

Stretch Roll Forming

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ABSTRACT

This paper documents the development of a novel CNC metal forming process called "Stretch roll forming". It is an extension of the three roll forming (or slip-roll) process, wherein many pairs of roller-like dies mounted on positioning slides are used to approximate the instantaneous geometry of the part being formed, and to guide the formation of extrusions and sheets into desired shapes. The revolutionary enhancement is that, a stretch force sufficient to induce tensile yielding of the entire section is superimposed on the workpiece while it is being formed, by applying appropriate traction forces on the workpiece at each of the contact points. Tensile stretching avoids buckling of the section, and increases the strength of the part while reducing spring back and residual stresses. A further revolutionary improvement arises from replacing rollers with short die segments. The shape of the die can be changed to accommodate different cross-sections of extrusions. Dynamic changes in the location of the die can be used to produce parts with varying curvature along the length of the part. In addition to forming workpieces to desired geometries, this process can also be used to straighten them. 2D and 3D finite element analysis has been carried out using LS-Dyna to simulate the stretch roll forming of flat sheets and T-section extrusions. Results indicate that this process can also be further extended to impart a controlled amount of compressive residual stress on the outer layer of parts, to improve fatigue life. A proof-of-concept machine has been developed and used to stretch form flat, T-section and L-section extrusions with uniform stretch along the length of the part. The uniform stretch results in parts with uniform strength and cross-section, which permits weight reduction of the parts. Parts with constant radius as well as variable radius along the length have been formed. This CNC metal forming process eliminates heat treatment and produces higher quality parts while eliminating the need to use part specific dies for a wide class of parts. Significant savings in tooling and setup costs can be realized, thereby reducing lead time and cost of producing the parts and allowing "just in time" production.

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INTRODUCTION

In stretch forming of extrusions using dies, a stretch is generated in the extrusion, which is then wrapped around a die (Figure 1). The stretch force should be sufficient to result in a tensile stress in the length direction that is more than the yield strength. This avoids buckling of thin walls, and aids in reducing the bending moment and springback, thereby increasing the geometric accuracy of formed components. The stretch also increases the strength (due to strain hardening) and reduces the residual stress, leading to improved fatigue life of the components. Due to the friction force between the die and the part as it is wrapped around the die, the stretch generated in the part varies along its length, typically being highest at the ends, implying that the parts are most strained and thinnest near the splices. While stretch forming can produce a variety of components, unique sets of dies need to be fabricated and used for each specific forming

operation of each part. This increases the cost and lead time of production, especially for low production run products such as aircraft, ships, light rail cars, etc. The need for dies prevents the production of spares at the maintenance site and the need to store, maintain, locate, setup, and dismantle these dies contributes significantly to the cost of producing spare parts. While a simpler process such as slip-roll forming can form simple sheet parts not prone to buckling, bending of extrusions without a stretch will cause the web to buckle. Additionally, the geometric accuracy of the part will be poorer due to springback (due to the inherent variability), the fatigue strength enhancement due to stretching will be lacking, and higher residual stresses will promote stress corrosion cracking.

BACKGROUND

Most so-called CNC metal forming machines are just automated machines that control the movements and task



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sequences as required. They require dies to impart the geometry required on the component, and do not produce the geometry by numerical control like CNC material removal processes do. However, recent developments are beginning to change this. Multi-point forming is carried out commercially, with reconfigurable dies comprised of a two-dimensional array of pins whose vertical positions are individually controlled to produce a desired shape (Webb and Hardt, [6]). The top of each pin has a spherical shape, which, in combination with a polymer pad laid over this array of pins, helps interpolate the sheet surface into smooth, commercially acceptable shapes. While some of the larger users of sheet metal forming have invested in reconfigurable dies, the number of parts formed with these is small, due to the difficulty of obtaining accurate parts, and the tool being too small for larger parts (56.0" w × 72.0" L).

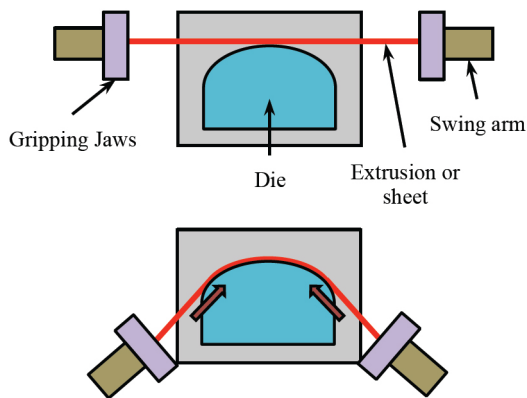


Figure 1. Schematic of stretch forming, showing a stationary die having the same geometry required of the part, and hydraulic cylinders mounted on swing arms that stretch and wrap the extrusion around the die. Note that the friction force that acts on the extrusion is also shown.

Matsubara [2, 3], describes the early development of Single Point Incremental Forming (SPIF) in the 1990s. A central post was used to produce conical and pyramidal shapes from flat sheet metal in one stage. A comprehensive study of the process parameters, as well as the elimination of torsion by reversing the traverse direction between passes, was reported. Jeswiet and Ali [8] describe a follow-up study of the SPIF process and showed results of two different approaches, one with the central tool post of Matsubara and one without. The tool path was reversed for the second case, to be outward-in. Kim and Yang [1] attribute the increased formability in SPIF to the uniformity of thickness reduction of the sheet. While the forming limit strains in SPIF are found to be larger than in drawing processes, this is tempered by the fact that the sheet thin-out is much higher (due to the peripheral material being locked in place in SPIF) as compared to drawing which allows the material to flow into the die, thereby minimizing thickness reduction (Pohlak et al., [5]).

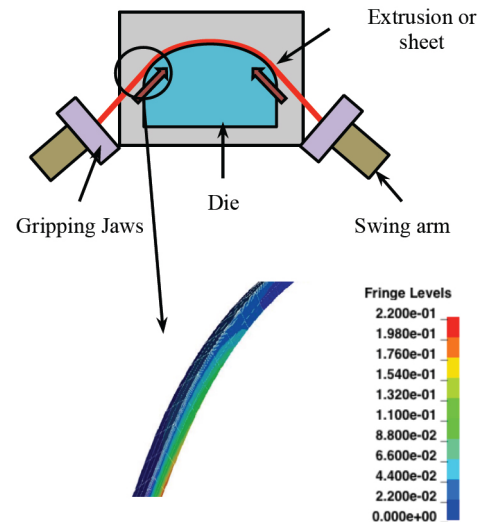


Figure 2. Stage in the FEA simulation of stretch forming shows the extrusion wrapped around a die specific to the profile of the part. A portion of the extrusion is magnified to show the non-uniform distribution of plastic strain within the extrusion. The plastic strain is 22% while the total stretch of the extrusion originally 57 inches long is only 0.4" (0.7%)

Mori et al. [4] describe an interesting incremental sheet forming approach developed by Matsubara and others, wherein the forming is accomplished by a sequence of blows exerted on the sheet by a hammer held in a mechanical press or by a laser beam. Yoon and Yang [7] have developed an "incremental roll forming" process for doubly curved sheet metal parts. The sheet is located on four ball-tipped supports in the middle of which a driven roll presses down into the sheet and moves the sheet. This causes the sheet to attain a doubly curved shape in the region scanned. Note that the mode of deformation is dominated by bending, which is likely to induce a large amount of residual stress in the sheet.

The relationship of the SRF process to SPIF is that, while the simple SPIF tool is one type of end effector, the end-effector developed by us for stretch roll forming (SRF) is another. It can directly control the strain imparted to any region of the sheet and is better suited for medium to large size parts such as aerospace components. In addition, the localized stretching and the normal compression both serve to improve the formability of parts. The end effector also induces a burnishing effect on the surface layers of the part. Since a controlled amount of strain can be imparted uniformly over the part, the material is strengthened by the corresponding amount of strain hardening that is characteristic of that material. The actual stretch achieved at any location along the part, and the force required to stretch the part can both be recorded and documented, serving as a proof test that also identifies variability in the material. Coupled with knowledge of the relationship between process parameters and outcomes such as fatigue life, the documented

stretch vs. stretch load will serve as proof that the part will actually function as intended in service.

Some quality and cost advantages of SRF are listed below:

- Improves the subsequent yield strength of the parts by 5% or more
- Reduces weight per unit length of the extrusions by the uniform stretch imparted
- Produces longer parts than currently possible; can reduce the # of splices from 3 to 1
- Forms parts with residual stress and geometric accuracy comparable to stretch forming
- Potential for increase in the fatigue life of the parts due to burnishing
- Reduces material wastage as stretch presses need extra length for gripping
- Eliminates dies and tooling, is ideal for prototyping, and enables faster design-to-market
- Can form parts in the final heat-treat condition in which they are used
- Small footprint reduces floor space requirements; also does not require space for painting/coating as it can form parts that are pre-finished
- Eliminates many production steps thereby reducing lead-time, WIP, and inventory costs
- Invites cellular manufacturing, just-in-time production, and one-off spare part production
- Improves productivity, has a small footprint, and frees up capacity on existing machines
- Energy regeneration by the brake stations keeps the energy required to the minimum. SRF is a green process

PROCESS CONCEPT

The concept behind the process is to approximate the geometry and to simultaneously apply tractions to the workpiece using rolls. Figure 3 shows a schematic sketch illustrating this. The traction force F_f exerted on the workpiece by a roll is obtained from equation (1) where r is the radius of the roll and M is the torque applied to the roll.

$$F_f = M/r \quad (1)$$

Each pair of rolls (above and below the workpiece) at one position along the workpiece forms a set. The torque applied on the two rolls of a pair is in opposite directions, so they result in a net traction force on the workpiece that equals to $2F_f$. In Figure 3 the two roll sets on the left exert a traction

force towards the left and the next two exert a force towards the right, using the workpiece as the “rope” in a game of tug-of-war. The total traction force and the tensile stress in the workpiece increase proportionate to the number of roll sets on each side. For n roll sets on each side, the stress σ in the workpiece is obtained from equation (2) where A is the area of the cross-section of the workpiece.

$$\sigma = 2nM/rA \quad (2)$$

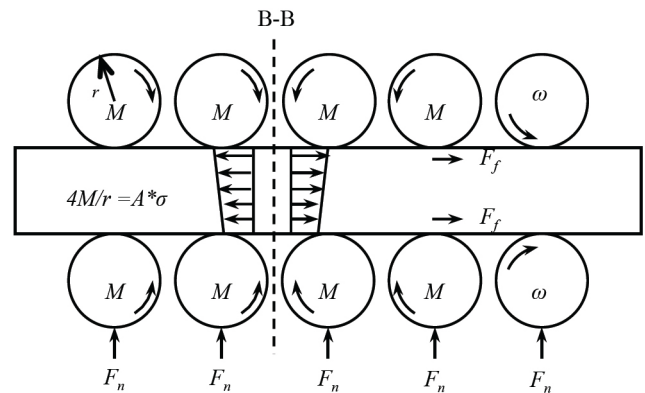


Figure 3. Schematic sketch of the stretch roll forming process showing how the moments applied by opposing rollers are converted into a stretch force along the length of a workpiece

The number of roll sets on each side and the torque exerted on each roll can be changed to induce a stress sufficient to cause the workpiece to yield and stretch plastically in the middle section (B-B), where the stress is highest.

Note that if all the rolls are driven at the same torque, the net force on the workpiece is zero. While all the rolls in these first four sets are driven in a constant torque mode, the last roll set is driven in a constant velocity mode, to pull the workpiece through from the left to the right.

For the traction force exerted by each roll on the workpiece to not cause slippage between the roll and the workpiece, the normal force exerted by the roll on the workpiece should be greater than F_f/μ . The maximum normal stress at the contact between the roller and the workpiece is typically limited by the maximum stress that the coating on the roller can withstand, P_{max} . Given a maximum normal stress, the average normal stress would be 2/3 of the maximum value based on Hertz contact theory (Figure 4). The width of contact would depend on the elastic properties of the coating, and for rubber-coated rolls is typically about one half of the outer diameter of the roll.

The number of roll sets on each side that are required to accumulate traction sufficient to cause yielding of the workpiece, can be obtained from equation (3), where Y is the material yield stress and w is the contact width between the workpiece and the roll. This is simply obtained by dividing