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Investigation of the stress state around the forming zone during the flow form process

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Abstract. Flow forming process is a cold metal forming process, which has great advantages over conventional forming techniques such as extrusion and tube drawing. Some advantages of the flow forming process are high material utilization, close dimensional tolerances and excellent surface finish. Flow forming finds extensive applications in industries such as aerospace, automotive, and manufacturing, where the demand for lightweight, durable, and intricately shaped components is crucial. Different types of geometries including thin-walled and axisymmetric cylindrical parts can be manufactured by flow form process. In flow forming process, the preform, which is clamped to a rotating mandrel, is formed by the rollers. It involves the incremental shaping of a rotating workpiece by applying axial compressive forces while simultaneously feeding it through a set of rollers. After the process, length of the preform is increased by decreasing the outer diameter. However, one of drawbacks of the process is the complex mechanical behavior around the forming zone. Understanding the material flow and stress state around the forming zone is crucial to perform a successful process. In this study, stress state around the forming zone was investigated numerically. After validating of 3-D explicit finite element model with the measured loads from experiments, a detailed examination of the stress state around the forming zone was performed numerically. Effects of different process parameters such as thickness on the stress state were emphasized. Also, differences between the stress states around the forming zone of the forward and backward flow form processes, which are two different techniques of the flow form process, were stated. It is also shown that different stress states occur at different stages of the process. Finally, the relation between stress state and failure mode was explained.

Introduction

In flow forming, rotating workpiece is supported by a mandrel while rollers move through axial direction. The rollers are free to rotate around their own axes. A lubricant is utilized between the workpiece-roller and workpiece-mandrel interface to minimize the shear stress and cool the workpiece. The thickness of the workpiece is reduced and the length is increased during the forming process. There are two main methods of the flow forming process, which are forward and backward. In forward flow forming process, material flow occurs in front of the rollers and in the direction of the roller movement. However, material flows in the opposite direction of the roller movement in backward flow forming process. Forward flow forming is used when no changes to the form on the tail side are requested for the preform. In forward method, the flow direction of the material is restricted by the tailstock. The mechanisms of the forward and backward flow forming methods are illustrated in Figure 1.

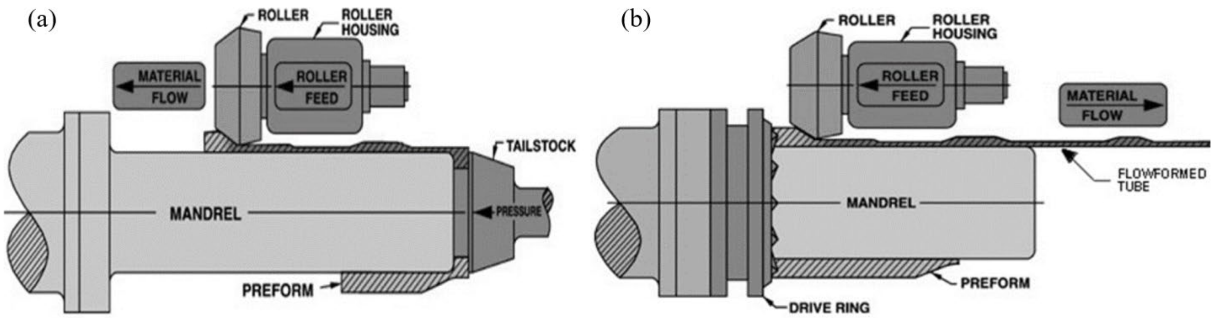

Fig. 1. Flow forming process schematic a) forward flow forming process, b) backward flow forming process

Incremental forming with localized contact area causes a complex behavior of the material around the roller contact zone. The deformation is strongly restricted by surrounding material, which causes a complex stress state around the forming zone. Xu et al.[1] performed an analysis to classify the stress state around the forming zone. They did not observe an apparent difference between forward and backward forming in terms of stress state. A non-homogeneous material flow arises resulting from a situation of local deformation between the workpiece and rollers. Because of non-homogeneous material flow, evaluating the workpiece's stress state is essential to its quality during the flow-forming process. S.C. Chang et al.[2] investigated the effects of inhomogeneous material flow on the incrementally thickness reduction for both forward and backward methods in aluminum alloys. However, taking into account the stress state on the preform and the contact pressures between surfaces will yield deeper understanding about this problem. In the study conducted by M.S. Mohebbi and A. Akbarzadeh [3], finite element simulations were carried out to explore the evolution of redundant strains in a single-roller flow forming process. It was observed that the occurrence of reversal straining significantly influences the redundant work in the process.

In this study, a detailed investigation was conducted on the stress state around the forming zone. The comparison was made mainly between forward and backward flow forming processes. In addition, thickness were also considered. Firstly, forces in different directions were compared. The forward and backward forming processes were then compared in terms of stress in various forming zones. In the context of the study, the stress state in the initial stages of the process is under scrutiny. Consequently, an examination is conducted on the impact of forming in the vicinity near the free edge of the tube on the stress state.

Methodology

Abaqus/Explicit [4], a commercial code was employed to simulate the forming process The workpiece material in this study was chosen to be S4140. The analyses utilized material properties depicted in Figure 2 generated from JMatPro [5], which varied with strain rate. Even though it is recognized that the material's sensitivity to rate has a limited impact in cold forming, the material was modeled to incorporate rate dependency. An elasto-plastic material model was defined for workpiece, while roller and mandrel were assumed to be rigid.

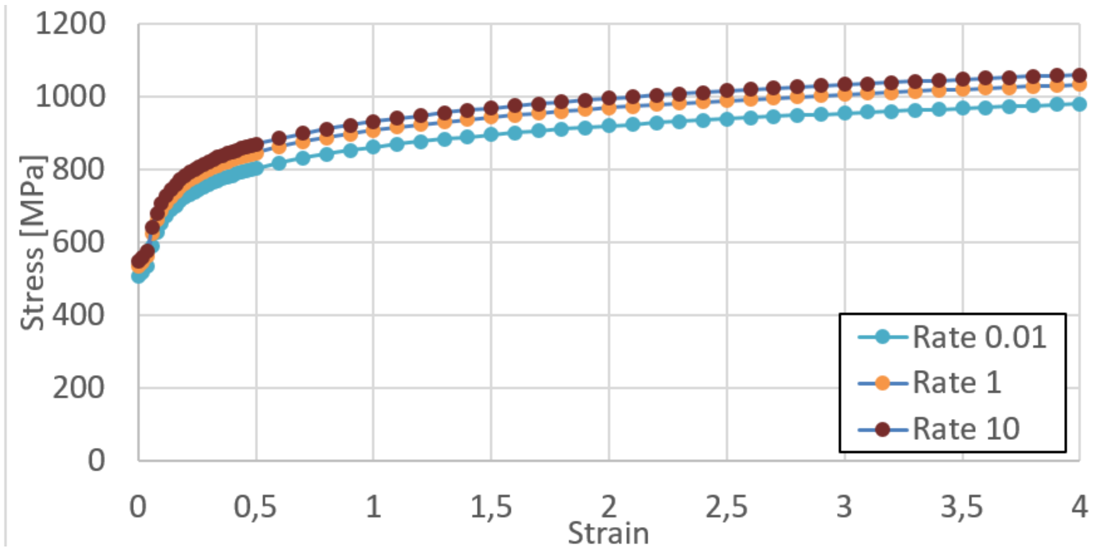

Fig. 2. Stress – Strain curve of the S4140 with strain rate sensitivity.

The finite element setup is depicted in Figure 2. In the analyses, temperature changes that may occur due to plastic deformation and friction have been neglected. A refined mesh was utilized around the forming zone to accurately capture the stress state, while a coarser mesh was employed far from the forming zone to reduce computational time. The linear reduced element type was used to shorten computational time and prevent the shear locking problem, but this element type, which has a one point integration, can cause hourglass, so the enhanced hourglass control was applied. A total of 83500 CD8R elements were used. Mass scaling, a technique to expedite computation by increasing the mass of the workpiece, was implemented in the simulation. Following the analytical solving stage, it was made sure to confirm that the mass scale factor (EMSF indicator) in ABAQUS was low enough to avoid having an effect on the solution. Artificial strain and kinetic energy parameters were checked to ensure that the inertial forces did not influence the solution. Since the purpose of the simulation was to investigate stress state solely, temperature was not included in the simulation. The process parameters and boundary conditions are summarized in Figure *3*.

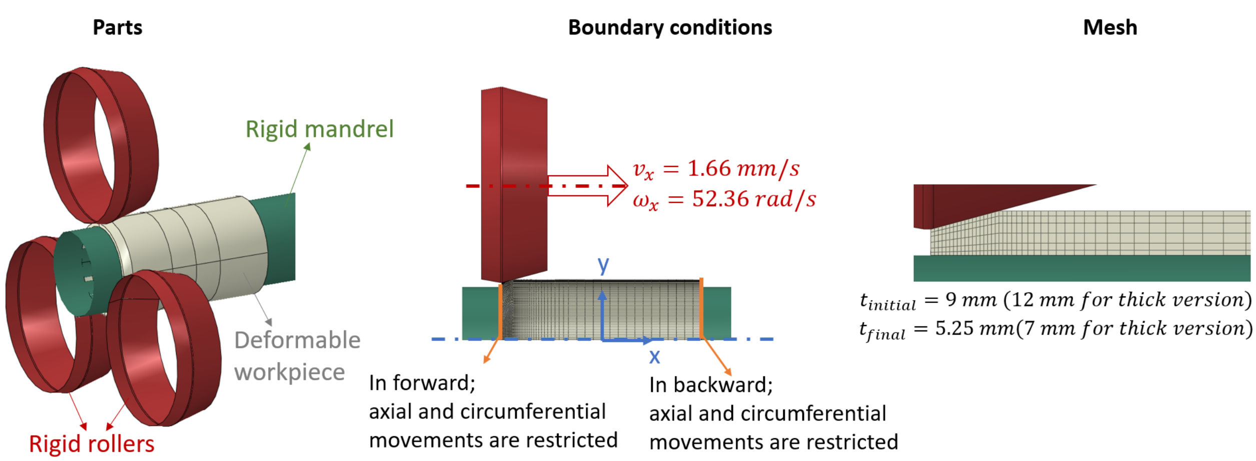

Fig. 2. Finite element model of the flow forming process with three rollers.

Results

Firstly, the forces occurring during the forming process were analyzed and compared with the experimentally measured results. The experimental measurement was performed only for the backward forming, and after verification of the analysis results, the analysis scenarios were continued. The verification results given in Figure 4 belong to the radial direction force data in the backward process performed in Repkon and the results performed in Abaqus/Explicit.

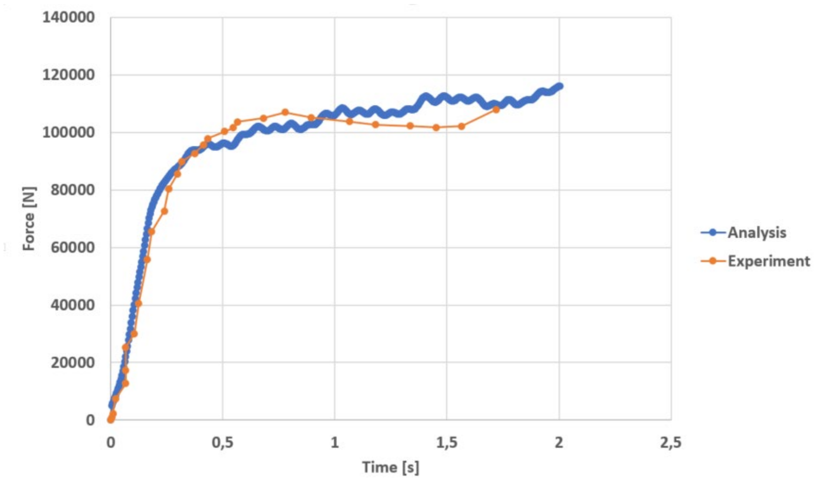

Fig. 3. Comparison of process forces obtained from experiments and analysis

As seen in the Figure 5 the forces obtained from the backward forming analysis were higher than those obtained from forward forming. The larger contact area observed on the bottom surface of the workpiece in backward forming is the reason for the higher forces in backward forming. In the force graph, it can be seen that the load increases rapidly in the first 0.4 seconds (transient), and remains constant during the process (steady state). The steady state region refers to the situation where full contact between the roller and the workpiece is achieved. The presentation includes only the initial 2 seconds of data to provide a detailed view of the initial increasing trend of the load.

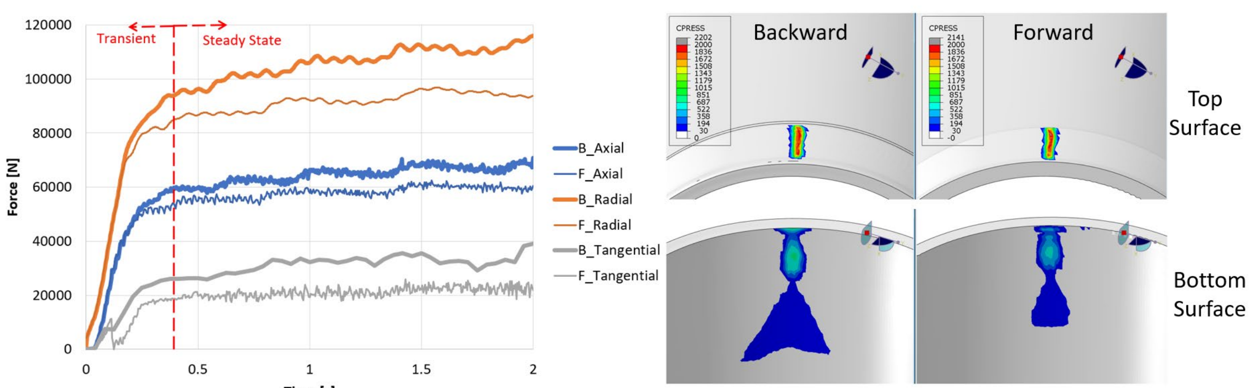

Fig. 5. The time dependent force variations and contact pressure distributions in the analyses (B and F refer backward and forward, respectively)

In the radial direction, a compressive stress state was observed on both top and bottom surfaces of the workpiece for the Backward process and these stress distribution are shown in the Figure 6. The contacts of roller/workpiece and mandrel/workpiece created a pure compressive stress in radial direction around the forming zone. This radial compressive stress state plays a crucial role in enhancing the material deformation characteristics during the forming process. The consistent application of compressive forces by the roller/workpiece and mandrel/workpiece contacts ensures a controlled and uniform shaping of the workpiece in the radial direction. The observed compressive stress on the top and bottom surfaces not only signifies effective material compaction but also contributes to the overall structural integrity and dimensional accuracy of the formed product.

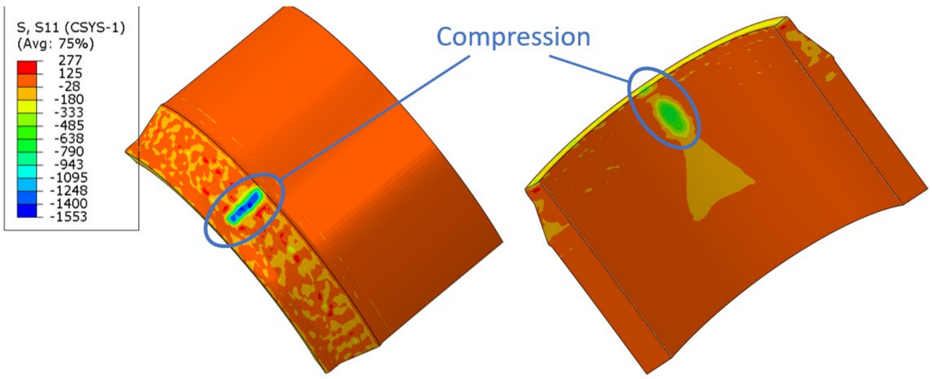

Fig. 6. Radial stress distribution on the top and bottom surface of the workpiece for backward process.

In the circumferential direction, a compressive stress state was inspected on both top and bottom surfaces of the workpiece along the roller path. However, residual tensile stresses appeared behind and in front of the roller on the top surface of the workpiece as shown in Figure 7 below. The mentioned expression of residual stress pertains to the stress that arises within the shaped part of the roller subsequent to the shaping process. Additionally, circumferential tensile stress occurred just in front of the roller on the bottom surface of the workpiece. The magnitude of the tensile stress occurred on the bottom surface in backward forming was more pronounced than in forward forming. Moreover, tensile stress seen on the bottom surface of the workpiece was more noticeable in the thick workpiece.

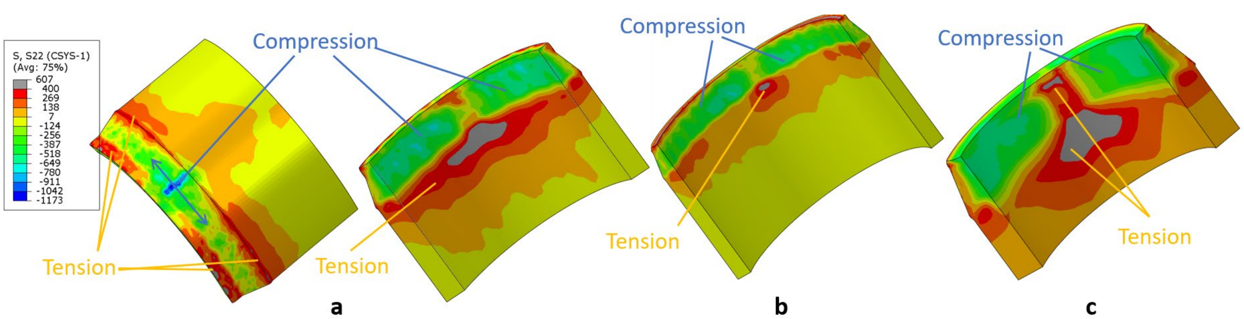

Fig. 4. Circumferential stress distribution on the top and bottom surface of the workpiece a) backward, b) forward, c) backward – thick workpiece

In the axial direction, a compressive stress state around the roller contact region raised on top surface of the workpiece. However, tensile stress was seen in front of the roller on the bottom surface due to material flow in the circumferential direction. The stress distributions for the forward, backward, and thick workpiece analyses are shown in Figure 8. The axial stress states observed in forward and thick workpiece situations were similar to those in backward forming.

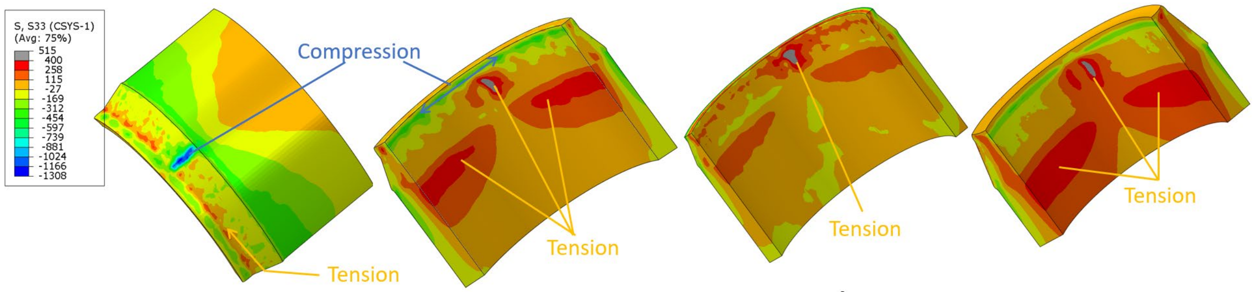

Figure 5. Axial stress distribution on the top and bottom surface of the workpiece a) backward, b) forward, c) backward – thick workpiece

Conclusion

Backward and forward flow forming process analysis was performed with three rollers. After the analyses, the stress state on the workpiece in both the backward and forward processes and the contact pressure between the rollers and the workpiece were evaluated accordingly. It is shown that the stress state varies around the forming area. The magnitude of the stress for backward forming was higher than the forward, while the stress state was similar. The contact pressure occurring on top and bottom face of the tube was observed more in the backward flow forming than in the forward. The compressive stress state was observed in the radial direction on the top and bottom surfaces of the workpiece. The compressive stress is higher in the backward flow forming analysis compared to the forward flow forming due to more contact areas on the bottom surfaces of the workpieces. The tensile stress occurring in front of the rollers was also more noticeable in the backward analysis. Tensile stress was observed in front of the rollers in the axial direction due to the material flow.

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