Abstract

The use of roll-formed products in automotive, furniture, buildings etc. increases every year due to the low part-production cost and the complicated cross-sections that can be produced. The limitation with roll-forming until recent years is that one could only produce profiles with a constant cross-section in the longitudinal direction. About eight years ago ORTIC AB [1] developed a method, “3D roll-forming”, that could produce profiles with a variable width (“3D roll-forming”) for the building industry. Experimental equipment was recently built for research and prototyping of profiles with variable cross-section in both width and depth for the automotive industry. The objective with the current study is to investigate the new tooling concept that makes it possible to roll-form hat-profiles, made of ultra high strength steel, with variable cross-section in depth and width. The result shows that it is possible to produce 3D roll-formed profiles with close tolerances.

Keywords: 3D roll-forming, Variable cross-section, Flexible roll-forming, Profile, Ultra high strength steel.

1. Introduction

1.1 Background

Roll-forming is a sheet metal forming process where the forming occurs with rolls in several steps, often from an undeformed sheet to a product ready to use. This is a highly productive process and the speed by which the profiles can be formed is between 5-60 m/min depending on a second operation such as welding, punching, etc that often is done in the same line. The use of the process increases due to the possibility to produce complex products in material as ultra high strength steel.

The limitation with the process until eight years ago was that only a profile with constant cross-section was possible to produce. At that time ORTIC AB [1] developed a method, “3D roll-forming”, that could produce panels to buildings where the cross-section was variable in the longitudinal direction, Figure 1.

![Figure 1. Roll formed panels with variable cross-section (3D roll-forming).](image)
The method used is very flexible which means that panels with different geometry in the longitudinal direction can be produced with the same set-up of roll-forming tools. The Budapest Arena for example is covered with 4700 different individually shaped panels. Today many buildings worldwide have been covered with panels produced using this method [2]. The success of the forming method has made other industries interested.

The automotive industry is one area where 3D roll-forming is of great interest since the industry can utilise the flexibility of the method together with the use of high strength steel with low part-production cost. A 3D roll-forming experimental machine has been built to use for research and to fulfil the needs of prototypes for the automotive industry. The difference compared to the machines for the building industry is that a profile with variable depth can also be produced.

The objective with this study is to investigate a new tooling concept that makes it possible to roll form hat-profiles with variable depth and width in longitudinal direction. To evaluate the new tooling concept three different hat-profiles, one with constant cross-section and two with variable cross-section in depth and width, are roll-formed and the tolerances from fifty profiles of each kind are compared.

1.2 Previous work

In 2001 ORTIC AB [1] developed a 3D roll-forming machine for conical profiles, Ingvarsson [3]. The machine was built in a mobile container and moved around the world to different construction sites. The machine was used for covering straight and circular roofs. In 2002 the technology was further developed, a 3D roll-forming machine, not only for conical profiles, and a curving mill were built for profiles with curvature and variable width in longitudinal direction. This technology made it possible to cover for example the Budapest arena and many other buildings world wide, [2].

Groche et. al. [4] described a new tooling concept for flexible roll-forming. A single flexible stand was integrated in a conventional roll-forming line. Through tests with finite element simulations and experiments it was shown that the flexible frame should be perpendicular to the bending edge to give a profile with quality. A CAD-system was also developed where the bending edge can be drawn and read by the control program for the machine.

Ona [5] studied the 3D roll-forming process with a single forming stand, that made it possible to rotate, turn and move the tools in and out. The movements were depending on feed rate of the sheet metal, which was measured with a rotary encoder. A U-profile with variable cross-section was studied. It was shown in the experiments that the material in the edge of the flange were compressed or stretched, Figure 2, which gave buckling or distortion, if the flange was too high. Ona also concluded that the increasing number of forming steps would decrease the buckling and distortion.

Groche et. al. [6] developed an analytic one-step-model to use for the design of wrinkle free 3D roll formed U-profiles. The model is semi-empirical and based on mechanics of buckling of plates and a series of finite element analyses. The model focuses on the compressed area, Figure 2, and is used as a feasibility check without simulation or experimental tests.

Güleceken et. al. [7] used COPRA® RF [8] coupled with finite element module MSC.Marc® [9] to simulate the 3D roll-forming process. The objective with the study was to explore the process using finite element simulation. The results from the simulations show end-flare in the back and front of the U-profile, which is common for roll-forming of pre-cut material. Due to the programmability of the tools they concluded that end-flare might be possible to compensate for by increasing the bending in the end and the beginning of the profile. The simulations also show a variation in the leg height of ±1 mm, they conclude it could originate from relatively rough finite element mesh.

Figure 2. A 3D roll-formed U-profile. Tension stress acts in transition zone where the U-profile is small and compression stress in the transition zone where the profile is wider.
2. Experimental procedure

2.1 The roll-forming machine and new tooling concept

A 3D roll-forming experimental machine is used to form profiles with variable depth and width. The machine has slitter heads, to fit the metal sheet, and six forming stands where every stand has four units. The units have servo control axis, two translations and two rotations axis. The unit can be moved up and down, in and out, rotate and the speed of the tool can be controlled individually.

The geometry of the tools is simple, i.e. the tools are completely cylindrical. This also means that the thickness of the material can vary without having to install new tools. The size of the machine decides which thickness of the material that can be roll-formed.

In this study a hat-profile with variable depth and width has been roll-formed and for this type of profile the new tooling concept demand two forming stands per pass, Figure 3. Forming stand number 1, 3 and 5 form the left side of the profile and the forming stand number 2, 4, and 6 the right side. For example the profiles are roll-formed in six forming steps with bend angles 15°, 30°, 45°, 60°, 75° and 85° and therefore the profile demands two laps in the machine, the first 15°-45° and then the control program of the machine is switched to the next lap 60°-85°.

The tools are the same for all stands, for example in Figure 4 one can see that the tools for the left and right side are the same for both 30° and 60°. The difference between the passes is that tools that hold the flange have moved up and moved closer to the tools that hold the web. The used “flower pattern” is a function of the length of the profile. This flexibility makes it possible to use as many passes as the cross-section requires without making more tools. It also makes it possible to produce profiles with, not only variable width, but also, variable depth in different thickness of the material.

![Figure 3](image1.png) View from the top. The profile is roll-formed in six passes and to do that the profile must go through the machine two laps. Forming stand number 1, 3 and 5 formed the left side and forming stand number 2, 4, and 6 formed the right side.

![Figure 4](image2.png) View from the back. The geometry of the tools is same for all forming stands. The only difference between, for example, bend angles 30° and 60° is that the tools for the flange are moving up and closer to the tools that hold the web. Tools with “constant radius” have been used, Lindgren et al.[10].
The horizontal distance between the forming stands is 400 mm. The production speed that is used during the tolerance tests is 2.6 m/min. A simple input and run out table is used and the profiles are hand fed both the first and the second lap. First all profiles with the same cross-section go through their first roll-forming lap. Then is the control program switch to the second lap and all profiles of same cross-section are finished.

2.2 The profiles and material

The used material is ultra high strength dual phase steel, Docol 1000 DP. The thickness of 30 sheets has been measured with micrometer and the mean value is 0.970 mm and with a standard deviation of 0.008 mm. The width and the length of the as-received material are 400 mm and 1500 mm respectively. The slitter heads in the beginning of the machine are used to give the blanks the right width.

Three hat-profiles with different cross-section have been studied, Figure 5, a straight, a conical in depth and width and a profile with a waist on one side. The length, the thickness, the inner radius of the cross-sections and the bend angles are the same for all profiles and they are 1500 mm, 1 mm, 2 mm and $85^\circ$ respectively. The number of hat-profiles, of each kind, that has been produced and measured are 50.

![Figure 5](image1.png) Three different hat-profiles have been roll formed.

2.3 The measurement equipment

An optical scanner, ATOS, [11], based on the principle of triangulation is used to measure the variation of the profiles. The accuracy of the measurement equipment and the fixture are tested and the variation is less than 0.07 mm.

The fixture positions the hat-profile in the web, z-direction see Figure 6, with three reference points and one support point, the distance between the points in the longitudinal direction is 1300 mm. In the y-direction the profile positions with two reference points and two support points and in the x-direction one reference point is used.

![Figure 6](image2.png) Points (light dots) on the flanges (F), at the sides (S) and in the bottom (B) are measured and this is done in eleven different cross-sections in the longitudinal direction.
Eleven different cross-sections in the longitudinal direction have been measured, five cross-sections in the middle part of the hat-profile and three cross-sections in the ends, Figure 6. The distance between the cross-sections is 100 mm. In every cross-section eleven points are measured, two on respective flange, two on respective side and three points in the web, notations for the points see Figure 6.

3. Result and discussion

3.1 Result

In the study 50 hat-profiles of each type, Figure 7, have been measured. The results from these measurements are compared to see if the new tooling concept works and can produce profile with same tolerances both for straight ones and ones with variable depth and width.

The variations between the measured points are presented with a range and standard deviation plot, Figure 8 – Figure 10. The surfaces in these plots are a function of position of the measured points (light dots) in Figure 6. In this figure the coordinate system is also defined for the profiles.

Figure 7. The produced hat-profiles. The top profile is straight, the middle one has a waist on one side and the bottom is a conical profile in both depth and width.

In Figure 8 the range, the difference between the maximum and minimum value, and the standard deviation are presented for the straight hat-profile. The result shows that most points are below 1.2 mm in range and a standard deviation of 0.3 mm or less. The maximum value is on the right flange, 1.46 mm, with a standard deviation of 0.26 mm. The web has less variation than the flanges and the maximum value is 0.78 mm with a standard deviation of 0.19 mm. It can also be seen that the profiles have low variation in the points, (B7, -600) and (B5, -600), this is where the profiles are fixed to the measurement fixture.

![Figure 8](image-url)

Figure 8. To the left is the range and to the right is the standard deviation for each point in longitudinal direction of the straight hat-profile. The coordinate system, x = longitudinal direction, y = measured point, see Figure 6.
The result for the conical hat-profiles in depth and width, Figure 9, shows that the range for most of the points is below 1.2 mm and with a standard deviation less than 0.3 mm. The highest value (range) is 1.52 mm with a standard deviation is 0.31 mm. This point is located in the left flange in the beginning of the profile.

In Figure 10 the range and standard deviation are presented for the hat-profile with a waist on one side. The range is less than 1.2 mm and the standard deviation is less than 0.3 mm for almost every point. The maximum value is on the right flange in the beginning of the profile. The value is 1.67 mm and the standard deviation 0.33 mm.

**Figure 9.** To the left is the range, the difference between the maximum and minimum value, and to the right the corresponding standard deviation for the hat-profile with conical width and depth. The coordinate system, x = longitudinal direction, y = measured point, see Figure 6.

**Figure 10.** The measured result for the hat-profile with a waist on one side is presented. To the left is the range, the difference between the maximum and minimum value, and to the right is the corresponding standard deviation. The coordinate system, x = longitudinal direction, y = measured point, see Figure 6.
3.2 Discussion

The focus in the current study is to investigate the new tooling concept and see if the cross-section tolerances are similar for different types of 3D roll-formed profiles.

The profiles can be divided into three types:

1. Straight profiles. The tooling is not translating or rotating in z-direction (**Figure 6**) during the forming. This is the same as in traditional roll-forming.
2. Conical profiles in depth and width. The tooling translates in z- and y-direction (**Figure 6**). This is only still a bending in longitudinal direction. Then the residual stresses are similar as for straight profiles.
3. Profiles with transition zones, similar to the profile in **Figure 3**. The tooling will translate and rotate in all direction during the forming.

It can be expected to be more difficult to fulfil tolerance requirements when forming conical profiles than for straight profiles. However, the study shows that the tolerances are at the same level, **Figure 8** and **Figure 9**. The range for most points is under 1.2 mm with a standard deviation of less than 0.3 mm. This means that only translation of the tools does not make it more difficult to fulfil the tolerances.

Comparing the result of the forming of the profile of the third type with the straight profile show that the tolerances are also in this case about the same in level, **Figure 8** and **Figure 10**. The difference, apart from that the tools translate and rotate in all directions, is that the profile will get residual stresses after forming completely different from profile 1 and 2. This is due to complex material flow in this forming process and it may warp the web and the flange, **Figure 11**. In the study the goal was to get a flange that was in the same plane throughout the complete profile. To do that the length of the leg has been made longer in this area, see **Figure 12**.

![Figure 11](image1.png)

**Figure 11.** The complex material flow warps the web and the flange so the flange is not on the same plane in the longitudinal direction.

![Figure 12](image2.png)

**Figure 12.** In the study was a goal to get the flange in the same plane in the longitudinal direction. To do that the length of the leg has been made longer in the warping zone. This is possible with the new tooling concept.

The tool concept requires one to hold on to the flange and the web in each forming station, **Figure 4**. To be able to do so the flange has to have a certain width so that the material does not slip away from the tool which would lead to variations of the width of the flange. During the test it has been noted that a width of at least 10 mm is needed to avoid this problem.
4. Conclusion

Probably one of the first 3D roll-forming machines in the world with two translational and two rotational degrees of freedom per axis has been built and used in the current study. Based on a specific tooling concept hat-profiles with variable cross-section in depth and width has been produced using simple cylindrical shaped rolls.

The main conclusions are:

- The new tooling concept makes it possible to roll-form hat-profiles with a variable cross-section both in depth and width with tolerances on the same level as for straight profiles.
- The tools make it possible to roll-form different thickness of the material with only software changes due to their simple, cylindrical shape.
- The flange of the hat-profile must be at least 10 mm to avoid that the flange slips in the tools and thereby cause variations of the width.
- Three different profiles have been identified in the study, type 1, which are completely straight, type 2 are conical profiles and type 3, profiles with transitions zones. The first two give similar residual stresses in the longitudinal direction and they are easy to produce. Type 3 gets residual stresses that can give wavy edges, distortion of the web and flange, these profiles require careful design of the process.

5. Reference

[1] ORTIC AB, (www.ortic.se)

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