"Side-Wall Curl" in High-Strength Steels

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A study has been made of "side-wall curl" in a series of low-carbon, HSLA 50 and 80 and DP-80 steels. "Curl" occurs when the sheet metal is drawn into a die cavity, as in the forming of hat-shaped sections. It is found that the curl increases with increasing tensile strength and decreasing thickness of the steels, and that there is no consistent variation of curl with die radius. However, the curl, which is a consequence of residual stresses generated by the forming process, is thought to be influenced by the strain-hardening rate of the material, since this will affect the strain distribution through the sheet thickness. It is shown that, by the imposition of plastic deformation, the curl can be eliminated, as the result of the removal of the nonuniform distribution of residual stresses.

INTRODUCTION

Over the past few years, an ever-increasing number of structural components of the automobile have been stamped from high-strength steels (HSS). The use of these steels has exacerbated the problems encountered in forming. With an increase in strength, there is a decrease in ductility (elongation) and formability, as judged by the forming limit diagram, and an increase in springback. For a simple flanging operation or the forming of a U-channel, it has been shown that the degree of springback is proportional to an initial flow stress. When a hat-shaped section is formed from thin-gage HSS, it is found that, in addition to the springback, the side walls are curved; this is referred to as side-wall curl. In the production of a hat-shaped section, the steel is pulled over a radius into the die cavity. In practice, curl is not observed in 1.5- to 2.0-mm (0.06- to 0.08-in.) thick low-carbon steel sections. However, when low-carbon steels are replaced with thinner-gage HSS, side-wall curl raises serious assembly problems with components that are basically hat-shaped.

The present study was initiated to provide data on the influence of material strength and thickness, and die radius, on the side-wall curl. The materials investigated covered the whole range of conventional, and readily obtainable, HSS; the yield strengths of the steels were from 200 MPa (28 ksi) to 600 MPa (87 ksi).

EXPERIMENTAL PROCEDURES

The steels studied were all of a cold-rolled gage (thickness less than 1.8 mm (0.072 in.)) and consisted of a low-carbon, HSLA 50; HSLA 80; and a high-alloy, air-cooled, dual-phase steel (DP-80). The range of thicknesses studied varied with availability of steels with similar mechanical properties; thicknesses were chosen such that the total variation in yield strength for a given grade of steel was no more than 34 MPa (5 ksi). Average tensile properties of the steels investigated are shown in Table I.

To simulate the side-wall curl that is produced when the sheet metal is pulled into the die cavity, a die set, shown schematically in Figure 1, was employed. The L-shaped specimen, approximately 2.5-cm (1-in.) wide by 30.5-cm (12-in.) long, was bolted to the platen, which was moved by a hydraulically controlled ram. For most of the experiments, the ram speed was 8.5 mm per second (20 in. per minute). The motion of the platen caused the specimen to be pulled around the radius, $R$, of the die block; the radii selected...
Table I. Typical Mechanical Properties of the Steels in the As-Received Condition

<table>
<thead>
<tr>
<th>Material</th>
<th>Yield Stress, MPa (ksi)</th>
<th>Tensile Strength, MPa (ksi)</th>
<th>Uniform Elong., Pet</th>
<th>Total Elong., Pet</th>
<th>n-Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Low-carbon</td>
<td>186 (27)</td>
<td>276 (40)</td>
<td>27.0</td>
<td>38.0</td>
<td>0.23</td>
</tr>
<tr>
<td>HSLA 50</td>
<td>379 (55)</td>
<td>455 (66)</td>
<td>18.0</td>
<td>22.0</td>
<td>0.15</td>
</tr>
<tr>
<td>HSLA 80</td>
<td>572 (83)</td>
<td>662 (96)</td>
<td>12.0</td>
<td>14.0</td>
<td>0.11</td>
</tr>
<tr>
<td>DP-80</td>
<td>324 (47)</td>
<td>662 (96)</td>
<td>23.0</td>
<td>26.0</td>
<td>0.22</td>
</tr>
</tbody>
</table>

*n = Work-hardening exponent, slope of log true stress – log true strain curve, at a strain of 0.10.

for study were 3.17, 6.35, and 12.7 mm (0.125, 0.25, and 0.5 in). Thus, part of the specimen [B to C, in Figure 1(b)] has been deformed in a manner similar to that observed in the forming of hat-sections. The die block was also mounted on a hydraulically controlled ram, and it was positioned at the start of each experiment to provide a die gap of approximately 10% of the material thickness. The retaining plate on the die block was tightened, so as to give a snug fit against the specimen; no attempt was made to apply a preload on the specimen. After removal from the platen and die block, the specimen was cut at point C to provide a curled sample, with section A–B being flat (no deformation) and section B–C curled. Figure 2 shows actual examples of the curl in various strength steels.

There is no standard way to measure the curl. It was determined that the curl is not an arc of a circle, but has a continuously varying radius. Thus, no attempt was made to fit a given radius even to a small section of the curl. If an arc of a circle could have been easily fitted to the curl, this measure would have had the disadvantage of giving a value of infinite radius when there was no curl. An arbitrary measure of the curl was adopted, as shown in Figure 3. The curl, which was measured by means of a dial gauge to an accuracy of 0.01 mm, is zero when the specimen is flat and only exhibiting springback. From multiple specimens of the same material, the total spread in curl was 0.1 mm.

RESULTS AND DISCUSSION

This part of the paper is divided into several sections: The initial portion is concerned with some of the experimental factors that may influence the observed value of curl. This is followed by a presentation of the results of material thickness and die radius on curl; and then the curl values are correlated with material strength. Finally, it will be shown that an understanding of the origin of curl makes it possible to eliminate the curl from the specimen.

Experimental Factors that Could Influence Curl

Prior to the major study, several subsidiary experiments were performed, in order to define better the conditions under which curl occurs. As stated in the introduction, curl is not observed when a specimen is bent at essentially one point; curl is seen only when the steel is bent and pulled into the die cavity, so that the whole of the section exhibiting curl has been deformed. It should be noted that at the end of the forming action, Figure 1(b), the specimen is still flat because it is physically constrained, and that only upon removal from the die does the specimen “curl.” The curl is a result of residual stresses in the specimen from the obviously