3D Numerical Simulation of Seamless Pipe Piercing Process by Fluid-Structure Interaction Method

Ameen Topa¹, Do Kyun Kim^{2,3,*}, and Youngtae Kim⁴

¹TAQA MISR, Kuala Lumpur, Malaysia

²Department of Civil and Environmental Engineering, Universiti Teknologi PETRONAS, Seri Iskandar, Perak, Malaysia

³Graduate Institute of Ferrous Technology, POSTECH, Pohang, Korea

⁴Smart Construction Technology Team, Daewoo Institute of Construction Technology, Suwon, Korea

Abstract. Seamless pipes are produced using piercing rolling process in which round bars are fed between two rolls and pierced by stationary plug. During this process, the material undergoes severe deformation which renders it impractical to perform the numerical simulations with conventional finite element methods. In this paper, three dimensional numerical simulations of the piercing process are performed with Fluid-Structure Interaction (FSI) Method using Arbitrary Lagrangian-Eulerian (ALE) Formulation with LS DYNA software. The results of numerical simulations agree with experimental data of Plasticine workpiece and the validity of the analysis method is confirmed.

1 Introduction

Metal pipes are classified into welded pipes and seamless pipes. Welded pipes are manufactured by bending and welding metal sheets while seamless pipes are produced using piercing process. Seamless pipes are more commonly used in oil and gas industries than welded pipes due to their higher reliability [1]. In rotary piercing process, a heated cylindrical workpiece is fed into a plug by the action of two skewed rolls which rotates in the same direction. The rolls are tilted and placed on opposite sides of the workpiece, thus they provide both rotation and translation to the workpiece. Since the invention of the piercing process over a century ago, numerous empirical and analytical studies have been conducted [2,3].

Finite Element Analysis (FEA) of metal forming processes is performed to obtain necessary information to properly design and control these processes. The number of experimental trials can be minimized with the exploitation of Finite Element Analysis which would significantly reduce the development lead time. Moreover, with the decrease of

* Corresponding author: do.kim@utp.edu.my

experimental work, the overall development cost of the product is reduced. Nowadays, the application of Finite Element Analysis into user-friendly software and the progress of powerful computers technology has revolutionized the metal forming analysis [4,5].

Finite Element Analysis is based on the concept of discretization. The physical structure is divided into a finite number of elements which has a finite number of degree of freedom. Since the physical structure has infinite degree of freedom, a discretization error exists. This error can be minimized if the object is discretized into more elements however this will cost more computational time [6].

Another drawback of conventional finite element analysis is its limitations in modelling fluid-like behavior in which there is excessive deformation in the material. Severe deformation may result in mesh entanglement and negative volume problems as illustrated in Fig. 1. Therefore, a new formulation called Arbitrary Lagrangian-Eulerian (ALE) was introduced to solve these challenges. This method was proven to be successful in modelling the Fluid-Structure Interaction problems [7,8].

Fig. 1. Severe element deformation in finite element analysis [9]

In this paper, the numerical simulations of rotary piercing process are performed with Fluid-Structure Interaction analysis. The workpiece has a fluid-like behavior due to its high workability and large deformation during the process. The results of the numerical simulations are compared to the empirical data available in the open literature [1,3,10,11].

2 Numerical Simulations

The stress strain curves of Plasticine are similar to those of steel in hot conditions, thus, it is a good substitute for modelling the material behavior during piercing process. Lead is another good choice however Plasticine is more commonly used due to its low cost and the simplicity of analyzing the kinematics of its material flow during forming processes [12]. The mechanical properties of standard Plasticine are obtained from previous works [13-15] which are listed in Table 1. The stress strain curve of Plasticine room temperature is illustrated in Fig. 2 and the following equation is derived to describe the curve [10]:

$$\bar{\sigma} = 0.23 \bar{\epsilon}^{0.08} \tag{1}$$

where the unit of the stress is MPa.

Table 1. Mechanical Properties of Plasticine

Property	Unit	Value
Density	kg/m ³	1800
Elastic Modulus	MPa	42.5
Yield Stress	MPa	0.18
Poisson’s ratio	-	0.434

Fig. 2. Flow Stress of Plasticine at room temperature [15]

The workpiece is a cylindrical billet with an original diameter of 45 mm which is fed between two tilted rolls with a feed angle of 9 degrees. The rolls have a maximum diameter of 292 mm and the distance between their axes of rotation is 330 mm. Thus, the minimum roll gap is 38 mm. The plug advance is 25 mm and its maximum diameter is 33 mm. These piercing process parameters which are listed in Table 2 are made identical to those the experimental work with Plasticine [16] for results comparison purposes. Schematic diagram for the process is illustrated in Fig. 3.

Table 2. Piercing Process Parameters

Parameter	Value	Parameter	Value
Initial workpiece diameter (mm)	45	Distance between roll axes (mm)	330
Minimum roll gap (mm)	38	Feed angle (deg)	9
Maximum plug diameter (mm)	33	Entrance face angle (deg)	3.5
Plug advance (mm)	25	Exit face angle (deg)	3
Guide shoe diameter (mm)	47	Roll velocity (m/s)	5

In order to perform Fluid-Structure Interaction modelling in LS-DYNA, special keywords and commands are required. First and foremost, Arbitrary Lagrangian-Eulerian Formulation must be invoked. This element formulation, two overlapping meshes exist. The first one is a fixed or movable background mesh while the second one is connected to the material which flows through the first mesh. This process can be visualized into two steps: the material

undergoes deformation as in standard finite element methods. Then, the element state variables such as stress, strain, and velocity are mapped or distributed back onto the background mesh. The Plasticine workpiece material is modelled with this formulation as it is largely deformed and has a fluid-like behavior during the process. The Power Law material model (MAT_018) is used to describe the workpiece material.

Fig. 3. Schematic diagram of the rotary piercing process

The interaction between the workpiece material (ALE parts) and the tools (Lagrangian parts) are defined with Constrained keyword. The ALE and Lagrangian parts are coupled with penalty-based formulation. This algorithm tracks the relative displacement between the fluid and the structure then applies nodal forces proportional to the magnitude of relative displacements to provide the interactions. This algorithm conserves energy [17]. Fig. 4 illustrates the mechanism of this method.

Fig. 4. Penalty-based formulation in Fluid-Structure coupling

The deformation of the tools (rolls, plug, and guide shoes) are negligible and not of interest as the purpose of this study is to investigate the flow of the workpiece material. Therefore, the tools are modelled with rigid shell elements. The developed finite element model for the rotary piercing process is depicted in Fig. 5.

Fig. 5. Finite element model showing: workpiece, rolls, plug, and guide shoes.

3 Results and Discussion

The simulation of the rotary piercing process is separated into two steps. First, the effects of the rollers on the workpiece is demonstrated. Here, the plug is not modelled and the process is considered as a rolling process. Afterwards, the process is simulated including the plug.

3.1 Rolling Process

The results of the simulation with of rolling process is shown in Fig. 6. The effects of the rolling contact with the workpiece material as observed as the values of the plastic strain increases. After the material passes through the rollers and there is no more contact, some residual stresses are observed on the workpiece material. However, the maximum value of the stress at any given time is at the contact point between the rollers and the workpiece.

As the rollers are skewed into the feed angle, a special effect is created which is called Mannesmann effect. This effect facilitates the piercing process as it creates a rotational movement in the workpiece material. This can be seen from the velocity vectors shown in Fig. 7.

Fig. 6. The rollers impose compressive loads on the workpiece material

Fig. 7. Mannesmann effect due to the feed angle of the rollers

3.2 Piercing Process

The result of the piercing process simulation is shown in Fig. 8. As the material is pushed through the plug, the values of the strain increases. The higher strain is concentrated around the tip area of the plug due to the convex shape of the plug which results in stress concentration. As the material moves along the rolling axis, the value of the effective strain decreases. This is illustrated in the diagram in Fig. 9.

Fig. 9. Maximum plastic strain is located around the tip of the plug

Fig. 8. Deformation of the workpiece as it contacts with the plug

3.3 Experimental Validation

The final outer and inner diameters were measured experimentally in three different feed angles [3] and illustrated in Fig 10. For comparison, the numerical simulations were performed at the same three feed angles. The similarity between the empirical values and numerical simulation results validates analysis as observed from the graph. The diameters were measured by finding the distance between two points as shown in Fig. 11.

Fig 10. Experimental results [3] vs. Numerical Simulations Results

Fig. 11. Measuring the inner and outer diameter

3.4 Effect of Maximum Plug Diameter

The thickness of the pipe is controlled by changing the maximum diameter of the plug. As it is reduced, the final thickness of the pipe increases. Fig. 12 demonstrates how smaller maximum plug diameter increases the values on of the strain. The concavity of the plug is higher in the case of lower maximum diameter. Thus, the stress concentration is higher which results in higher strain values. This effect is more significant at the tip of the plug diameter.

Fig. 12. Effect of different plug diameters on the effective plastic strain

However, with smaller plug diameters, the thickness of the pipe is higher which allows smoother flow of the material at the end of the pipe. Fig. 13 – 15 show as the material moves along the rolling axis, the stress values decreases. Comparing the stresses in the three different cases reveals that with lower maximum plug diameters and higher thickness, the stress values reduces. This is favorable as higher residual stress would negatively affect the structural properties of the final product.

Fig. 13. Von-Mises Equivalent Stress Contours for Maximum Plug Diameter of 33 mm

Fig. 14. Von-Mises Equivalent Stress Contours for Maximum Plug Diameter of 30 mm

Fig. 15. Von-Mises Equivalent Stress Contours for Maximum Plug Diameter of 27 mm

4 Conclusion

This paper introduces the utilization of Fluid-Structure Interaction method in the simulation of rotary piercing process of seamless pipes. This method is suitable as the workpiece material has a fluid-like behavior as it is preheated into elevated temperature. Three-dimensional model of the rotary piercing process was developed and the numerical simulations were conducted with Arbitrary Lagrangian-Eulerian formulation in LS-Dyna software and successfully described the deformation of the material throughout the process. The numerical simulations were validated with experimental data and therefore, proving the Fluid-Structure Interaction method to be successful in simulating the piercing process. The effect of the pipe thickness was investigated by performing the numerical simulations at three different plug diameters.

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