Understanding and Controlling End-Flare Error in Rollforming

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Abstract

Roll forming is a continuous cold forming operation in which a strip of material is progressively shaped into a desired cross-sectional profile in a series of roll stations. It is preferred in high-volume production environments because of the high production rates and low labor needs. Its use in low-volume production contexts is, however, restricted by lengthy setup times. There is plastic deformation of the material in the process of roll forming that leads to residual stresses, which result in permanent geometrical transformation. This transformation can be in the form of defects like bowing, twisting, waviness, loss of straightness, and end flare that become most apparent after the cutting operation. End flare is a critical defect that undermines the performance of profiles, particularly in assembly-dependent uses in several industries like automotive, electronics, home appliances, horticulture, and photovoltaic systems. The aim of the study is to describe the mechanisms underlying the formation of end flare in roll-formed U-section profiles. There is a marriage of finite element analysis and experimental confirmation used to study the defect with the final goal of seeking and suggesting viable solutions for minimizing its occurrence.

Keywords: Roll Forming, End Flare, Residual Stress, Geometric Defects, U-Section Profiles.

1. Introduction

Sheet metal forming processes shape metal sheets into intricate geometries by subjecting them to pressure from tools or dies [1]. Roll forming is particularly important in the production of long parts with unchanging cross-sections [2].

Roll forming is a continuous cold process where a strip of metal is passed through roll stations that form it into a required profile. The main advantage is that the thickness of the material is almost the same, preserving mechanical properties, mass distribution, and surface quality [3].

Roll forming is a favored production process across the automotive, construction, and energy sectors due to its high throughputs, low costs, and low labor demands [3–6]. They need close tolerances for reliability and strength. The automotive industry demands high geometric precision because small tolerances can retard assembly and lower part performance.

The most critical roll-formed product defect is end flare, which is deformation at the end after cutting. The defect is caused by the residual stresses in the roll forming bending operations. Stresses are relieved when cutting the profile, causing the undesired warping or bending of the ends [4,7]. End flare diminishes part appearance and dimensional integrity and can interfere with downstream processes like welding and assembly, particularly where precise end geometry is critical.

Finite element analysis (FEA) has been widely used to simulate roll forming operations and predict defects like end flare [8].

FEA provides data on stress distribution, material flow, and profile variation in various conditions. Nevertheless, manual intervention is still needed during machine setup because of uncertainty in practical scenarios, such as material variability, unknown roll stand stiffness, and mounting misalignments [4,7]. These elements make it difficult to accurately predict and control defects, necessitating empirical verification in production. Rolling is both efficient and versatile, yet residual stress release end flare makes dimensional accuracy problematic. Understanding formation mechanisms through simulation and experiment is significant to develop solutions that minimize the degree of this defect and improve process reliability.

2. Material and Method

In the present research, the specific material chosen for the purpose of this research is DX51D galvanized steel. The steel is reported to have widespread application in cold forming operations, and it may be because of its desirable chemical composition combined with its outstanding mechanical behavior. According to the standards laid down by EN 10346, DX51D is a low-carbon steel. It has a balanced medium strength in combination with high formability. The characteristic presents it as particularly suited for roll forming operations, which are operations where maintenance of precise dimensional accuracy and offering of shape stability is of paramount importance.

The finite element model was meticulously constructed with the utmost attention to detail, fully exploiting the capabilities of Copra FEA [9], an extremely advanced and highly specialized simulation software specifically tailored for the roll forming process. This high-end software utilizes an implicit solver that significantly enhances the accuracy of capturing and analyzing the behavior of the material under various different loading conditions. Following beneficial experience from previous studies aimed at "FEA in Roll Forming Processes," eight-node isoparametric arbitrary hexahedral elements were utilized. More specifically, Element Type 7 of the MSC Marc Element Library, as updated throughout the year 2024, was chosen to effectively mesh the metal strip for this analysis. In order to achieve a complete and true representation of the deformation that occurs in the materials, a single element was particularly defined through the entire thickness of the strip. This approach accurately captures the steep gradients of stress and strain that develop through the thickness of the material, which are necessary to achieve accuracy and precision in the roll forming process.

The specific boundary conditions, along with the fundamental assumptions made and which have been presented for the finite element analysis, are the following:

- The frictional contact between the forming rolls and the strip material is explicitly neglected here.
- The rotational movement of the rolls, which is a basic component, is not taken into account in this analysis.
- The strip material is generally assumed to possess uniform mechanical properties that remain constant along its entire length without any difference or variation.
- Any strain hardening that may have taken place because of the processing operations that were performed earlier is not considered and is therefore altogether neglected.

- Both rolls and roll shafts are assumed to be ideal rigid bodies without any deformation due to the applied stresses or loads.

As depicted in Figure 1, the rolls shown in this figure are particularly defined as rigid surfaces that will not deform under pressure. The strip material is, however, depicted as deformable so that its behavior can effectively be captured and represented while it undergoes the applied forming conditions being exerted during processing.

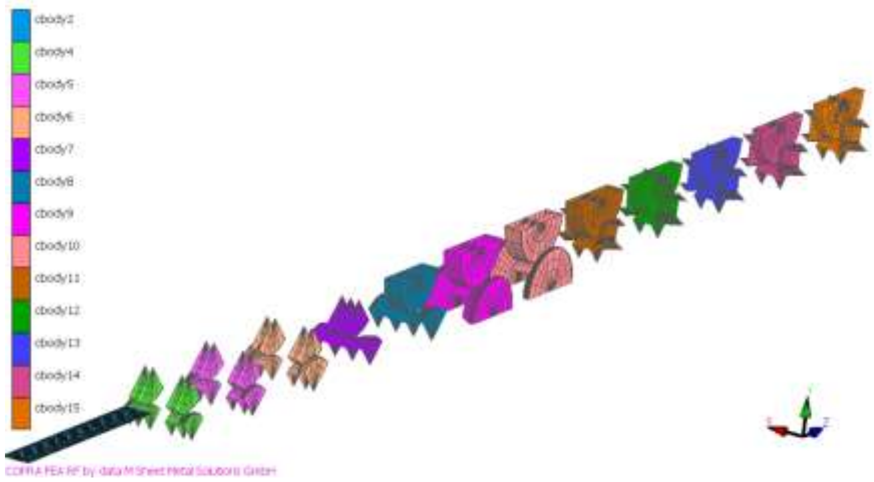

Figure 1: Visualization of the Simulation Model

3. Results

This study analyzed U-profile forming through two roll forming set-ups consisting of 4 and 6 stations. To understand material behavior, measurements of plastic strain and stress were taken from two points of significant concern on the flange edge. Node 5861 is located at the extreme top of the flange, i.e., the projecting rim. Node 2117 is at the outer edge of the flange.

3rd and 6th stress and plastic strain terms were compared since they are major contributors to out-of-plane deformation and residual stress build-up causing end-flare defects. Analysis utilized last increment values to follow the history of deformation over time. We will summarize stress and plastic strain trends and relate them to node locations and forming station numbers.

In order to measure the influence of station numbers on the accumulation of stress in roll forming, the 3rd stress component σ_{33} was plotted at Nodes 5861 and 2117.

Figures 2 and 3 show the evolution of the stress component σ_{33} related to the forming increment for the 4-station and 6-station designs. Both arrangements experience intense compressive and tensile changes due to the bending-unbending process. However, the 6-station profile illustrates more dispersed peaks along increments There are comparatively lower local minima and maxima being observed in the value of σ_{33} for only Node 5861. Smooth stress changes, especially for Node 2117.

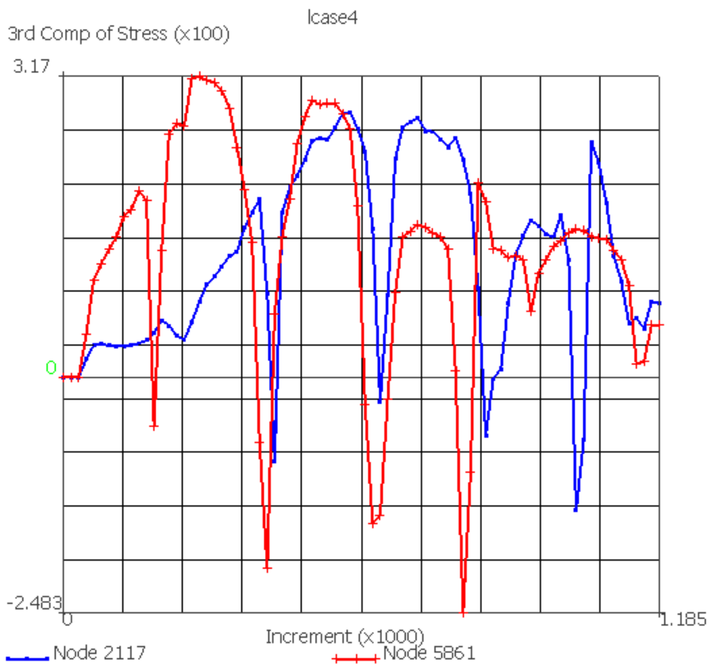

Figure 2: Third Stress Component Analysis for 4-Station U-Shaped Profile

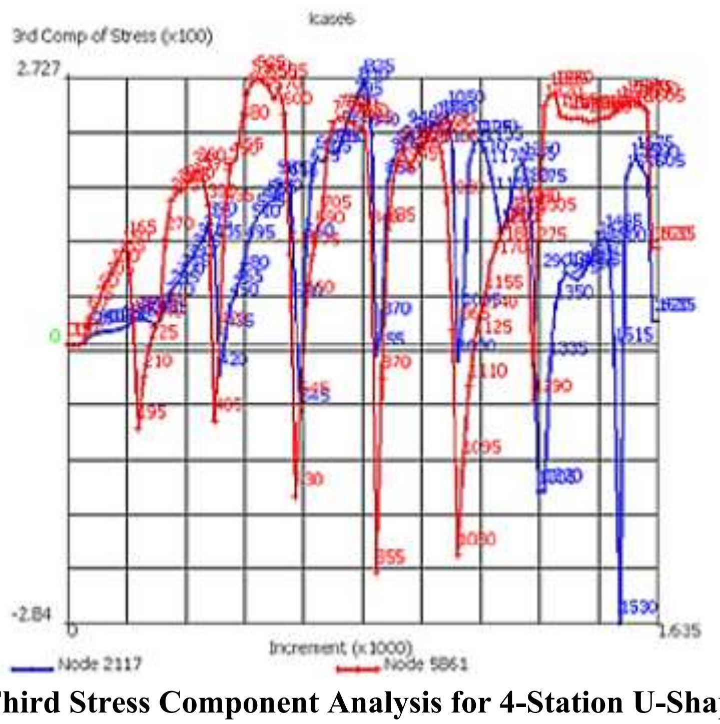

Figure 3: Third Stress Component Analysis for 4-Station U-Shaped Profile

The findings from the numerical solution serve to confirm observations that both the 4-station and 6-station roll forming processes effectively produce the required plastic deformation in the process materials. This observation is strongly backed by evidence that both layouts' stress levels reach or even marginally exceed the material's yield strength, determined as a value of 277 MPa. This observation is an indication that both the 4-station and 6-station layouts effectively fulfill the main requirement of permanent shape formation through yielding, in this way confirming that they are efficient at shaping material.

But even though equal levels of stress have been obtained, the plastic strain distribution is dramatically different. Such a distribution is one of paramount significance in the defect formation process with relevance to phenomena such as end-flare. In the case of the 4-station arrangement, the plastic strain accumulation is featured by more steep gradients and more pronounced localized peaks. These peaks are very pronounced at the leading as well as the trailing edge of the profile, showing a clear concentration in those very positions. The abrupt accumulation of strain observed in this instance is a very strong indication of the reality that the material goes through a quick process of plastic deformation in a considerably shorter forming length. This quick deformation ultimately leads to an uncontrollable flow of the material particularly at the extremities of the formed section. Due to this, such a condition gives rise to large and considerable dimensional deviations, which were verified through post-cut measurements. These measurements sufficiently reveal that there are larger mouth openings at the top as well as tail ends of the formed section.

By contrast, the 6-station layout achieves a more progressive and even development of plastic strain along the length of the profile. The lower peak values of strain and less steep strain gradients allow a more controlled deformation trajectory and allow the material to progress more smoothly into the forming geometry. The result is a more stable dimensional outcome with much smaller deviations in mouth opening, as confirmed by post-cut measurement.

Comparative research clearly establishes and highlights the fact that the determining factor for end-flare is not just the amount or level of applied stress, but it is much more related to the specific way the plastic strain is developed and distributed during the whole forming process. Furthermore, through the addition of increased numbers of forming stations to the process, it becomes achievable to minimize strain localization effectively, which also enables improved dimensional control and plays a significant role in the minimization of end-flare defects to a large degree. Such findings highlight and enhance the need for effective management of strain in the process of roll forming design. In this case, it is important to understand that the addition of additional stations is an essential function in streamlining gradients of strain, allowing even distribution of material flow, and thereby enhancing the quality of the resultant profile.

4. Conclusion

This in-depth and detailed study carried out an advanced quantitative analysis with a view to analyzing the effect that the number of roll forming stations has on the deformation behavior, strain accumulation, and general dimensional accuracy that occurs during the continuous forming process of U-shaped special profiles. In achieving this, FEA was utilized with the aim of simulating and analyzing two quite different roll forming configurations; specifically, one with a 4-station process and the other with a 6-station process, under accurately controlled process parameters. The simulations were designed with a view to detailed representation of the development of stress and strain state in detail during the process. They also examined the initiation, as well as the incremental build-up, of plastic deformation as a function of time. Finally, the simulations provided information regarding the geometric distortions that take place once the cutting of the part is complete.

The results from the simulation were conclusive, in that they clearly and unequivocally confirmed that both roll forming set-ups were able to induce the plastic deformation essential to achieve a permanent shaping of the profile. In both of the cases considered, the von Mises stresses developed approached, or in certain instances, even marginally exceeded the yield strength of the material used in the analysis, which is indicated to be 277 MPa. This observation is confirmation of the fact that an energy input sufficient to surpass the elastic limit of the material in consideration was present. However, in spite of this resemblance in the observed magnitudes of the stress in both cases, appreciable and significant differences were noted in the plastic strain response. This difference in plastic strain response ultimately turned out to be the controlling parameter that had a central role to play in maintaining the dimensional stability of the material as well as in the generation of any defect that may arise during the process. The 4-station process had a very localized and swift plastic strain accumulation, which was especially pronounced in the areas located near both leading and trailing edges of the profile. These localized maxima of strain were directly caused by the high and forceful bending that had been applied over a relatively small length in the forming process, which ultimately restricted the capability of the material for smooth redistribution of internal strains and stresses over the entire section. The material's failure to effectively respond to the applied curvature, without local overstressing, resulted in higher-than-normal levels of residual strain in the structure. The condition in this way encouraged an asymmetrical and non-uniform flow of material at the outermost ends of the profile. In direct consequence of these conditions, excessive geometric shape deviations after forming were observed, especially in the form of end-flare. Moreover, measurements at the mouth openings indicated that deviations exceeded 5 mm both at the front and rear ends. The focus of this localized thinning has also brought with it an increased risk related to localized thinning, which may cause edge waviness, as well as the possibility of the surface defect initiation that may occur.

As opposed to other configurations, the 6-station roll forming setup in comparison had a significantly better mechanism for effective control of strain. The improved configuration included additional stages of forming, which contributed significantly towards distributing the overall plastic deformation over a significantly larger forming length. As a result, this configuration facilitated a progressive development of strain in addition to a smoother redistribution of internal stresses in the material. This innovative staged deformation technique has been found to be extremely efficient in considerably lowering the peak plastic values of strain, which tend to occur during the cutting process. Moreover, it was instrumental in preventing the formation of sharp strain gradients, which tend to cause problems within the material properties. Through efficient management of the localized material flow, this technique also assisted in reducing the concentration of unwanted excessive strain energy at the profile edges. Due to these advancements, there was a noticeable improvement in the cross-sectional geometry uniformity. This was followed by a considerable decrease in post-cut dimensional deviations. These results were also confirmed through mouth opening measurements, which reported that the deviation was still well within the scope of acceptable manufacturing tolerances.

The general observations of this study strongly emphasize that, though roll forming operations are employed to shape complicated profiles, the overall stress transmitted during the process can serve as an important prerequisite for successful plastic deformation. However, it is important to understand the fact that it is the plastic strain that is distributed in both its value and gradient, which actually regulates and determines the occurrence or non-occurrence of dimensional defects. These defects, in their occurrence, can take various forms like end-flare, twisting, and cross-sectional asymmetry of the formed material.

The introduction of roll stations provides an essential step towards a more desirable energy partitioning strategy. This development enables the roll-forming process to proceed along much more stable strain paths. In this way, it leads to an improvement in both the structural strength and the dimensional accuracy of the profiles produced by the process.

It is also worth noting that the current research effort employed an extremely specific set of modeling assumptions that were carefully chosen to isolate and analyze significant forming behaviors in an efficient manner. The simulations employed in this study used rigid roll tools, which will not deform when subjected to applied pressure, and idealized roll geometries, which are theoretical constructs and not models of all potential real-world scenarios. Further, the study employed simplified Coulomb friction models and quasi-static loading conditions, which, while useful for some theoretical studies, do not fully capture all the complexities and variations one would encounter in actual real-world manufacturing processes. In actual manufacturing scenarios, there are numerous additional factors and variables that can influence forming behavior, including:

- The compliance of the tooling system, i.e., bending of the roll shaft and frame deflection, can result in introducing undesired bending or misalignment in the forming process.
- Rotational roll tooling dynamics, where inertial forces and roll eccentricities can potentially alter contact pressures and deformation trajectories;
- The intricate frictional behavior is characterized by introducing variable friction coefficients influenced by various lubrication regimes, surface roughness levels, and the velocity of strip movement;
- Material behavior complexities such as cyclic hardening/softening, kinematic hardening, anisotropic yield behavior, strain rate sensitivity, temperature effects, and the Bauschinger effect during multi-pass deformation;
- Post-forming effects, such as springback, relaxation of residual stress, and long-term dimensional stability under service conditions.

In order to achieve a better, more accurate, and more reliable simulation of real roll forming conditions in practical applications, and also to enable predictive models to be more accurate and more reliable, it is essential that future research and development efforts concentrate on incorporating advanced multi-physics simulations. The essential approach involves not just coupling structural mechanics with dynamic roll kinematics but incorporating detailed contact mechanics as well as thermomechanical interactions occurring during roll forming. In addition, the use of advanced constitutive models, such as the Chaboche model, specifically developed for nonlinear kinematic hardening, and combined isotropic-kinematic models and crystal plasticity frameworks, will have a critical role in enhancing simulation accuracy in relation to material responses. This enhancement is particularly crucial if the complex loading paths inherent in roll forming processes are taken into consideration. By facilitating such sophisticated modeling capabilities, FEA simulations can be evolved from predictive software to integrated process design platforms with high-fidelity capability for optimizing roll tooling geometries, process conditions, and material selection. This would directly impact on enhanced product quality, increased process robustness, lower scrap rates, and improved sustainability in continuous forming processes. In summary, the present work clearly indicates that an increase in roll forming stations is of fundamental significance in effectively improving control over strain distribution. This enhancement makes localized deformation reduce, which is a very critical variable in the quality of the produced part. It also makes dimensional accuracy increase during the process of roll forming complex U-shaped profiles. However, it is important to note that for the complete fulfillment of the potential offered by numerical simulation in optimizing the roll forming process, there is an urgent requirement for additional development. This development should be geared towards moving in the direction of multi-physics, multi-scale, and multi-parameter simulation environments, which are imperative in achieving full optimization in this area. Those advances would enable producers to attain higher process reliability, cost-effectiveness, and product performance in traditional as well as future-generation roll forming operations.

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