The geometrical robustness of roll formed profiles in ultra high strength steels

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THE GEOMETRICAL ROBUSTNESS OF ROLL FORMED PROFILES
IN ULTRA HIGH STRENGTH STEELS

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ABSTRACT. To determine the geometrical robustness and process stability of roll formed profiles in Ultra High Strength Steel (UHSS) an investigation combining physical testing and FE simulation was conducted. The influence of roll forming on the tolerances of holes punched prior to roll forming and on the profile springback was studied. Measurements confirm that hole shapes are preserved also close to flange edges in UHSS, and that the standard design recommendations apply close to formed radii. This data will be used in new design rules for roll formed UHSS profiles. The conclusions are that UHSS are suitable for roll forming and that holes with high tolerance demands can be pre-punched in the vicinity of flange edges prior to roll forming.
1. INTRODUCTION

The industrial interest for roll forming has increased considerably since the method was recommended for forming of ultra high strength steel (UHSS). Not only is the method cost efficient with respect to material utilization, it can also be used for high-rate production of complex profiles where welding, punching and clinching operations are included in the roll-forming line.

Roll forming is suitable for components in UHSS, as successive bending enables forming of smaller corner radii than in press-brake bending. UHSS are suitable for roll forming, as their high material yield strength prevents plastic longitudinal strains and flange elongation. For that reason, roll forming of simple beams in UHSS demands a lower number of roll stations compared to when forming in mild steel. This has been verified both in research projects and in several successful industrial products [1-6]. As the industrial use of high strength steel is growing, so is the interest for design guidelines and numerical methods predicting roll forming of complex high strength profiles, including holes and pierce-nuts.

This article presents mid-term results from a research project concerning product development and production in ultra high strength steel. One objective of the project was to provide experimental and numerical data to new design guidelines for roll formed UHSS profiles [7-10]. The study includes roll forming experiments in an industrial environment, using four different UHSS materials to analyse the influence of material properties on the geometry of the formed profiles.

The study had two purposes:

- To determine the final tolerances of a hole stamped before roll forming at different positions in the unformed sheet.
- To determine the process robustness of roll forming with respect to springback and flare.

2. MATERIALS

To investigate the influence of material properties on the final geometry of the roll formed profiles, four different ultra high strength steels were used, see Table 1. Material 1, used as the reference UHS steel in this study, is a hot-dip galvanised, cold rolled, dual phase steel with a tensile strength of 1104 MPa. Material 2 has a lower martensite level, and thus a lower ultimate tensile strength. Material 3 has the same ultimate tensile strength as Material 1, but is designed for a high yield-to-tensile-strength ratio. Material 4 is almost fully martensitic, and has thus a higher strength value than Material 1.

Table 1. Materials used in the roll forming experiments.

<table>
<thead>
<tr>
<th>Material</th>
<th>Thickness [mm]</th>
<th>Rp0.2 Yield strength [MPa]</th>
<th>Rm Ultimate Tensile strength [MPa]</th>
<th>Rp0.2 /Rm</th>
<th>A80</th>
<th>Surface</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1.5</td>
<td>948</td>
<td>1104</td>
<td>0.86</td>
<td>8</td>
<td>Hot dip Zn</td>
</tr>
<tr>
<td>2</td>
<td>1.5</td>
<td>659</td>
<td>857</td>
<td>0.77</td>
<td>16</td>
<td>Hot dip Zn</td>
</tr>
<tr>
<td>3</td>
<td>1.5</td>
<td>993</td>
<td>1003</td>
<td>0.99</td>
<td>7</td>
<td>Cold rolled</td>
</tr>
<tr>
<td>4</td>
<td>1.5</td>
<td>1286</td>
<td>1522</td>
<td>0.84</td>
<td>5</td>
<td>Cold rolled</td>
</tr>
</tbody>
</table>
3. EXPERIMENTAL PROCEDURE

3.1. Roll forming experiments

The profile selected for the roll forming experiments was an open U beam with flanges, see Figure 1. The width of the beam, including flanges, was 105.75 mm. The smallest inner bending radius between roof and wall was 1.5 mm, \((R = t)\).

\[\text{Figure 1. Shape of the studied profile.}\]

The roll forming was performed in a manufacturing roll forming line at the company Bendiro Profile Tech in Falkenberg, Sweden. The line consisted of 12 forming stations, where the first tool produces no bending operation, see Figure 2. To enable testing of pierce-nuts in the roll forming line, allowances were made in the tools for pierce-nuts in the centre of the profile [11]. The tools were hardened to 60 HRC and lubricated before forming with mineral oil. Roll forming was performed from 256 mm wide coils, and the profiles were cut after forming to lengths about 3.2 m.

\[\text{Figure 2. CAD model of the roll forming line used in the FE analyses The coil is moving from the right to the left in the figure.}\]
One design guideline that needs to be revised for UHSS is how close to intended radii and edges a pre-punched hole can be located. For soft steels, one recommendation is to place the hole not closer than $3t$ to a radius or flange edge, where $t$ is the sheet metal thickness. In the current experiments, series of three holes with 9.5 mm in diameter, displaced 50 mm in longitudinal $(Y)$ and 1 mm in radial $(X)$ direction, were placed to cover the vicinity of edges and corners with radial steps of 1 mm, see Figures 3 and 4. Pre-punching was performed in an excenter press in the roll forming line, at every 200 mm interval of the sheet coil.

![Figure 3. Example on localisation of pre-punched holes in the coil.](image)

The reference material Material 1 was formed both with and without pre-punched holes and pierce nuts to evaluate the process limits for hole location. The remaining materials were formed to profiles without pre-punched holes, to compare the shape accuracy of the different materials.

### 3.2. FE analysis

The numerical simulations were carried out with finite element programs ABAQUS [12] and LS-DYNA [13]. The roll forming tools were modelled as rigid bodies based on geometrical input on the complete roll forming line. In this study the blank was modelled with shell elements, which consist of 7 to 9 integration points through the thickness. In the FE simulation, the friction is modelled using the Coulomb friction law. An appropriate constitutive model is used that depends on the material properties of the blank [14]. The results from the FE investigation will be presented in a separate paper.

### 3.3. Measurements

The geometry of the formed profile was measured by optical 3D scanning and compared to the nominal geometry of the profile as well as to the FE simulated profile. Measured parameters were:

- Springback of flanges
- Increased springback in the profile ends (“flare”)
- Hole dimensions in roll formed profiles
Optical scanning was performed with the system Atos II with measurement areas: 500x450 mm and 135x175 mm. To combine the different measurements of each 3 m long profile, the full reference system of the profiles was captured with a Tritop system [15]. The data from each material variant stems from measurements of 25 cross sections in three different profiles, ten sections in each profile end and five in the profile centre, see Figure 4. The pre-punched holes were measured with the higher resolution.

![Reference system of the formed profiles](image)

**Figure 4.** Reference system of the formed profiles (X upwards in the figure, Y to the right towards the front edge of the beam) and localisation of shape measurements.

3.4. **Methods of evaluation**

The radii and wall angles captured by 3D scanning were compared to planes and radii to evaluate the springback and flare of each cross section. As the beams were not equal in length, the centre of the beam was used as one reference point, see Figure 4.

4. **RESULTS AND DISCUSSION**

4.1. **Roll forming experiments**

The profiles without pre-punched holes were formed without cracks or deformed radii in all investigated materials. The profile cross section had a deviation from the nominal profile in all materials, as a consequence of springback in the wall and flange. As the entry of the sheet into the roll forming line allowed for some lateral movement, the radial distance of the pre-punched hole from coil edge was registered for each hole series. All holes except one, 1 mm from the flange edge, were formed without cracks.

4.2. **Measurements**

**Springback**

The following Figures 5 to 8 describe the springback of the flanges and the flare of the formed profiles in the four different materials. What is apparent is that Material 3 has the lowest springback, although it is higher in strength than Material 2. It is also surprising that Material 4 has a lower springback in the centre of the profile than Material 1, a material with a much lower strength. Material 4, with the highest yield strength, should have the largest springback of all materials in this study, according to general bending theory.
Flare

The flare, defined as the increased springback at the ends of the profile, is concentrated to 500 mm of each profile end, representing a third of the total profile length. The flare has almost the same shape over the profiles for three of the materials: Material 2, Material 1 and Material 3. The flare of the steel with the highest strength, Material 4, is much lower. In the area where the flare starts, the springback reaches its minimum, in all studied materials.

Figure 5. Measured total width in the centre of formed profiles.

The different appearance of Material 4 compared with the other materials is even more obvious in Figure 7, an enlarged portion of the diagram.

Figure 6. Measured profile width over the entire profile length.
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Figure 7. Flare in the front portion of the profiles.

We here introduce the result parameter “Delta Flare”, defined as the difference between the springback at the end of a profile and the springback in the centre of the profile. Using this parameter, the different appearance of Material 4 compared with the other materials is clear, see Figure 8. The difference is reduced from 6 mm to 2 mm for Material 4.

Figure 8. Delta Flare: Difference between springback in the profile centre and front end, in relation to material yield strength.
Pre-punched holes

The optical scanning measurements of the hole geometry were used to calculate the maximum diameter deviation compared with the nominal value, 9.5 mm, and the hole out-of-roundness. The results are shown in Figures 9 and 10, in relation to the distance from hole edge to flange edge. The flange width in the profiles was 28 mm. Only the holes on the upper flange are discussed below.

The holes close to the flange edge had a smaller diameter than in the centre flange area and close to the wall radius, see Figure 9. The largest deviations were found in the centre of the flange, where positive deviations up to 0.17 mm were measured.

![Figure 9. Maximum hole deviation on the flange in relation to the distance to the flange edge. Points denoted by squares represent holes within the distance 3xt to edge or radius.](image)

To place holes close to the flange edge or centre of the flange caused low problems with out-of-roundness. Close to the wall radius, the hole shapes deviated more, but the out-of-roundness did not exceed 2% at any location of the flange, see Figure 10.
4.3. Discussion

That all materials could be formed with radius 1.5 mm, $lxt$, once again proves how suitable ultra high strength steels are for roll forming. For the material with the highest strength, Material 4, the recommended minimum radius for a 90-degree bend is $3xt$ for other forming methods, such as press brake bending and stamping.

The low springback and flare of Material 4, with the highest strength in the study, is noticeable. One possible explanation for the lower springback can be strain localisation caused by the small radius formed in the high strength materials. This effect was also observed for roll formed V profiles, where a material similar to Material 4 obtained smaller radii (without micro-cracks) than lower strength materials [2].

One suggested explanation for the flare effect is that the residual stresses introduced during roll forming differ at the profile ends. The longitudinal stress release in the free profile ends may cause increased springback. If the material has a sufficiently high strength in relation to the forming complexity, the difference between the stress in the outer and inner fibres of the sheet thickness is low in comparison to the yield strength, resulting in a smaller flare in the roll formed profile. It is shown that the peak longitudinal strain decrease with increasing material yield strength. The materials in this study, that are all UHSS materials, should not differ significantly in peak longitudinal strain, at most 0,1 % according to [3]. Also, the high strength of the material can have a restraining effect on the profile end flare. Further studies including the FE analyses will be reported in the following papers.

Material 3 has a lower springback than expected, if only the material ultimate tensile strength is considered. This material is specially designed for roll forming, as it has a high yield-to-tensile-strength ratio (0.99), which reduces the tendency for edge elongation during roll forming.

Figure 10. Out-of-roundness of holes on the flange in relation to the distance to the flange edge. Points denoted by squares represent holes within the distance $3xt$ to edge or radius.
What is similar for Materials 3 and 4 are that these materials have a lower potential for deformation hardening compared with the other two, and for different reasons: Material 3 has a narrow distance between yield strength and ultimate tensile strength, while Material 4 has a very low volume of remaining ferrite that may transform to martensite during deformation.

Holes can be punched prior to forming with good tolerances close to the formed profile flange edges. To avoid out-of-roundness, it would be preferable to place the holes closer to the edge than to the corner: the out-of-roundness of the holes remained low as close as $2xt$ from the edge. For high tolerance holes close to the flange radius, a distance of $3xt$ from the start of the radius is recommended to avoid out-of-roundness, according to these experiments in UHSS.

The maximal positive deviation in hole diameter was observed in the centre of the flange. This could be correlated to preliminary results from the FE analyses, indicating that the flange is in radial compression close to the edge and corner radius, but that tensile radial stresses are obtained in the centre of the flange.

For a reference vehicle component, all the pre-punched holes in the flange were within the Swedish H13 tolerance, but only the holes close to the edge were within the H12 tolerance.

5. CONCLUSIONS

- Ultra high strength steels are suitable for roll forming, and radii close to $1xt$ could be formed in the studied U-beams
- Ultra high strength steels with a lower tendency for deformation hardening had a lower springback in relation to their ultimate tensile strength
- Pre-punched holes with high tolerance demands can be placed close to flange edges in UHSS profiles prior to roll forming
- New design guidelines for roll forming of complex profiles of ultra high strength steels are needed.

6. ACKNOWLEDGEMENTS

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7. REFERENCES

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