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Numerical study of strain-rate effect in cold rolls forming of steel

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Abstract. Cold roll forming (CRF) is a well-known continuous manufacturing process, in which a flat strip is deformed by successive rotating pairs of tools, without changing the material thickness. In the past decades, to lessen the process-development efforts, finite-element simulations have been increasingly employed to improve the process design and predict the manufacturing-induced defects. One of the important aspects in design of the CRF process is consideration of resulting strains in the final product as the material passes through several complex forming stands. Sufficient knowledge of longitudinal strain in the workpiece is required to set various process parameters. Increasing a process speed in a roll forming operation can bring cost advantages, but the influence of the forming speed on the strain distribution should be explored.
This study is focussed on a strain-rate effect in the CRF process of steel sheets. The strain-rate dependency of a plastic behaviour observed in most metals can affect the finished product's quality as well as process parameters. This paper investigates the influence of the strain rate on longitudinal strains induced in the roll forming operation by incorporating a phenomenological Johnson–Cook constitutive model, which allows studying the impact of the process speed on the output product. Taking advantage of 3D finite element analysis, a roll forming process was simulated using MCS.Marc, comprising a complete set of forming stations. Through the changing of the process speed, the strain rate impact on longitudinal peak strains and forming length was investigated. The results highlight the effect of the strain rate on edge thinning and subsequent undesirable distortions in the product.

1. Introduction

Cold roll forming is a highly productive method for the production of long profile. In this forming process, the material undergoes progressive forming by a series of rolls into a certain cross-section product. The sequence of rolls breaks the forming process down to several stages. Each stage comprises two stands between which the sheet metal is deformed.

The distance between one forming stages to the next is called the forming length. In roll-forming process elongation occurs in the edges because they travel a longer path than the centre line. If the lead-in length is not sufficiently long, the edges will elongate plastically and in the finished product the edges are

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longer than the mid line, causing the edge wrinkles, warp or twist in the product. Figure 1 depicts how further elongation occur around flange edge compared to the web of a U channel.

Since the deformation in cold-roll forming is quite complex and the curved surfaces are difficult to describe, the process design mainly used to be developed from experimental knowledge on an empirical basis. However; in the last decade the finite element analysis has been shown to provide reasonably good prediction of what takes place in the roll forming process. Based on the level of complexity of the model and the expected accuracy, the solution time can be from a few hours to several days.

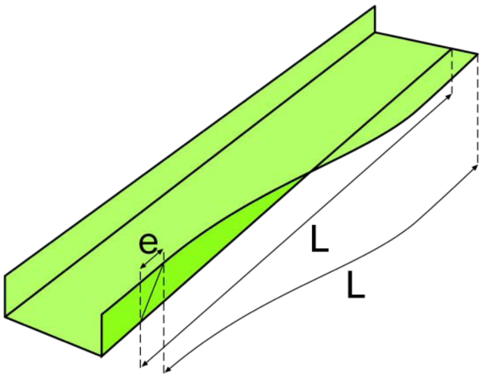

Figure 1. The material at the edge travels a longer distance than the rest of the material which makes it prone to buckle

Determination of strain distribution based on the process and materials product have been main objective of many recent researches. Lindgren Lindgren [1] studied the influence of yield strength on the longitudinal peak membrane strain in the flange and the deformation length. It was shown that when the yield strength is increased, the longitudinal peak membrane strain decreases and the deformation length increases. Han et al. [2] declared the same dependency. Zeng et.al [3]investigated the product quality with respect to material properties. They observed significant impacts of the yield point as well as the work-hardening exponent on the final product quality, whereas forming speed and friction at roll-sheet interface appear to play a minor role. Bui and Ponthot [4] demonstrated a combined experimental and numerical study sensitivity of the springback behaviour with respect to material properties. The effect of the yield limit and the strain hardening exponent on springback and edge waviness was highlighted. Wiebenga et al. [5] presented a robust optimization techniques to obtain settings of adjustable tools in the final roll forming stand. The results highlighted significant effect of tool adjustment on the dimensional quality of the product by compensating for scattering material properties.

Additional to the material properties, several studies also focused on the relation between redundant straining and the process design. Li et al. [6] carried out extensive experimental studies on the resultant residual stresses in roll formed square hollow sections. It was highlighted that the forming process has a significant effect on the distribution of longitudinal residual stresses on the outside surface of the product, while the distribution of transversal residual stresses is similar for the same dimension. Jeong et al. [7] investigated the longitudinal strain in U channel using FEM as a result of two types of flower patters for forming process of the same product. Salmani Tehrani et al. [8] studied the roll forming process design on local edge buckling, demonstrating a critical value of profile angle of the rolls to prevent local edge wave in the product. Optimization on the basis of different influential parameters Paralikas et al. [9]optimised the inter-distance between roll stations to minimize the elastic longitudinal and shear strains as well as the strip edge wave. A similar numerical optimization presented by Zeng et al. [10] to obtain the optimal settings for the forming angle increment and roll radius in order to reduce the springback and peak longitudinal strains.

All the above mentioned researches studied upon influence of material and process parameters in the longitudinal edge straining. The material model used does not include the implications of strain rate, though some of them tried to considerate speed parameter. This paper investigates the influence of the strain rate on longitudinal strains induced in the roll forming operation by incorporating a phenomenological Johnson–Cook constitutive model, which allows studying the impact of the process speed on the output product.

2. Theory, Johnson-Cook model

In order to predict the response of a material at various strain rates, the constitutive material model must include strain rate effect. The J-C model is simple approach to correlate flow stress to strain rate and primarily intended for use in computer codes[11]. The equivalent Von Mises flow stress according to Johnson-Cook model is given in generic form of equation(1):

$$\sigma = [A + B\varepsilon^{n}][1 + C.\,ln\dot{\varepsilon}^{*}][1 - T^{*m}] \quad (1)$$

Where ε is the equivalent plastic strain, $\dot{\varepsilon}^{*} = \dot{\varepsilon}/\dot{\varepsilon}_0$is the dimensionless plastic strain rate for $\dot{\varepsilon}_0 = 1\ s^{-1}$.$T^{*m} = (T - T_r)/(T_m - T_r)$, in which T^{*} is the homogeneous temperature, T_r, T_m are room and meltingtemperature, respectively. Five material constants are *A*, *B*, *C*, *n* and *m*. *A* is the yield stress; B and exponent *n* represent the strain hardening effects of material. The expression in the second set of brackets represents the strain rate effect through constant *C*. the third bracket is to incorporate the temperature effect into the material model.

3. Modelling and Simulation

3.1 Finite Element Modelling of the roll forming process

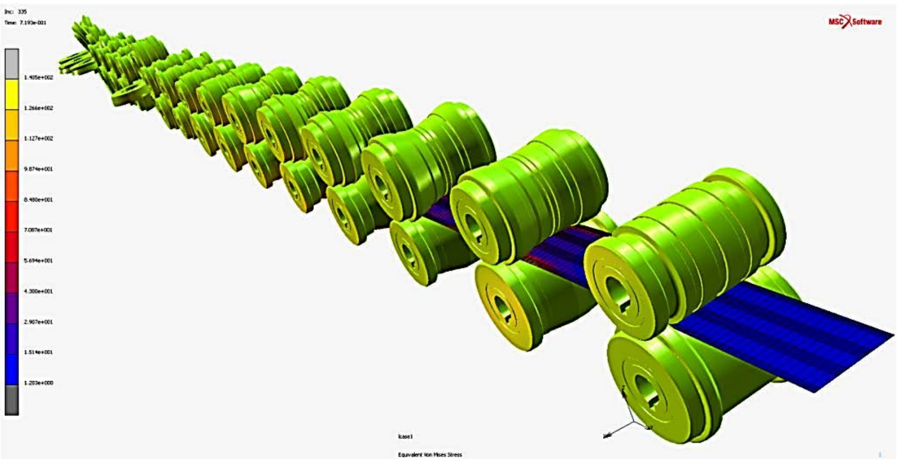

Figure 2. 3D finite element model of the roll forming process

The three-dimensional FE simulation has been carried out using MSC.Marc 2012. Complete geometry of real roll forming process has been created as shown in Figure 3. This complete roll forming process comprises 25 forming stands. There are two options available to simulate such process, first is to rotate the rollers with friction accounted, which move the strip forward and form it. Second is to keep the strip in place and move the non-rotating rollers with constant speed over the material without friction. This speaks to the idea of rolling without slipping between rollers and the surface of material. As for second technique Sheu [12] simulated a six stand CRF, in which the tools were moved over a fixed end blank at a defined speed. It was found that the resulted motion is the same, but boundary conditions are easier to specify. In this study the second approach has been opted.

To describe the contact condition and the interaction between the tools and the sheet, the analytical surface of rollers are defined as rigid bodies, and the element-based surface as the deformable body. In a sheet material, thickness is significantly smaller than other dimensions and the through thickness stress is negligible; hence shell and membrane elements can be used to model the sheet. In this simulation a bilinear thick shell element (Element 75) [13] has been used to model the sheet with nodes in the centre plane and 13 integration points in the thickness direction. Figure 4 depicts mesh in the width direction is distributed in a way to have finer mesh around bending regions. Mesh size in longitudinal direction is quite coarse and there is no remeshing involved in the simulation. In total the model comprise 6700 elements 67 transverse and 100 longitudinal elements. The simulation is performed at different speeds, 300, 1000, 5000, 15000 mm/sec.

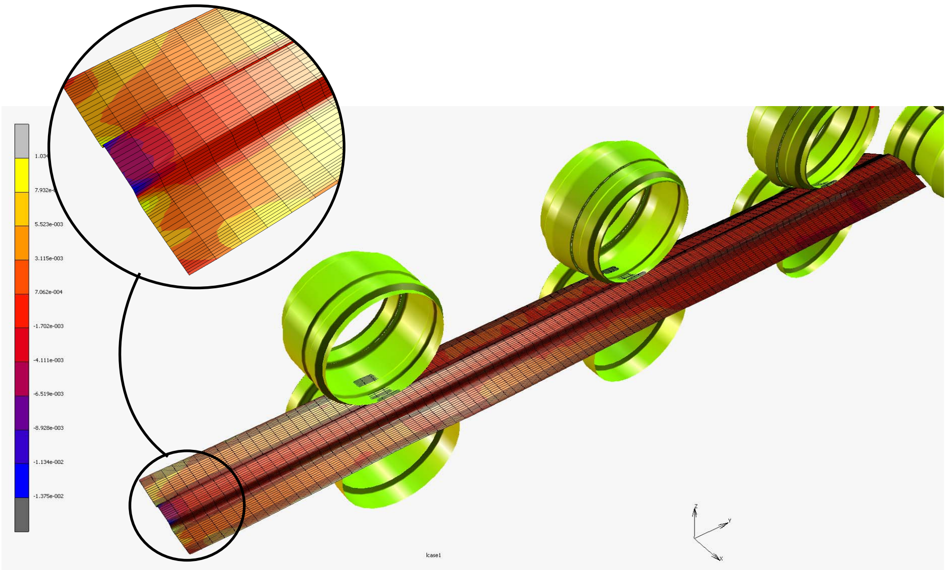

Figure 5. 3D finite element model of the strip and forming stands

3.2 Material:

The material is modelled as an elasto-plastic material. Isotropic hardening and the Von Mises yield surface and the Johnson –cook flow rule are used. For the cold roll forming simulation the influence of temperature is neglected. The set of J-C material constants for mild steel modelling is taken form literature, Vedantam[14] as equation.(2).

$$\sigma = \left[217 + (234)\varepsilon^{(0.643)}\right]\left[1 + (0.0756) ln\dot{\varepsilon}^{*}\right] \quad (2)$$

Summary of the material and geometry parameters employed for the sheet are listed in Table 1.

Table 1. Summary of simulation parameters

Material	Mild Steel
Material Model	Isotropic Elasto Plastic, Johnson-Cook
E	210 GPa
ν	0.3

A	217 MPa
B	243 MPa
C	0.0756
n	0.643
Sheet Thickness	1 mm
Strip Length	850 mm
Velocity	300, 1000, 5000, 15000 mm/s
Friction Coefficient	0.0
Roll Material	Rigid

3.3 Boundary Condition

Two different boundary conditions have been used in the simulation, the first is defined to suppressed the front edge in longitudinal direction, and second; suppression of translation in out of plate direction of a line of nodes which do not move during the forming process. This choice of boundary conditions represents the situation in which a plane remains a plane during the deformation.

4. Results and analysis

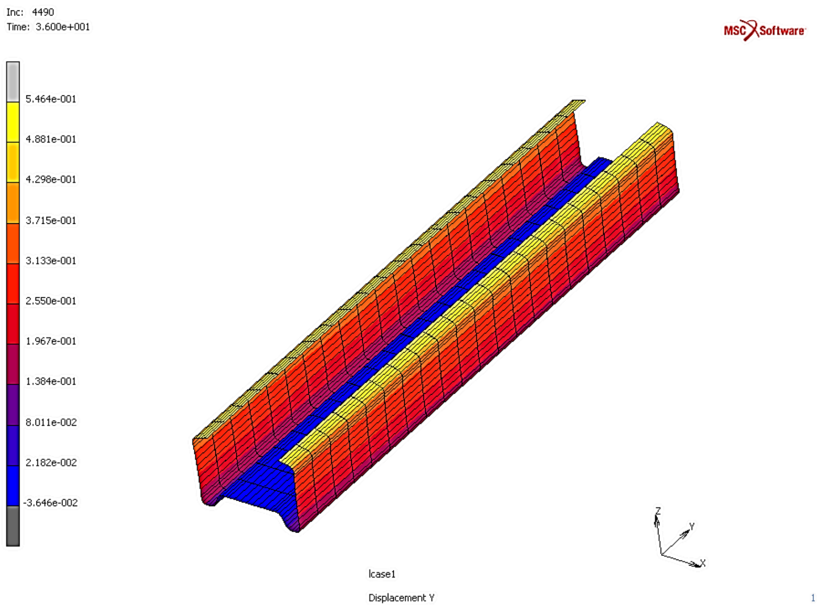

Figure 6. The geometry of final product

Figure 4 shows the final geometry of the product at the end of analysis. Based on the simulation the longitudinal membrane strain developed in the material is shown in Figure 5. As we may observe the longitudinal strain as the plates passes the forming stand gradually accumulates to the final residual values. It is readily seen that the fluctuations are in part due to elastic part of the strain. The sharp rises take place when the element came in proximity of forming stand, then it settles back. In the roll forming process of a U channel, web is the centre of a strip, while the flange is the part to be bent. The web first undergoes compression and then becomes tensile as it leaves the stand, while the flange first becomes tensile and then is compressed at the roll exit. This is the mechanism behind the residual strain in the finished product [7, 8]. In the current case the complexity of the cross section and numerous forming stands, cause more complex behaviour in the material.

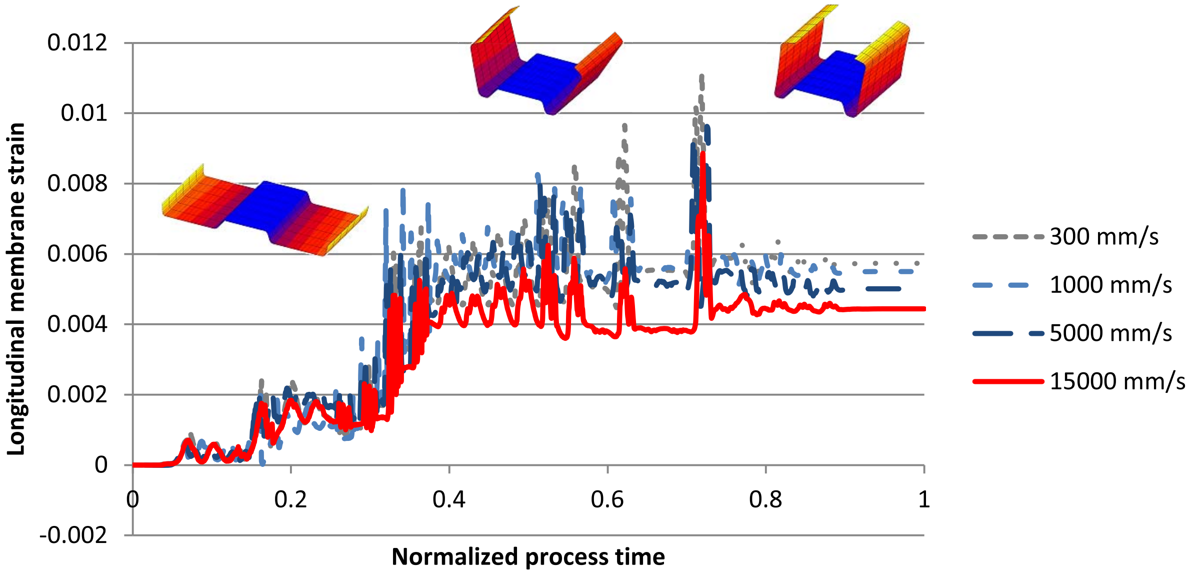

Figure 7. Longitudinal membrane strains at various process speeds

As for the comparison obviously Figure 5 is demonstrating the existence of a permanent deformation between 0.4 % to 0.6% in the final product depending on the speed level. The lower the speed is the more residual plastic strain observed in the model. This is in agreement with the result of [1,2,3] in a sense that lower strain rate constitute lower yield point, and consequently higher strain rate delays the material yield. Figure 6 demonstrate the rotation along lateral direction. The result shows that changes in the process speed only have a slight influence on the spring back behaviour of the product.

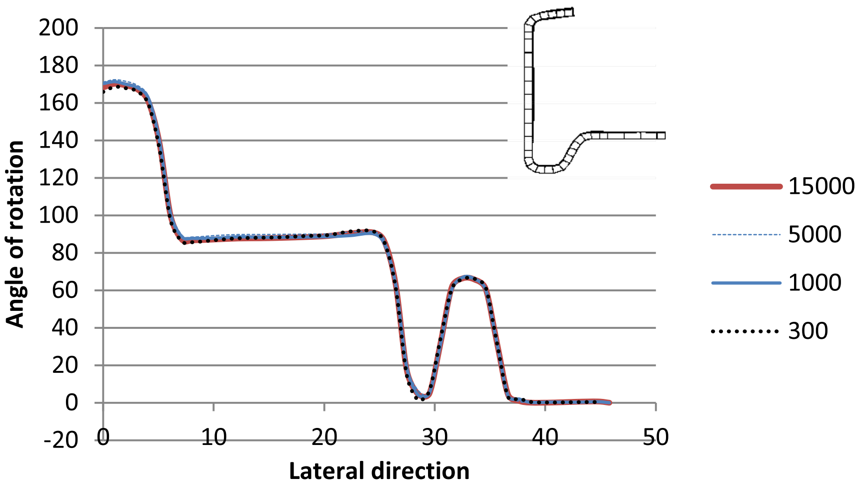

Figure 8. Angle of rotation along lateral direction

5. Conclusion

This study is focussed on a strain-rate effect in longitudinal strain of the CRF process of steel sheets. The strain-rate dependency of a plastic behaviour observed in most metals can affect the finished product's quality as well as process parameters hence the influence of the forming speed on the strain distribution should be explored. By incorporating Johnson–Cook constitutive model, the longitudinal strains induced in the roll forming operation has been investigated. In a 3D finite element analysis of complete set of forming stations with varying process speed, the strain rate impact on longitudinal peak strains was investigated. The results highlight the influence of speed in longitudinal strains and subsequent impact that can be observed in the geometry of the product. The impact of process speed on spring back was observed to be insignificant.

6. Acknowledgement

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