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ORIGINAL ARTICLE

The effect of process and geometric parameters on longitudinal edge strain and product defects in cold roll forming

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Abstract Roll forming has been used traditionally in the construction and housing industry for the production of longitudinal components but is now increasingly applied in the automotive industry for the manufacture of structural and crash components from ultra high-strength steel (UHSS); the incremental nature of this process allows these hard-to-form materials to be shaped with higher efficiency and less shape defects than observed in common sheet forming processes such as stamping. Tight dimensional tolerances are imposed on automotive components, and this can lead to problems when roll forming UHSS where the high material strength results in shape defect and forming problems. Recent work has therefore increasingly focused on developing process monitoring and control routines for roll forming to improve process robustness and part quality. In roll forming, the longitudinal edge strain is considered to be related to product defects such as bow, twist and end flare. Process and part shape parameters have been shown to significantly influence peak longitudinal edge strain, and the link between process and product parameters, longitudinal edge strain and shape defects needs to be understood for the roll forming of UHSS if routines for process monitoring and control are to be established. Previous studies were mainly focused on traditional roll forming materials used for building products and the like. In this paper, the effect of process and part shape parameters on the peak longitudinal edge strain, longitudinal bow and springback is experimentally and statistically investigated for three different advanced high-strength steel (AHSS) and UHSS commonly used in automotive manufacturing. The results show that there are significant differences in behaviour when forming UHSS and that forming trends differ from those reported for softer steel grades. The experimental data presented in this paper should contribute to the further development of advanced process monitoring and part shape quality control routines in the roll forming AHSS and UHSS.

Keywords Roll forming · Peak longitudinal edge strain · Longitudinal bow · Springback · Sensitivity study · High-strength steel

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1 Introduction

Roll forming is a continuous sheet forming process in which metal strip is formed incrementally into the required shape using a number of rotating rolls; it allows materials that combine high strength with limited ductility to be formed to tight radii [1] and with less springback than commonly found in bending operations [2–4].

The conventional roll formed products are gutters, roofing, windows, doors and other building products in which dimensional accuracy requirements are not particularly stringent. Nowadays, the process is being used increasingly in the automotive industry for the manufacture of structural and crash components from ultra high-strength steel (UHSS). The main drawback in using advanced high-strength steel (AHSS) and UHSS is the high value of springback and unacceptable product quality. This is due to their higher material strength, which leads to higher levels of residual stress and elastic recovery compared to conventional lower-strength steels. Tight dimensional tolerances are imposed on automotive components, and

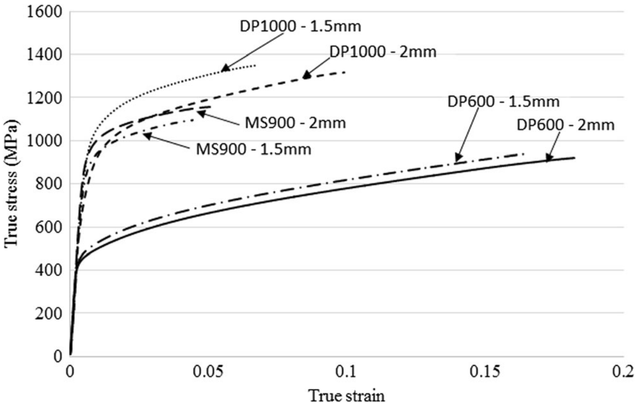


Fig. 1 Average true stress–strain curve along the rolling direction for DP600, DP1000 and MS900 in 1.5- and 2-mm thicknesses

this is in contrast to the housing and construction industry where roll forming has been traditionally applied. To improve process robustness and part quality when roll forming UHSS, research has focussed increasingly on the development of process monitoring and control techniques [5, 6].

In roll forming the part, shape depends on material, part dimensions and process parameters. The edge of the flange travels a larger distance than the centre-line material leading to longitudinal strain at the edge of the flange [7]. The level and distribution of longitudinal edge strain have been shown to be a prominent factor in common roll forming defects such as longitudinal bow, twist and camber [8]. To permit the introduction of process monitoring and in-line shape compensation routines, the effect of process, material and part shape parameters on longitudinal edge strain as well as final part shape needs to be understood for the forming of AHSS and UHSS.

According to the literature, part shape parameters that influence the peak longitudinal edge strain are the material thickness, the width of the web and the flange length. In addition, process and material parameters such as forming angle, inter-station distance, bottom roll diameter and material yield strength play a significant role. Experimental studies that investigate the effect of these parameters on the longitudinal edge strain are limited, possibly because of the difficulty of obtaining strain values during the roll forming process [9–11]. Analytical [11–13] and numerical [14–17] studies can be found in the literature, and some give contradictory results. For example, while the numerical study performed by Han et al. [14, 15] showed an increase in peak longitudinal strain with material yield strength, Lindgren [13, 18] and Azizitafti [17] observed the opposite trend in numerical studies of a U-channel profile. All previous experimental studies are limited to traditional and softer material grades and therefore may not be representative for the roll forming of AHSS and UHSS.

The effect of material properties, on longitudinal bow, a common defect in roll forming, is still under investigation, and only limited experimental work restricted to softer steel grades such as aluminium and mild steel can be found in the literature [9]. A previous work further suggests that longitudinal bow is the result of an uneven longitudinal residual strain distribution over the length of a part [19]. Since residual strain is partly a material-dependent parameter, longitudinal bow may be greatly affected by material strength. Abeyrathna et al. [20] further showed that longitudinal bow depends not only on the material strength but also on the profile geometry, and this, together with previously mentioned, suggests that understanding the combined effect of material properties, process and part shape parameters on longitudinal bow is essential to ensure a robust roll forming process especially when forming AHSS and UHSS.

AHSS and UHSS exhibit higher springback than mild steel, and therefore, a good understanding of how it is affected by process, part shape and material parameters is important to achieve a robust process design. Unlike V-die forming or folding, very few experimental investigations have focused on springback in roll forming [2, 8, 21–25]. Springback is considerably smaller in roll forming than in V-die forming [21], and some studies have related this to the incremental nature of the process [2]. Another investigation suggested that the low level of springback observed in roll forming is a result of redundant deformation [8], and this would indicate that it may be related to roll forming process parameters. The effect of process and geometrical parameters such as the inter-station distance, forming angle and flange length on springback has not been investigated before and will be part of this study.

The previous review has shown that even though some studies have investigated longitudinal edge strain and part shape defects in roll forming, they were mostly limited to numerical work and lower-strength steel grades. UHSS and

Table 1 Material properties determined from the Hollomon's law fitted to the true stress–effective plastic strain curves for DP600, DP1000 and MS900

Material	Material thickness (mm)	Yield strength $R_{p0.2}$ (MPa)	Young's modulus (GPa)	Ultimate tensile strength (MPa)	Elastic limit (m/m)	n
DP600	2	446	200	768	0.0022	0.12
DP1000	2	764	200	1194	0.0038	0.12
MS900	2	932	205	1103	0.0045	0.06
DP600	1.5	469	200	797	0.0023	0.10
DP1000	1.5	955	200	1261	0.0048	0.09
MS900	1.5	851	205	1046	0.0042	0.07

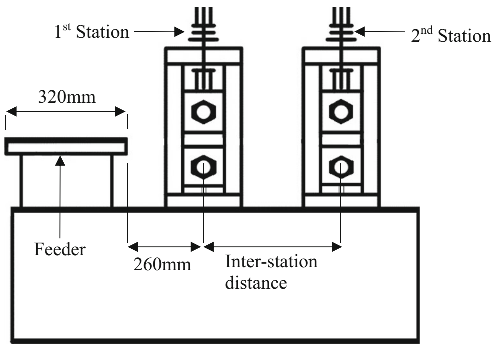


Fig. 2 Schematic of the roll forming setup used for the roll forming experiments

AHSS show yield strength levels that are more than triple those found in traditional and softer steel grades, and their strain hardening rates can be significantly different. This may lead to a different material behaviour in the process and may also affect part quality. This paper experimentally investigates the effect of the inter-station distance, flange length, forming angle and material thickness on the peak longitudinal edge strain, longitudinal bow and springback. In addition, the effects of material parameters such as yield strength and material hardening are investigated by performing roll forming trials on three AHSS and UHSS—a DP600, a DP1000 and a MS900 steel. The DP600 steel and the DP1000 steel show different levels of yield strength, but similar hardening characteristics. The DP1000 and the MS900 have higher yield strength levels but different material hardening. This allows the separation of the effect of material hardening and yield strength on longitudinal edge strain, bow and springback which, to the authors' knowledge, has not been experimentally investigated before. Significant variations in material strength and thickness from coil to coil are common in UHSS and need to be adjusted to maintain high part quality. For this, the effect of material property variations on part shape needs to be understood depending on part shape parameters and process conditions to enable estimating the level of tool adjustment or compensation required.

The experimental work of this paper will produce this information and therefore will be a vital step towards the further development of advanced process monitoring and part shape quality control routines in the roll forming of AHSS and UHSS.

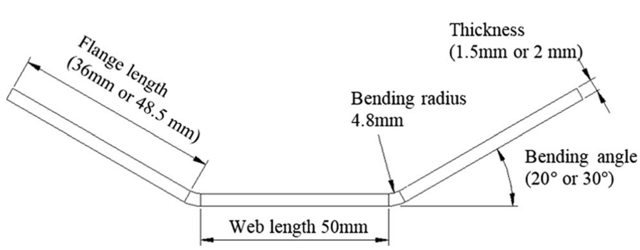


Fig. 3 Part shape parameters investigated in the analysis

Table 2 Different parameter levels

Parameter	Level 1	Level 2
Flange length (mm)	36	48.5
Bending angle (°)	20	30
Inter-station distance (mm)	250	400
Material thickness (mm)	1.5	2

2 Experimental procedure

2.1 Materials

Two dual-phase steels, DP600 and DP1000, and one martensitic steel, MS900, supplied by the Svenskt Stål AB (SSAB) Steel Company were analysed. Tensile tests were carried out on bone-shaped samples oriented along the rolling direction, according to ASTM E8/E8M [26]. An Instron 5967 with a 30-kN load cell was used, and the test speed was 0.025 mm s^{-1} giving a constant strain rate of 0.001 s^{-1}. The average true stress–strain curves of the various material grades were obtained by testing three samples from each material and are shown in Fig. 1 for the two thickness ranges tested. The elastic limit and the yield strength of the material were determined applying the 0.2% strain offset ($R_{p0.2}$) [27]. The ultimate tensile strength was obtained from the engineering stress–strain curves. The other material parameters were determined by fitting Hollomon's equation (Eq. (1)) to the averaged true stress–effective plastic strain curve of each material and are given in Table 1. It can be seen that the yield strength levels are higher in the thinner strip for the two dual-phase grades, while the opposite trend is observed for the martensitic grade. The materials selected permit the study of the effect of yield strength and material hardening as well as material thickness on longitudinal edge strain, bow and springback for various process and part shape parameters.

$$\sigma = k\varepsilon_{eps}{}^{n} \quad (1)$$

where σ is the true stress, n is the hardening exponent, k is the strength coefficient, and ε_{eps} is the effective plastic strain.

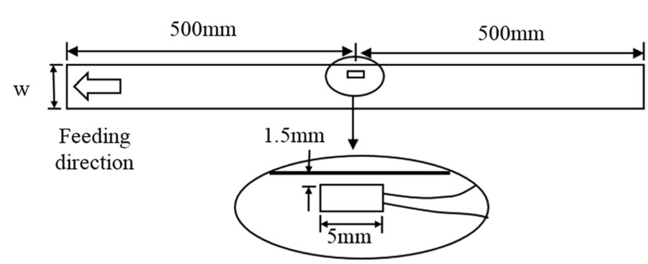


Fig. 4 Location of the strain gauge on the strip used for the roll forming trials

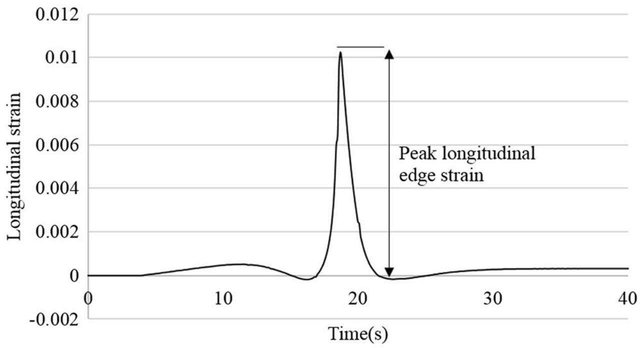


Fig. 5 The distribution of longitudinal edge strain for the roll forming with a single forming station

2.2 Experimental roll forming trials

The laboratory roll former shown schematically in Fig. 2 was used. A channel section was roll formed in one forming station with pre-cut sheet samples coming from a feeder. For this, the strip was first fed into station 1 where it was pushed forward by two cylindrical rollers into station 2 (Fig. 2) to form the desired angles of 20° and 30° (Fig. 3). Each bottom shaft is driven separately by identical AC motors giving a line speed of 17.3 mm s^{-1}. All experiments were carried out without lubrication, and strips of 1-m length were formed. Since the material properties are different between the two material thicknesses, the effect of flange length, forming angle and inter-station distance on the peak longitudinal strain, longitudinal bow and springback, was investigated separately for both material thicknesses. The different variables and their levels are indicated in Figs. 2 and 3 and in Table 2.

With four variables and two levels of each, there are 16 combinations which will be tested in the experiments as shown in Table 3 (see the Appendix). The same set of experiments is carried out for each material.

2.3 Measurement of longitudinal edge strain

Longitudinal edge strain was measured on the top surface near the edge of the strip as shown in Fig. 4. Single-element TML electrical resistance strain gauges [28] with 120-Ω gauge resistance were used; these are capable of measuring the strain up to 3%. An ALMEMO 2590-4S universal data logger [29] together with a 120-Ω Wheatstone bridge recorded strain during the test.

A typical longitudinal surface strain measurement for roll forming with one single stand is shown in Fig. 5. The peak longitudinal edge strain can be seen just before the strip passes the roll centre. Only the peak longitudinal edge strain on the top surface was analysed in the following work.

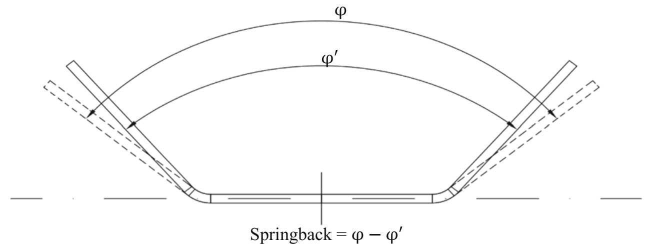


Fig. 7 Springback definition

2.4 Measurement of bow and springback

To measure longitudinal bow after releasing the section from the roll former, the outer surface was scanned using an "ExaScan" 3D scanner [30] as described by Abeyrathna et al. in [6]. Bow is defined as the vertical height deviation of the web over the length of the part compared with the target shape as shown in Fig. 6.

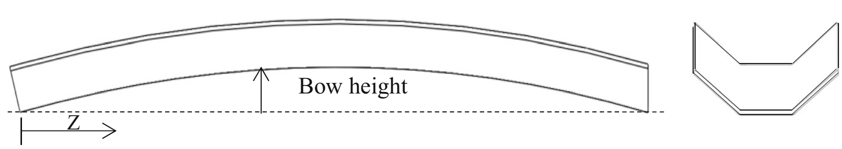
For measuring springback after roll forming, it is assumed that the loaded part has a final bending angle that corresponds to the profile of the bottom roll in the last forming station. Springback can then be considered as the angular difference between the final roll formed part (φ) and the part before unloading (φ′) and is shown in Fig. 7.

Figure 8a illustrates the procedure used to measure the angle on one side of the final roll formed part with a protractor. The springback was measured at a specific distance away from the part ends in three locations of the sample as shown in Fig. 8b, and the average of these measurements was taken. To give an example, the average springback angle measured for a section roll formed from DP1000 with a flange length of 36 mm, a forming angle of 20°, a station distance of 250 mm, and a material thickness of 1.5 mm was calculated to be (13° + 12.5° + 13.5°)/3 = 13°.

3 Results and discussion

The results obtained for the different experiments detailed in Table 3 were analysed statistically to investigate the effect of the different parameters on the peak longitudinal edge strain, longitudinal bow and springback. The "main effect" was determined; this represents the influence of independent variables on one dependent variable while averaging across the other independent variables [31]. The main effect was

Fig. 6 Definition of longitudinal bow



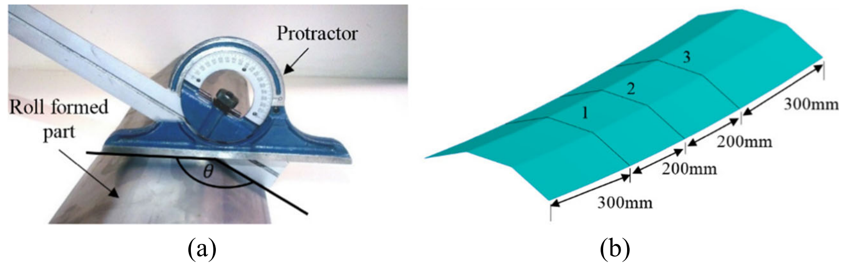


Fig. 8 **a** Procedure for measuring the product angle. **b** Location of the springback measurements in the roll formed part

determined for each material thickness, because the material properties are different from one material thickness to the other. This means that if, for example, the main effect of the forming angle on the peak longitudinal strain is determined, the effect of the variation of the other parameters such as the station distance and the flange length on peak longitudinal strain is averaged out. In this paper, the main effect was determined separately for the high and the low levels of the input parameters given in Table 2. Equations (2) and (3) are the equations used to determine the main effect of the forming angle on the peak longitudinal strain. The main effect of each of the other parameters was determined in the same way.

$$\text{Main effect of } (\text{FA}^{+}) = \frac{\sum \text{PLES}(\text{FA}^{+})}{N/2} \quad (2)$$

$$\text{Main effect of } (\text{FA}^{-}) = \frac{\sum \text{PLES}(\text{FA}^{-})}{N/2} \quad (3)$$

where PLES(FA^{+}) is the peak longitudinal edge strain value for a high level of forming angle while PLES(FA^{-}) is the peak longitudinal edge strain value for a low level of the forming angle and N is the number of experiments, which in our case is 8 (for each material thickness).

3.1 Main effects on peak longitudinal strain

3.1.1 Main effect of flange length on peak longitudinal strain

The main effect of the flange length on the peak longitudinal edge strain is shown for the two material thicknesses in Fig. 9a, b. According to Fig. 9a, the DP600 shows the lowest peak longitudinal edge strain among all three materials while the highest values are observed for the DP1000. This indicates that the peak longitudinal edge strain increases with material yield strength. For the case of a 2-mm material thickness (Fig. 9b), the highest peak longitudinal strain is observed for the MS900 and this supports the trend since for this material thickness, the MS900 has the highest level of yield strength (see Table 1). This opposes the trends observed in some previous numerical investigations [13, 17, 18].

Comparing Fig. 9a, b indicates an increasing peak longitudinal edge strain with material thickness for all three materials grades. In roll forming, both stretching and curving deformation occur in the flange edge [32] when the material is pushed over the forming roll, and in [33], it has been proposed that longitudinal edge strain consists of two components, namely bending, ε_b, and mid surface strain. According to the simple bending theory, bending strain increases with material thickness (Eq. (4)).

$$\varepsilon_b = \frac{t}{2R} \quad (4)$$

where the bending strain is ε_b, t is the material thickness, and R is the radius of curvature of the neutral plane.

This explains the increase in peak longitudinal edge strain with material thickness. A similar trend was observed by other researchers in their numerical work with traditional material grades [14, 15, 17] and in analytical investigations [11–13]. According to Fig. 9a, b, the peak longitudinal edge strain decreases with increasing flange length for all three materials. With a smaller flange length, l_1, the flange edge contacts a

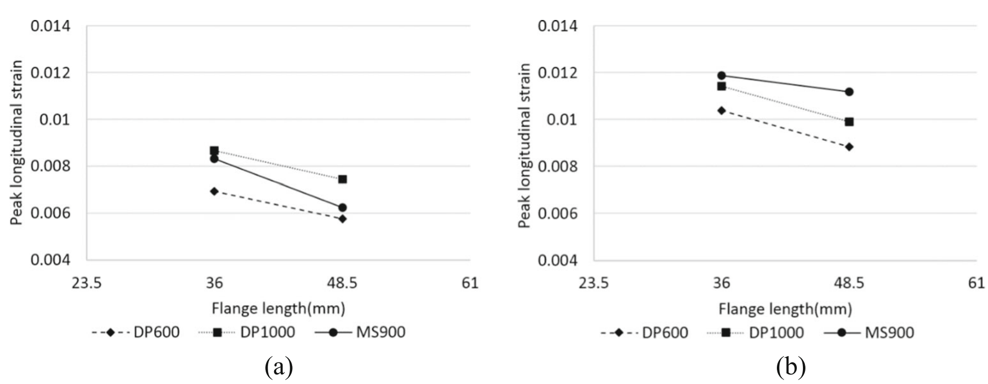
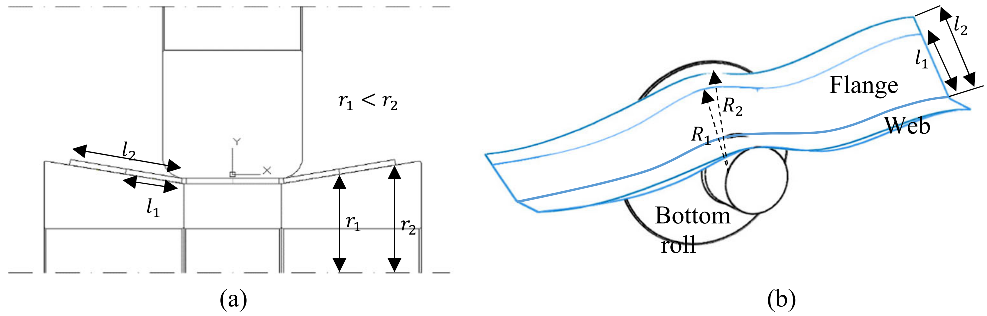


Fig. 9 Main effect of flange length on the peak longitudinal edge strain for **a** 1.5- and **b** 2-mm thicknesses

Fig. 10 **a** Effective radius of the tool when the strip passing the roll station. **b** Radius of curvature of the strip edge



smaller roll radius, r_1, compared with a longer flange length, l_2 (leading to contact with roll radius r_2), as illustrated schematically in Fig. 10a. This corresponds to a larger radius of curvature of the flange edge (R_2 for the larger flange length l_2) when the sheet is bent over the bottom roll (Fig. 10b). That is, the higher is the flange length, the higher is the radius of curvature of the neutral plane of the strip edge. This results in a decrease in bending strain ,ε_b (Eq. (4)), and through that a reduced longitudinal edge strain with increasing flange length. Zhu et al. [12] observed an increase in peak strain with flange length up to a flange length level of 5 mm followed by a continuous decrease, which is in accord with their analytical equation which is independent of material properties. Azizitafti et al. [17] also obtained a similar trend in their numerical simulation for a material with 400-MPa yield strength but observed the transition at a flange length of 60 mm. This suggests that material properties do influence the change in peak strain with the flange length. In contrast to this, the results of the current study, which are for the roll forming of high-strength steel, do not show a shift in the effect of the flange length on longitudinal edge strain. Nevertheless, this could be due to the flange length levels analysed which were limited to 36 and 48.5 mm.

3.1.2 Main effect of forming angle on peak longitudinal strain

The main effect of the forming angle on the peak longitudinal edge strain is shown in Fig. 11a, b and suggests that for both material thicknesses, the peak strain increases with forming angle. A higher forming angle introduces greater stretching due to the increased movement of the flange edge. The same trend was obtained experimentally for softer material grades such as mild steel by several researchers [10, 11], while some numerical investigations also confirmed a trend for some artificial material grades with 400-MPa yield strength or less [14, 15, 17]. In addition, some analytical equations [11, 12, 32] that did not take into account the effect of material properties presented a similar trend. The present study confirms this trend for AHSS and UHSS.

3.1.3 Main effect of inter-station distance on peak longitudinal strain

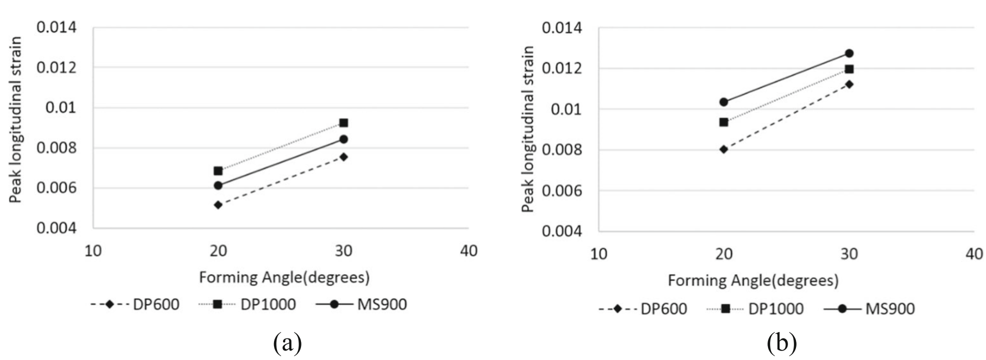
Figure 12a, b illustrates the main effect of the inter-station distance on the peak longitudinal edge strain for 1.5- and 2-mm strip, respectively.

There is no obvious effect of station distance on the peak longitudinal strain for either material thicknesses; this differs from previous numerical investigations [14–16, 34] which suggested that the peak longitudinal edge strain decreases with increasing inter-station distance. In general, if the deformation length in roll forming is lower than the station distance, there should not be an effect of the station distance on edge strain. Based on the work of Bhattacharyya et al. [35], the deformation length, L, in roll forming can be calculated as follows:

$$L = \sqrt{\frac{8a^3\Delta\theta}{3t}} \quad (5)$$

where a is the flange length, $\Delta\theta$ is the forming angle increment, and t is the material thickness.

Fig. 11 Main effect of the forming angle on the peak longitudinal edge strain for **a** 1.5- and **b** 2-mm thicknesses



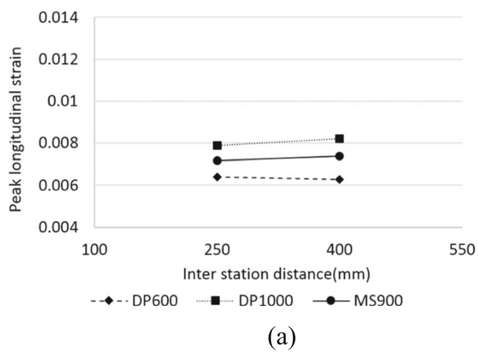


Fig. 12 Main effect of inter-station distance on the peak longitudinal edge strain for **a** 1.5- and **b** 2-mm thicknesses

For most of the forming conditions investigated in this study, the deformation length was lower than the inter-station distance explaining the small effect of the station distance on longitudinal edge strain shown Fig. 12.

3.2 Main effects on longitudinal bow

3.2.1 Main effect of flange length on longitudinal bow

The main effect of the flange length on the longitudinal bow is shown in Fig. 13 for both material thicknesses. Even though the lowest level of maximum longitudinal edge strain was observed for the DP600 steel for both material thicknesses (Fig. 9) for this material, the highest magnitude of longitudinal bow is observed. The reason for this may be that the yield strength of DP600 is significantly lower than that of DP1000 and MS900. A lower yield strength leads to less resistance by the material to permanent deformation; i.e., there is a higher likelihood for longitudinal strain to be permanent in the strip edge. An increased level of longitudinal bow with decreasing material yield strength has also been observed for common and soft steel grades in previous studies [17, 36]; however, Galdos et al. [37] observed an increase in bow with material yield strength for the forming of a U-channel section from UHSS. This suggests that the level of longitudinal bow is not solely dependent on the material yield strength. According to the literature, the effect of peak longitudinal edge strain on bow can vary with part geometry [20] and the magnitude of longitudinal bow is a function of the mismatch between longitudinal strain in the edge and the web of the section [19]. This suggests that the level of peak longitudinal edge strain alone does not give a direct measure for longitudinal bow as reported by previous studies [11] but that a lower peak longitudinal strain generally leads to less tendency of shape defects.

Longitudinal bow is low for all materials at a thickness of 1.5 mm (Fig. 13a), while at 2-mm material thickness, significant bow is observed for all materials. This indicates that the longitudinal bow increases with increasing material thickness, which relates well to the increase in maximum longitudinal strain with material thickness shown in Fig. 9a, b. A similar trend as shown experimentally in this study was observed in a numerical study performed on mild steel [17].

According to Fig. 13a, for a material thickness of 1.5 mm, both MS900 and DP1000 show less than 3-mm bow for both flange lengths. As a result, a significant difference in longitudinal bow is not seen between the two materials even though they are significantly different in yield strength level. On the other hand, for the case of a material thickness of 2 mm, the MS900 shows a higher level of bow compared to the DP1000 as shown in Fig. 13b even though its yield strength is higher. Based on the observations made earlier, a higher yield strength should give a higher resistance to permanent deformation in the edge and lead to less bow. Figure 1 shows that material hardening close to yield of the DP1000 (n = 0.12) steel is significantly higher compared to the MS900 (n = 0.06), and this may have led to a higher resistance to permanent longitudinal deformation than suggested by the yield strength. This

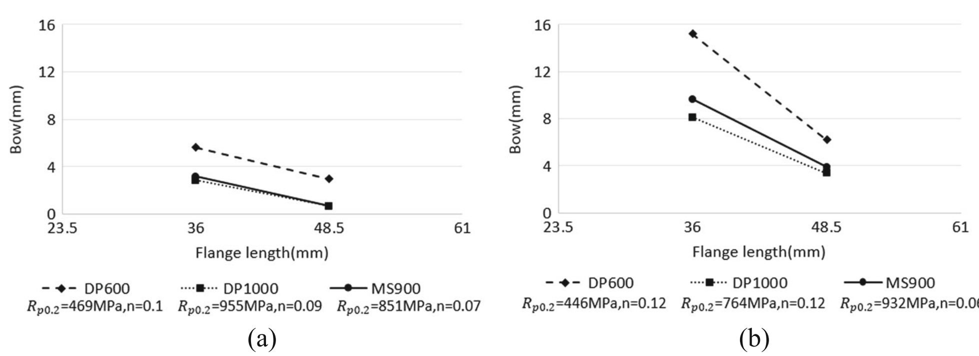


Fig. 13 Main effect of flange length on the longitudinal bow for **a** 1.5- and **b** 2-mm thicknesses

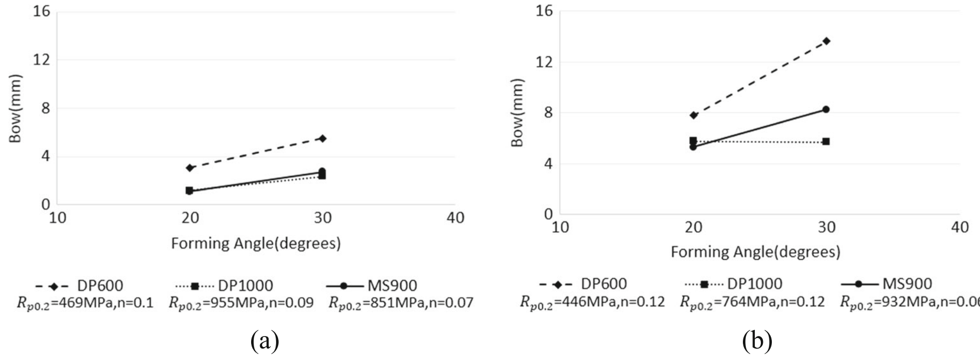


Fig. 14 Main effect of forming angle on the longitudinal bow for **a** 1.5- and **b** 2-mm thicknesses

suggests that not only the yield strength, but also the level of material hardening may be important with regard to longitudinal bow when AHSS and UHSS are roll formed.

Figure 13a, b also shows that longitudinal bow decreases with increasing flange length. This agrees with Fig. 9a, b where the peak longitudinal edge strain decreases with increasing flange length; i.e., the level of permanent longitudinal strain in the edge is lower at higher flange length levels and this results in less bow.

3.2.2 Main effect of forming angle on longitudinal bow

According to Fig. 14a, b, longitudinal bow increases with the forming angle for all materials and this is in accordance with previous literature that focused on bow in the roll forming of mild steel grades [11, 17, 36]. The only exception is the DP1000 where for a material thickness of 2 mm, there is no effect of the forming angle on longitudinal bow. The peak longitudinal edge strain increases with the forming angle (Fig. 11a, b), leading to a higher level of permanent longitudinal deformation in the edge; this explains the trends shown in Fig. 14a, b. Nevertheless, while in Fig. 11a, b, all three steels show a similar increase in maximum longitudinal edge strain with forming angle, in Fig. 14b, as mentioned earlier, there is only a minor effect of the forming angle on longitudinal bow for the DP1000.

A high difference in longitudinal bow can be seen between DP1000 and MS900 for a material thickness of 2 mm and a forming angle of 30° (Fig. 14b). For this condition, the MS900 should show lower bow given that its yield strength is significantly higher compared to the DP 1000 steel. Nevertheless, considering the high material hardening of the DP 1000 steel and that the bending strain will be high for this forming condition, the lower bow observed for the DP1000 could be due to strain hardening effects that strengthen the material and through this reduce permanent longitudinal strain in the edge and through that bow. This observation is in contrast with previous studies which generally suggest that bow reduces with increasing yield strength of the material [17, 37]. Our experimental results indicate that if material hardening is high as it is for the case for the DP1000 steel and a significant longitudinal strain is exerted, then longitudinal bow is influenced by strain hardening.

3.2.3 Main effect of inter-station distance on longitudinal bow

Figure 15a, b shows the main effect of inter-station distance on longitudinal bow for two thicknesses. Longitudinal bow decreases with increasing inter-station distance for both thicknesses, and the influence of the inter-station distance is highest for the DP600 steel and small for the two UHSS. This cannot be explained by the results shown in Fig. 12a, b where the influence of the inter-station distance on the peak longitudinal strain was minor. An increased station distance allows a smoother bending progression, and this may result in lower residual stresses through the cross section of the final part compared with a short inter-station distance. This could reduce longitudinal bow but would not influence peak

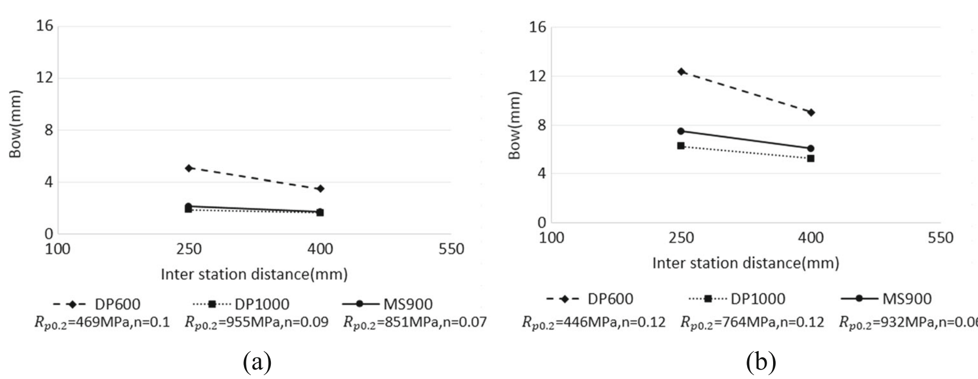


Fig. 15 Main effect of inter-station distance on the longitudinal bow for **a** 1.5- and **b** 2-mm thicknesses

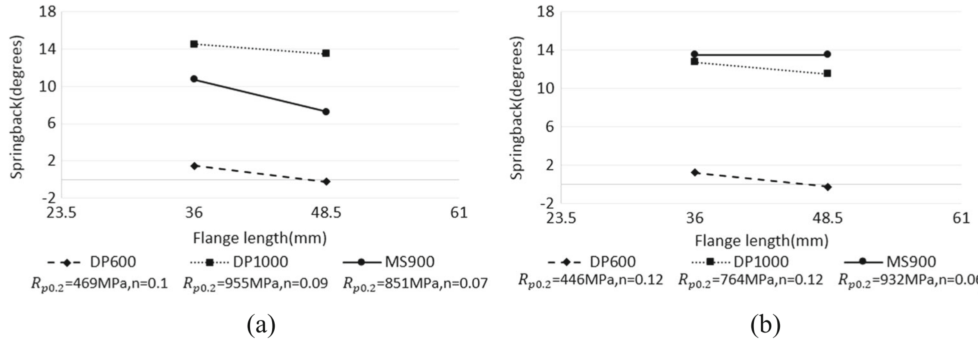


Fig. 16 Main effect of flange length on the springback for **a** 1.5- and **b** 2-mm thicknesses

longitudinal strain. It is important to note that even though both inter-station distances are longer than the theoretical deformation length, there is an effect on longitudinal bow.

3.3 Main effects on springback

3.3.1 Main effect of flange length on springback

The main effect of the flange length on the springback for the two material thicknesses is shown in Fig. 16a, b.

The springback increases with increasing material yield strength for both material thicknesses (Fig. 16); however, there is a large difference in springback between the MS900 and the DP1000 for 1.5-mm-thick material while this difference is minor for 2-mm thickness. The difference of yield strength between the DP1000 and the MS900 is significantly higher for a material thickness of 1.5 mm, and this would explain the trends shown in Fig. 16.

For some forming conditions, negative springback was observed for the DP600 (Fig. 16). This negative springback (springforward) has been reported before for press braking operations [38]. If a softer material is formed into a large angle with a sharp forming radius, then springforward can take place due to the coining of the material at the corner of the bend. This scenario is also observed in industrial roll forming practice [39]. For this reason, in the industrial case, the roll gap is generally set as a fraction larger than the material thickness [39]. In the current experimental study, the roll gap was set to be the material thickness and was kept constant to maintain consistency between material grades and process conditions. Negative springback was only observed for the relatively soft DP600 steel at high levels of forming angle and flange length as can be seen in Fig. 16.

Figure 16a, b further suggests that for most cases, springback decreases with increasing flange length. When the flange length increases, the deformation in the bending region will not change, but the length of the flange outside the bend increases (see Fig. 10). This indicates that not only the deformation in the bending area, but also the amount of material outside the bend will influence springback in roll forming. Previous studies have further shown that the springback in roll forming is influenced by the strain distribution in both the transverse and the longitudinal directions [7]. Therefore, the decrease in springback with increasing flange length may be also related to the change of longitudinal edge strain with flange length observed earlier (Fig. 9a, b).

3.3.2 Main effect of forming angle on springback

For most cases, springback varies within ±1° when the forming angle increases from 20° to 30° (Fig. 17a, b), but for MS900 of 1.5-mm thickness and DP600 with 2-mm material thickness, there is a larger decrease in springback with increasing forming angle. A simple trend between the forming angle and springback is therefore not observed.

3.3.3 Main effect of inter-station distance on springback

The main effect of the inter-station distance on the springback for 1.5- and 2-mm material thickness is given in Fig. 18a, b,

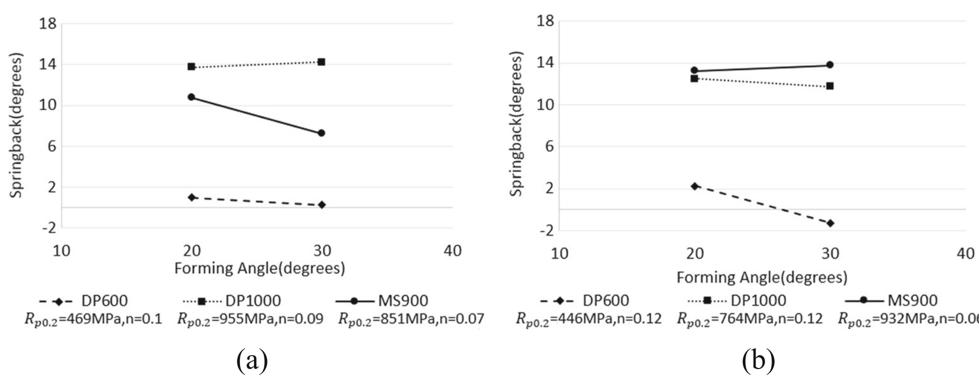


Fig. 17 Main effect of forming angle on the springback for **a** 1.5- and **b** 2-mm thicknesses

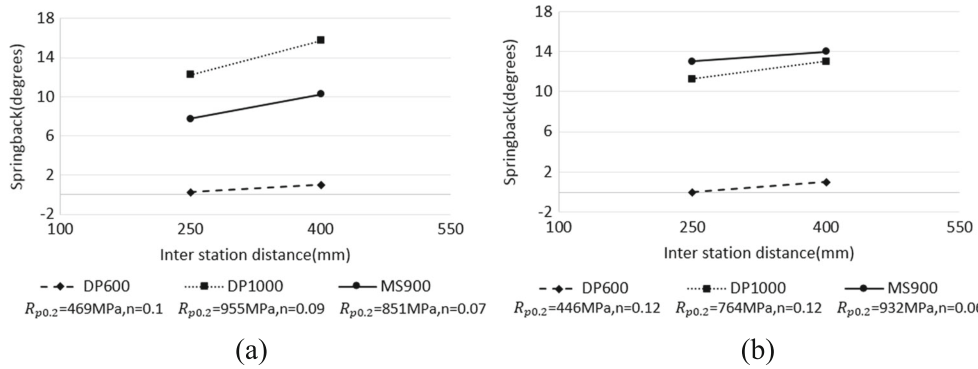


Fig. 18 Main effect of inter-station distance on springback for **a** 1.5- and **b** 2-mm thicknesses

respectively. The experiments shown here clearly indicate that springback increases with increasing inter-station distance (Fig. 18a, b). A previous work suggested that transversal springback reduces with increasing level of redundant deformation in the part such as longitudinal edge strain [8] and is related to the presence of residual stresses that restrict elastic recovery in the transverse direction. Figure 12a, b has shown that the peak longitudinal edge strain does not change with increasing inter-station distance. However, in addition to longitudinal edge strain, there are several additional forms of redundant deformation in a roll formed part, such as transverse strain and shear [19], which were not experimentally investigated here. In general, it can be assumed that a higher inter-station distance leads to a smoother and more progressive deformation in the strip [24]. This may have reduced the overall level of redundant deformation in the section, which may explain the increased level of springback with station distance observed here. Previous numerical results reported that springback in roll forming is independent of the inter-station distance [24]. However, our experimental results determined for high-strength steel suggest that inter-station distance has an effect on springback in the roll forming process.

4 Conclusion

The effect of different process and geometric parameters on peak longitudinal edge strain, longitudinal bow and springback was experimentally investigated for the roll forming of a channel section. Three different AHSS and UHSS materials and two material thicknesses were analysed to investigate the effect of material yield strength, hardening exponent and thickness separately.

The results confirm previous observations made for common and low-strength steels in that peak longitudinal edge strain in roll forming increases with forming angle but decreases with increasing flange length. In addition, our results show an increase in peak longitudinal edge strain with material yield strength, which resolves some contradictions identified in literature. The peak longitudinal strain was not significantly affected by the inter-station distance, as in this study, the inter-station distance was larger than the theoretical deformation length for most of the experiments.

Even though DP600 showed the lowest peak edge strain compared to the other two high-strength steels, it had the highest level of bow for both material thicknesses. This is due to the lower yield strength of DP600, which gives less resistance to the permanent plastic deformation and suggests that peak strain alone does not give an accurate estimate of the level of shape defect or, in this case, bow in a part produced from different materials, unless the material properties are similar. Even though MS900 has a higher yield strength than DP1000 among 2-mm-thick materials, MS900 showed higher bow than DP1000 for most of the cases. This suggests that DP1000 has a higher resistance to permanent deformation despite its lower yield strength compared with MS900. This is due to the higher level of material strain hardening close to yield in DP1000, and it can be concluded that not only the material yield strength but also the material hardening influence longitudinal bow in the roll forming of UHSS. Even though the inter-station distance does not influence peak longitudinal strain, it does influence longitudinal bow. This may be due to a smoother forming progression if the inter-station distance is high and may not be related to changes in peak longitudinal edge strain.

Springback increased with yield strength for both material thicknesses, and slight springforward (negative springback) was observed for some forming cases involving the lower-strength DP600 material. This was related to the introduction of excessive plastic stresses and can be observed in practice when a relatively soft material is roll formed into high forming angles. For most cases, springback decreased with increasing flange length, suggesting that not only the bending region, but also the adjacent regions (flange area) influence springback in roll forming. Springback further increased with inter-station distance for all materials and thickness ranges. When the inter-station distance increases, more progressive bending will take place, and this may reduce redundant deformation and lead to increased springback. This experimentally confirms suggestions made by previous authors that springback reduces with increasing redundant deformation in the part.

The results of this experimental study can be used to improve process and product design as well as the development of routines for process monitoring and in-line shape control when roll forming AHSS and UHSS. This may help achieving the tight tolerances required for roll formed sections in the automotive and the aerospace industry.

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Appendix

Table 3 Experiment plan to be carried out for each material

Experiment	Material thickness (mm)	Flange length (mm)	Forming angle (°)	Inter-station distance (mm)
1	2.0	36.0	20	250
2		36.0	20	400
3		36.0	30	250
4		36.0	30	400
5		48.5	20	250
6		48.5	20	400
7		48.5	30	250
8		48.5	30	400
9	1.5	36.0	20	250
10		36.0	20	400
11		36.0	30	250
12		36.0	30	400
13		48.5	20	250
14		48.5	20	400
15		48.5	30	250
16		48.5	30	400

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