are superimposed on the same diagram (Fig. 3.a). From this diagram one may observe that when the BHF increases from 10 to 13 kN, the DF vs. punch stroke curve moves slightly to higher DF values. In this case, the maximum DF increases from 35.02 to 35.88 kN. This increase in DF can be attributed to the friction force between the blank and blank holder which increases when BHF increases.
Figure 3.b compares the DF versus punch stroke curve recorded in conditions of a constant blank-holding force (BHF=13 kN) with that obtained using a variable BHF. On this diagram are also shown the trajectories of constant variable BHFAs, respectively, used in these experiments. From this diagram one can observe that the variable BHF has little effect on the DF.

Figure 4 shows the results of deep-drawing experiments of cylindrical cups for the DC04 steel. Figure 4.a shows the evolution of DF as a function of the punch stroke for constant BHFAs: 13 and 19 kN, respectively. From this diagram one may notice that when BHF increases from 13 to 19 kN the curve moves to higher DF values and the maximum DF increases from 42.57 to 45.32 kN.

Figure 4.b compares the DF vs. punch stroke curve obtained in the case of applying a constant BHF of 13 kN with that recorded in the conditions of a variable BHF whose initial value is also set on 13 kN. It can be observed that by adopting a time variable BHF, DF decreases after reaching its maximum value. At this stage of the deep-drawing process, BHF decreases significantly and this can explain the decrease in the DF. One may also notice that the maximum DF decreases from 45.32 to 40.24 kN.

Square deep-drawn cups. Figure 5 shows the results obtained from the deep-drawing experiments involving AA6016-T4 square cups. Figure 5.a shows the effect of a constant BHF on DF. As in the previous cases, one may observe that the increase in BHF leads to an increase in DF. When BHF increases from 13 to 19 kN, the maximum DF increases from 32.87 to 33.90 kN.
Figure 5.b shows the effect of a variable BHF on DF. As can be noticed, in the first stages of the drawing process (up to 10 mm punch stroke) the variable BHF coincides with the constant BHF of 9kN. As a consequence, the DF is not influenced by the variable BHF. After the first 10 mm of punch stroke, the variable BHF begins to decrease which leads to a decrease of DF. In this case, by applying a variable BHF, the maximum DF decreases from 33.90 (constant BHF) to 33.54 kN.

Figure 6 shows the effect of constant and variable BHFs on DF in the deep-drawing process of DC04 square cups. From Figure 6.a, one may notice that as the BHF increases from 10 to 13 kN, the maximum DF increases from 39.27 to 39.82 kN. As one may notice from Figure 6.b, up to a 10 mm punch stroke the variable BHF has the same value as the constant BHF and there is no effect on DF. After the value of 10 mm punch stroke, the variable BHF decreases and this leads to a decrease of DF. By applying a variable BHF, the maximum DF decreases from 39.82 to 38.44 kN. This decrease is more significant after the maximum value of DF. The reason for this behavior is that, at this stage of the deep-drawing process, the variable BHF decreases with higher increments.

Conclusion

The goal of this work was to investigate the effect of blank-holding force on the drawing force in the deep-drawing process. Two types of BFH have been adopted in experiments: constant and time variable. Both cylindrical and square cups made from AA 6016-T4 aluminum alloy and DC04 steel sheets have been considered to perform the study in this paper. On the basis of the experimental results, the following conclusions can be drawn. In the case of the AA6016-T4 cylindrical deep-drawn cups, DF is influenced by the amount of BHF (the DF increases when the BHF increases) and less influenced by its type, constant or time variable. In the deep-drawing process of the DC04 cylindrical cups, DF is influenced both by the amount and type of BHF. In the case of a time variable BHF, a decrease in DF occurs after it reaches its maximum value. In the case of square deep-drawn AA 6016-T4 cups, DF is influenced by the amount and the type of BHF. A decrease in DF occurs only in the second stage of the drawing process, after it reaches its maximum value. In the first stage of the drawing process, the variable BHF is equal with the constant BHF. As a consequence no effect on DF occurs in first stages of the drawing process. In the case of square deep-drawn DC04 cups, a significant decreasing in DF has been observed in the second stage of the drawing process, when a variable BHF is used, as compared to the case of a constant BHF.
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