Finite element simulation of rotary swaging process of tube-shaped workpieces

Renganathan Sekar[*],
Metal Forming Research Corporation (MFRC)
r.sekar@afdex.com

Mohd Kaswandee Razali, ManSoo Joun
Gyeongsang National University, South Korea
kas2393@afdex.com, msjoun@gnu.ac.kr

ABSTRACT

The applications of tube-shaped workpieces have been growing steadily across many industries, thanks to its advantages like lightweight and versatility in assembly. This increase in demand must be met with efficient near net shape manufacturing processes like rotary swaging which is also gaining industrial prominence in the recent years. The process investigated in this paper is a category of recess type swaging process with mandrel where there is no axial movement of the workpiece. Initially, the FE methodology is validated by comparing the predictions of a similar process with the experiments. Using the same methodology and FE tools, a FE model is created for the rotary swaging process with six dies. The nodal velocity, effective strain and effective stress distribution from the simulation were investigated and a good agreement was found between the theory and predictions. The intelligent metal forming simulator AFDEX is used for carrying out the finite element analysis. The axial velocity is found to be maximum in the sizing zone during the deformation process and the tube-shaped workpiece experiences triaxial stress states. This simulation framework can be used for quicker development and optimization of process design for tube shaped workpieces.

Keywords: *Finite Element Method (FEM); Incremental Bulk Forming; Rotary Swaging; Tube-Shaped Workpieces; Cold Forging.*

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Introduction

Near net shape manufacturing processes are crucial for increased productivity and are always aimed at optimizing the number of processes as much as possible. Rotary swaging is one such incremental forming process, which has huge potential to be applied in a massive scale across automobile, aviation and aerospace industries [1].

The process has been predominantly used for reducing cross sections of metal tubes and rods and is categorized under the open die forming processes according to DIN 8583 – Forging [2]. Due to the versatility of its applications and the obvious advantages from a strength to weight ratio perspective, tube shaped workpieces are finding their way almost in every major industry. And rotary swaging processes are preferred for forming tubes owing to their precision and the automation ability.

In a rotary swaging process, multiple dies are arranged radially around the workpiece. The process mechanism can be understood by referring to Figure 1 where six dies are used to plastically deform the tube to resemble the shape of the mandrel. The dies move up and down with a constant velocity. The mandrel remains stationary and the workpiece is rotated with a velocity synchronous to the motion of dies.

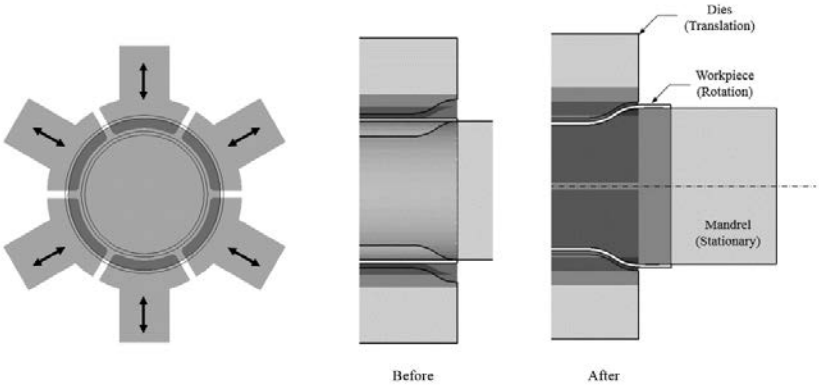


Figure 1. Schematic illustration of the rotary swaging process.

By virtue of the high-frequency radial movement of the dies which in turn leads to the multidirectional forging, the tube undergoes uniform necking. Theoretically, rotary swaging processes can full under two categories namely, infeed methods and recess methods.

The difference between these two methods is based on how the workpiece is fed. As the name suggests, in the infeed method, the workpiece is gradually fed along its axis. In the case of recess method, the workpiece does not have any axial motion. This paper is based on the latter method which is often used for reducing the diameter only at a certain position of the workpiece[1].

Finite element simulations of manufacturing processes have become inevitable these days for reducing the development time as well as use innovative methods to reduce energy and material consumption. In this paper, FE simulation of a rotary swaging process with 6 dies is carried out in order to investigate the process mechanism and establish a generic framework to simulate different variants of the process efficiently.

Literature Survey

Most of the literature that exists in the public domain are based on the infeed rotary swaging process where the workpiece has axial translational motion during the deformation process. Recess method based swaging process, which is the focus point for this research work, still needs to be investigated in detail to get a comprehensive understanding of the process mechanism. The literature corresponding to rotary swaging process can be classified into three categories listed below.

Theoretical analysis

Ghaei et. al[3] examined the deformation history and the quality of the radially forged parts by designing different die inlet zones like linear, convex, concave and hybrid surfaces. In subsequent research, the authors tried to predict the theoretical maximum deformation load and assess the effect of various process parameters. In order to predict the neutral plane and the radial forging load, Sanjari et. al[4] developed a new velocity field.

Experimental analysis

Abdulstaar et. al[5] studied experimentally, the effect of swaging process on the microstructural properties like grain size for commercially pure aluminium (Al 1050) and concluded that rotary swaging process resulted in reduced grain size. Experimental studies of rotary swaging process for micro components by Kuhfuss et. al [6] also revealed a change in microstructure and residual stress distribution. Rotary swaged light-weight components were studied from the perspective of production capabilities by Piwek et. al[7] for increasing productivity and component quality.

Numerical analysis

The authors group [8] used finite element method and microhardness test to find out the strain field and component heterogeneity in radial swaging process. Li et. al [9] simulated the radial forging process of thin-walled copper tubes with micro grooves on the inner side and compared their predictions with experiments.

Herrmann et. al[12] investigated the impact of serrations on the interior surface of the tools in the rotary swaging process and concluded that the serrations reduced the axial reaction forces when the value of friction coefficient was low(dry swaging process). But the authors have also emphasized that axial force reduction happened at the cost of reduction of workpiece quality(surface roughness and deviation).

Ishkina et. al[13] established the influence of fluctuating process parameters on residual stress distribution and highlighted the importance of its close control. But this was again for an infeed rotary swaging process where the workpiece had an axial motion. A FE simulation of a radial swaging process with 6 dies have never been carried out before for manufacturing tube shaped workpieces and through this research work, a simulation methodology, which has been validated with experiments, is established.

Finite element simulation of rotary swaging

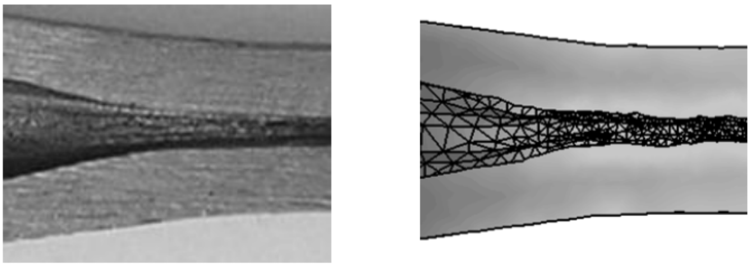
The commercially available intelligent metal forming simulator AFDEX is used for simulating the rotary swaging process. Some engineering assumptions are made in order to simplify the FE analysis without losing out on the simulation accuracy.

- The thermal phenomenon between workpiece and dies is neglected
- The effects of acceleration and inertia were neglected
- Workpiece material is isotropic
- Elastic deformation component of workpiece is neglected
- Workpiece obeys von Mises yield criterion and associated flow rule
- A pusher supports the workpiece which initially rests on the mandrel
- The mandrel and dies are assumed to be rigid

Validation of FE methodology

One of the authors of this paper [10] have used the same simulation program to simulate the round-round in-feed swaging process with 4 dies, without a mandrel and with a back-pressing force exerted on the pusher by the axial motion of the workpiece (Figure 2). The predicted tube thickness ranged from 3.66 mm to 3.84 mm where the experimental thickness was 3.75 mm. The details of the experiment carried out by one of the authors is explained in [14].

Around 100000 tetrahedral elements were used for discretization. The wrinkles in the inner surfaces, observed in the experiment, were predicted well by the simulation. This shows that the FE methodology for infeed swaging process without mandrel matched well with experiments and the same can be applied for the recess swaging process (current research) with 6 dies.



(a) Experiments (b) Predictions

Figure 2. Comparison of experiment and FE prediction for radial in-feed swaging process of a steel tube without mandrel [10].

Current FE Model, material properties and die velocity profile

The rotary swaging process is widely used for producing components like hollow drive shafts, gear shafts as well as the control rod of the steering gear [7]. The process chain consists of cutting the raw material into required length, radially forging the cut blank into desired shape and then trimming off the elongated length by virtue of swaging process. Keeping this in mind, the analysis model is constructed. Figure 3 shows the FE analysis model of the process under investigation. The tube-shaped workpiece is 1.5 mm thick and 143 mm long with an outer diameter of 75 mm. The material of the tube is AISI_1020 and is characterized by Equation (1) at room temperature.

$$\bar{\sigma} = 300(1 + \bar{\epsilon}/0.01194)^{0.20618} \quad \text{MPa} \qquad (1)$$

The friction between the dies, mandrel and the workpiece are defined using Coulomb friction model with a frictional coefficient of 0.05. The velocity profiles of the dies and the workpiece is shown in Figure 4. Around 77000 tetrahedral elements are used for discretizing the analysis domain. Remeshing is avoided while simulating this process in order to avoid the undesired but inevitable smoothening of state variables.

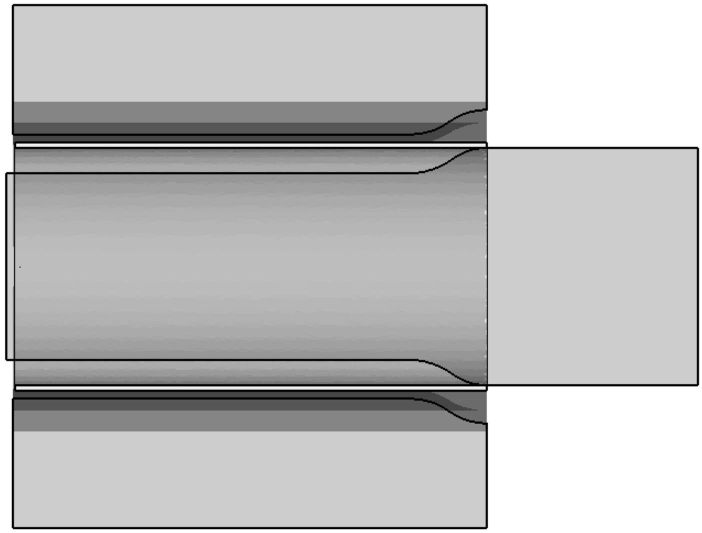


Figure 3. FE Analysis model under investigation

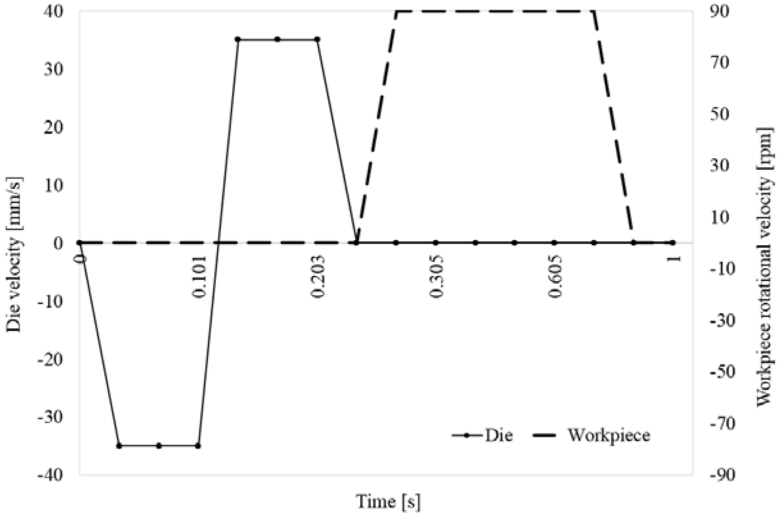


Figure 4. Velocity profiles of die and workpiece

Results and discussion

The rotary swaging process consisted of 8 blows to carry out the incremental forming of the tube. The outer diameter of 75 mm was reduced to 60 mm in 8 blows incrementally as can be seen in Figure 5 which shows the blow-wise deformation history as well as the comparison of initial and final deformed shape. Thinning was observed near the end of the tube as a result of increase in length. This trend was in line with literature where similar processes were simulated [11].

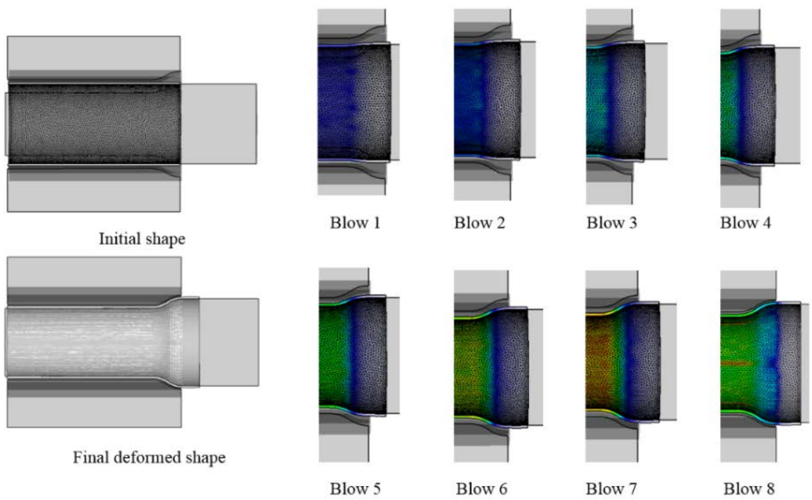


Figure 5. Blow-wise deformation history of the swaging process

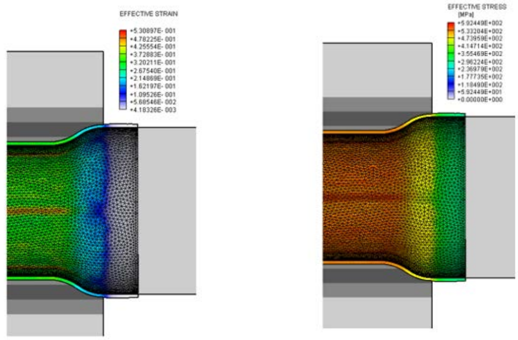


Figure 6. Effective strain and effective stress

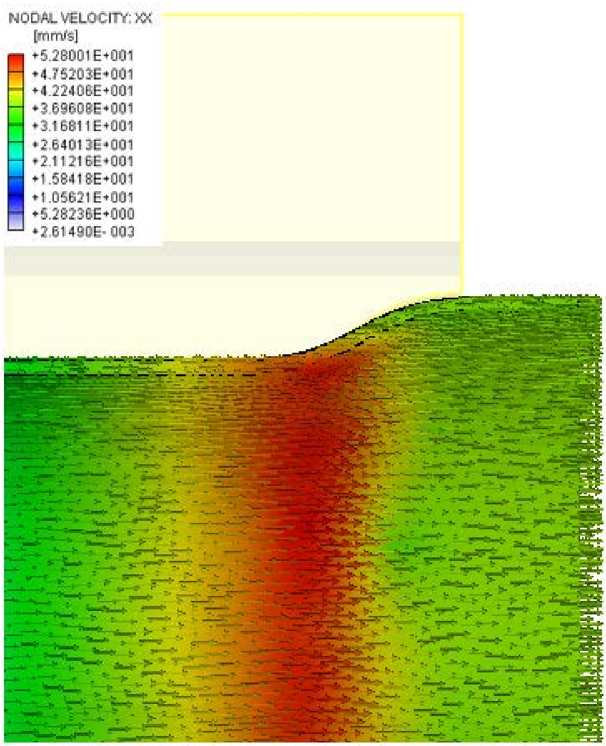


Figure 7. Nodal velocity vectors in the axial direction

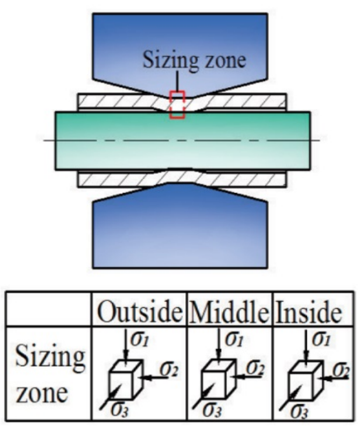


Figure 8. Stress states of the tube [1]

Figure 6 represents the effective strain and stress distribution respectively. To understand the effective stress distribution predicted, one must investigate the velocity distribution during the forging process (Figure 7) and the internal stress states of the tube (Figure 8). The nodal velocity significantly increases along the axial direction at the sizing zone. This is in line with the theoretical understanding of the process mechanism.

Rotary swaging processes of this category experience triaxial stress state. The three stress components ($\sigma_1, \sigma_2, \sigma_3$) in Figure 9 are the axial, radial and circumferential stress components respectively. The axial stress is tensile and the radial, circumferential stresses are compressive in nature. In order to have a minimal variation of wall thickness, the radial stress must be kept minimal compared to the circumferential stress. This is controlled by adjusting the die advancement per blow.

Obviously, the stresses increase significantly as the dies contact the workpiece. The axial elongation of the workpiece as well as the necking predicted in the simulation is because of the axial tensile stress by virtue of the deformation happening in the sizing zone. The axial elongation is inevitable in this process owing to the process mechanics and the excess length must be trimmed as per subsequent assembly requirements.

Conclusion

In this paper, FE analysis of rotary swaging process for forming tube shaped workpieces was carried out using a commercially available metal forming simulation software. The phenomenon predicted in the simulation matched well with the theoretical understanding of the process. So far literature is highly skewed in favor of the infeed swaging process highlighting the importance of this research work. Recess swaging processes with mandrel experience triaxial stress states and the axial stress is responsible for elongation of the tubes.

With complex material flow phenomenon, usage of FE analysis methodology is very crucial in arriving at creative and optimum process designs quickly. The effect of die velocity and the number of blows on the deformation of the workpiece will be investigated in more detail in the near future in order to optimize the process design and reduce the development time.

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