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Enhancing tube hydroformability by reducing the local strain gradient at potential necking sites †

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Abstract

Bursting in tube hydroforming is preceded by localized deformation, which is often called necking. The retardation of the initiation of necking is a means to enhance hydroformability. Since high strain gradients occur at necking sites, a decrease in local strain gradients is an effective way to retard the initiation of necking. In the current study, the expansion at potential necking sites was intentionally restricted in order to reduce the strain gradient at potential necking sites. From the strain distribution obtained from FEM, it is possible to determine strain concentrated zones, which are the potential necking sites. Prior to the hydroforming of a trailing arm, lead patch is attached to the tube where the strain concentration would occur. Due to the incompressibility of lead, the tube expansion is locally restricted, and the resultant strain extends to adjacent regions of the tube during hydroforming. After the first stage of hydroforming, the lead is removed from the tube, and the hydroforming continues to obtain the targeted shape without the local restriction. This method was successfully used to fabricate a complex shaped automotive trailing arm that had previously failed during traditional hydroforming processing.

Keywords: Tube hydroforming (THF); Hydroformability; Free bulging; Local strain gradient; Necking; Trailing arm

1. Introduction

Tube hydroforming (THF) has the advantages of weight reduction, improved structural rigidity, lower tooling costs, fewer secondary operations, and reduced scrap, as compared to conventional stamping [1-3]. However, failures can occur during THF, because the internal fluid pressure in conjunction with the axial feeding interact when they are simultaneously imposed. Therefore, suitable loading conditions, with regard to internal pressure and axial feeding, should be designed to improve formability and to reduce failures in hydroformed products [4-7]. In many cases, the determination of appropriate loading paths has largely depended on trial-and-error methods. The limitations of a particular loading path can be found with the aid of a process diagram [8-10]. This diagram shows that the internal pressure and the axial feeding are interrelated. In a process diagram, the boundary between failure and the safe region (that is, the process window) may change for different tube and process parameters. In estimating the maximum expansion of the tube, detailed investigations on wall thickness distribution and strain hardening are necessary. As can be expected, significant difference exists between the properties determined from a tensile test or from a bulge test, which is more simulative of hydroforming [11, 12]. A possible explanation for these differences is that the loading paths for the two test methods are not the same. The material is strained in both the circumferential and longitudinal directions during bulge testing, and with plastic anisotropy, these strain components can vary [13-15].

The results and observation from these previous studies imply that the strategic control of the loading path can be used advantageously to enhance a tube's hydroformability. Before fracture occurs, localized deformation (namely, necking) occurs in a small region of the tube. Material outside that region is not deformed once necking begins. Since bursting during THF is a consequence of prior necking, the retardation of necking is an important way to increase the overall hydroformability of a tube [16-18].

In the current study, experiments were performed to estimate the effect of a reduced strain gradient on hydroformability at potential necking sites on a tube. During free bulging, the expansion at potential necking sites (i.e., the highly bulged region of the tube) was intentionally restrained by a restrictive tubular ring to reduce the strain gradient and delay bursting. The expansion in regions away from the potential necking point will be larger during the restrained hydroforming. The

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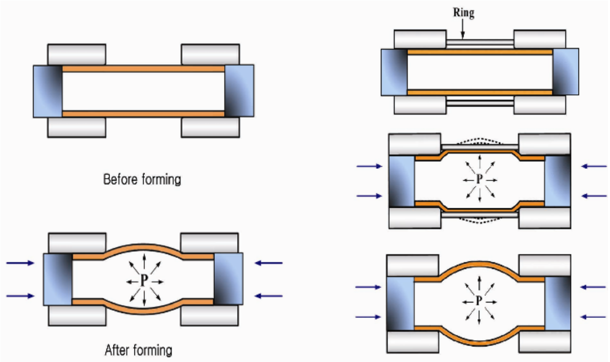


Fig. 1. Schematic drawing of bulge tests; (a) free bulge test; (b) restrictive bulge test.

improvement in formability by decreasing the local strain gradient at potential necking points was analyzed both experimentally and by finite element simulation.

The proposed restrained hydrofoming method was applied to the fabrication of a complex shaped trailing arm. From the strain distribution obtained from the FEM, the concentrated strain zone, which would be a potential necking site, was determined. Before hydroforming started, lead which is a dense material maintaining its original volume regardless of pressure, was attached to the tube surface where the strain concentration would occur. Since the leads attached to the die surface, the tube expansion was locally restricted, and the resultant strain was extended to adjacent regions during hydroforming. After the initial hydroforming, the lead was removed from the die surface and hydroforming was continued in order to obtain the targeted shape. A series of experiments were conducted to validate the effect of the proposed method in enhancing hydroformability.

2. Description of enhancing hydroformability by reducing the local strain gradient

In order to estimate the effect of a reduced strain gradient at potential necking sites on the hydroformability of a tube, the restrictive bulge process was evaluated. During free bulging, the expansion at a potential necking site (i.e., the highly bulged part of the tube) was intentionally limited by a restrictive tubular ring, in order to reduce strain gradient and prevent bursting. Fig. 1 schematically shows the bulging process, both without and with the restrictive ring. Fig. 1(a) shows free bulging, where bursting occurs as a consequence of necking. The maximum amount of bulging primarily depends on the material's inherent properties. As a high strain gradient occurs at the necking region in a bulged tube, the decrease in the local strain gradient is an effective way to retard necking initiation. Fig. 1(b) shows the restrictive tubular ring that is used to reduce the strain concentration at the potential necking point. The resultant strain at the potential necking point will be reduced, and strain in the adjacent zone will be larger, due to the

Table 1. Analysis conditions for FEM.

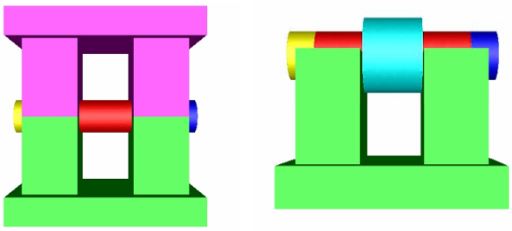
Simulation model	Full model
Tube material	HF440
Friction coefficient between die and tube (μ)	Coulomb 0.02
Number of elements	About 100000
Mesh type	Tetra
Axial feeding during bulging test	0
Maximum pressure (MPa)	50, 75

Table 2. Material properties of tube.

Young's modulus (GPa)	209
Tensile strength (MPa)	518
Yield strength (MPa)	404
Elongation (%)	26
n-value	0.106

Table 3. Dimensions of the tube and rings (mm).

Tube	Outer diameter	65.0
	Inner diameter	60.0
	Tube thickness	2.5
Restrictive ring	Outer diameter	98.0
	Inner diameter/thickness	70/14, 72/13, 74/12, 76/11, 78/10



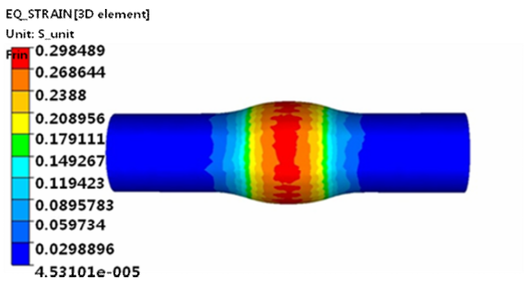
(a) (b)

Fig. 2. Initial configuration for the simulations: (a) free bulge test; (b) restrictive bulge test.

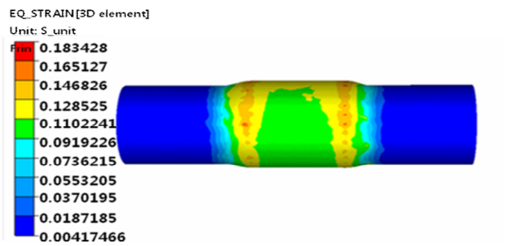
restriction of the ring.

The improvement in formability by decreasing the local strain gradient at these potential necking sites was investigated by finite element (FE) analysis using the commercial finite element code, FORGE^{TM}. The restrictive ring was regarded as a rigid body, and a 3D model was used. Fig. 2 shows the initial configurations for bulging simulations, and Table 1 gives the analysis conditions. Tables 2 and 3 show the material properties and dimensions of tube and rings for FE simulations of the restrictive bulge tests.

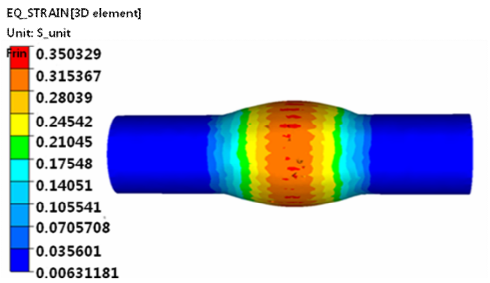
Fig. 3 shows the simulation results for the restrictive ring with inner diameter/thickness equal to 72/13. Fig. 3(a) shows that for the free bulged tube, the maximum percentage expansion obtained is 28.8%. Fig. 3(b) shows 10.8% expansion at the potential necking point after the restricted expansion. The



(a)



(b)



(c)

Fig. 3. FE analysis results: (a) free bulging of non-restricted tube; (b) restrictive bulged tube; (c) free bulging of restrictive bulged tube.

10.8% resultant strain is extended uniformly along the tube at this stage of the process. The lengths of the uniform expansion zones are 70 mm and 120 mm at internal pressures of 50 MPa and 75 MPa, respectively. Fig. 3(c) shows the final hydroformed tube that was produced from the preformed tube with a hydraulic pressure of 75 MPa. In this case, a maximum expansion of 33.6% was attained. The decreased local strain gradient at the necking point, due to the extensive 10.8% prestrain along the tube during the restrictive bulging, significantly enhanced the formability by retarding the initiation of necking.

Fig. 4 compares the maximum expansion obtained from free bulging after forming with the restrictive rings for tubes with various inner diameters. Although the length of the uniform expansion zone and expansion amount during the restrictive bulging could be influenced by the inner diameter of the restrictive ring and the internal pressure, the maximum expansion was found for an inner diameter of 72 mm in these simulations.

3. Tube bulging experiments

The mechanism of improved formability by decreasing the local strain gradient at the necking point was experimentally verified through laboratory experiments. Bulging tests of mild steel tubes under both free and restricted conditions were compared.

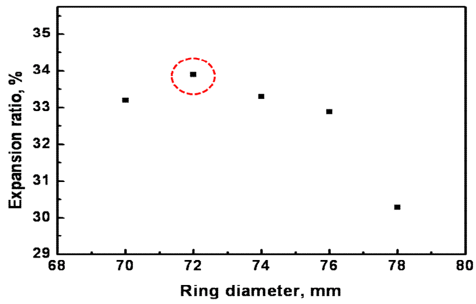


Fig. 4. Variation of maximum expansion obtained from free bulging of restricted tubes formed at various inner diameters.

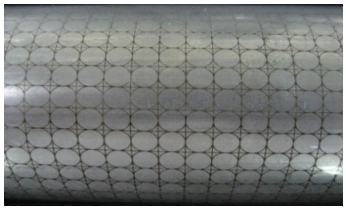


Fig. 5. Circular grid etched tube.

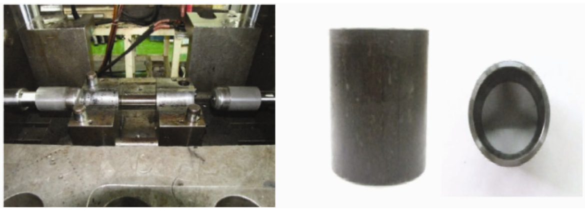
3.1 Experimental details

The experimental tube bulging system is capable of applying a pre-programmed path for the axial feed and for internal pressure. It consists of two 80-ton actuators that are horizontally mounted to supply the axial feed to both ends of the tube. A vertical hydraulic cylinder that is capable of delivering a clamping force of up to 100 tons provides the upper die movement.

A pressure intensifier unit with a maximum capacity of 200 MPa is used to pressurize hydraulic fluid during the experiment.

The strains during the free bulging test were measured using circular grid patterns that were electrochemically etched onto the tube surface. With this method, the strain during the bulging test, which is indicated by the deformed circles, can be estimated. Fig. 5 shows the circular grids etched onto the tube.

For a free bulging test, the tube end faces were loaded by the two horizontal feeding actuators. The force from each actuator on each end of the tube was sufficient to seal the tube interior. The internal pressure was increased until bursting occurred. After bursting, the internal pressure was lowered to ambient, the axial feeding actuators were deactivated and the hydraulic press was opened for removal of the bulged component. For the restrictive bulging test, the tube was inserted in the restrictive ring with a 72 mm inner diameter, and was pressurized to 75 MPa. After removal of the restrictive ring, a free bulging test was performed on the preformed restrictive bulged tube. Fig. 6 shows the die set and restrictive ring for these tests.



(a) (b)

Fig. 6. (a) Die set for free bulging test; (b) restrictive ring.

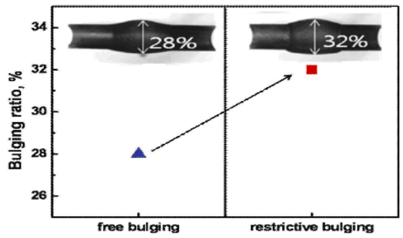
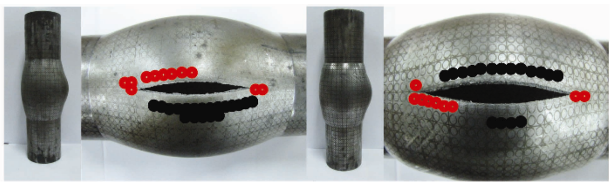


Fig. 7. Comparison of expansion percentage between free bulging and restrictive bulging.



(a) (b)

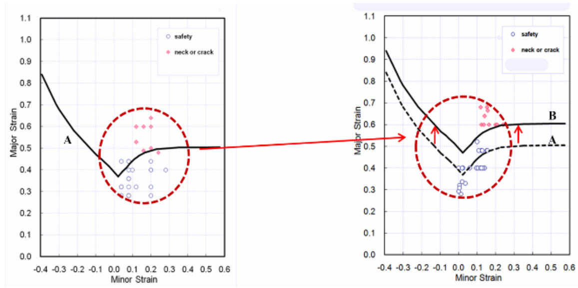
Fig. 8. Deformed grid: (a) non-restricted tube; (b) restricted tube.

3.2 Experimental validation

Fig. 7 compares the measured expansion that occurred between the free bulging and the restrictive bulging. A maximum expansion percentage of 28.0% was obtained for the free bulged tube. For bulging of the restricted tube, a maximum expansion percentage of 33.0% was obtained under the same processing condition. Decreasing the local strain gradient at necking point enhances formability by retarding the initiation of a neck. Fig. 3 shows similar deformation behavior between free and restricted bulging experiments that were obtained from the finite element simulations.

Fig. 8 shows the deformed circular grid patterns, which confirm the effectiveness of the restrictive bulging. For a free bulging test, a round bulge with local thinning was observed, whereas for the restricted condition, the strain is redistributed to adjacent regions of the tube, away from the potential necking point, and local thinning is delayed. Due to the decreased local strain gradient at the necking point, uniform expansion in the bulging region was obtained for a longer period of time, and the formability was improved. In addition, a similar deformation behavior was obtained for both the free and restricted bulging experiments of mild steel tubes from the finite element simulations.

The forming limit curve (FLC) indicates the combinations



(a) (b)

Fig. 9. Forming limit curves: (a) non-restricted tube; (b) restricted tube.

Fig. 10. Schematic drawing of a trailing arm.

of the major and minor strains for various strain paths at the onset of necking, which leads to failure. Material properties have a strong influence on the strain distribution during the bulging of a tube. For example, when the material's work-hardening exponent, n, is high, the strain distribution will be relatively homogeneous. In contrast, materials with lower n values develop steep strain gradients—and strain concentration in a very small region leads to premature failure. However, the FLC does not completely characterize a material's capability during hydroforming, because the strain path also has an effect. Fig. 9 shows the effect of strain path for the restrictive bulging. The restrictive bulging in effect moves the FLC from position A to position B, and the material accommodates more strain than from free bulging alone.

4. Application of proposed method in the fabrication of a trailing arm

The simulations and experimental results showed the outstanding potential of the proposed restrictive bulging process to enhance hydroformability. To demonstrate validation, a trailing arm was fabricated by the proposed method. Fig. 10 shows a trailing arm for a vehicle suspension design, where one or more arms connect the axle to a pivot point located on the chassis of a motor vehicle.

The hydroforming process to fabricate the trailing arm was simulated by FEM. For the simulation of the trailing arm, HF440 pipe having an outer diameter of 65 mm with 2.5 mm thickness was used for the material. Fig. 11 gives the results of the FE simulation.

For the fabrication of the trailing arm, an HF440 pipe having an outer diameter of 65 mm with 2.5 mm thickness was

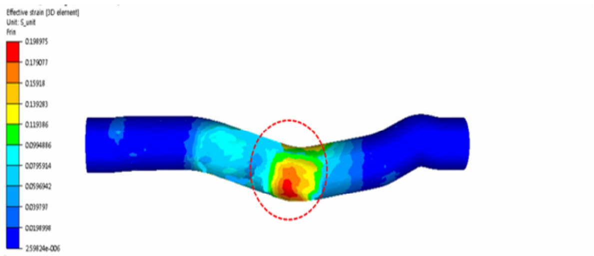
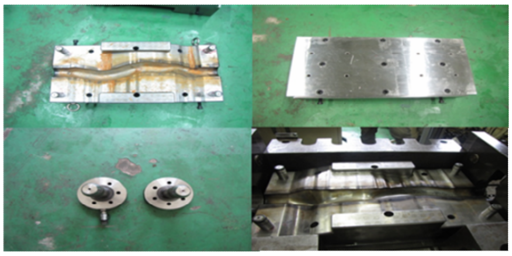


Fig. 11. Effective strain distribution obtained by FEM.

(a)



(b)

Fig. 12. (a) Pre-bent tube; (b) die set for hydroforming of trailing arm.

pre-bent, as shown in Fig. 12(a), and the pre-bent tube was hydroformed using the die sets shown in Fig. 12(b). Fig. 13 shows the hydroformed trailing arm, where cracking has occurred at the position predicted by FEM.

Based on the knowledge obtained from the prior experiments and simulations, the proposed restrictive bulging method was applied to the hydroforming of this component. For the restriction of bulging at the potential necking position, a lead patch was attached to the tube. Fig. 14 illustrates this attachment. The lead patch locally restricts the strain concentration and reduces the strain gradient. After the first stage hydroforming, the lead patch was removed and the second hydroforming step was performed to achieve the target shape.

Fig. 15 shows the trailing arm that was produced without cracks or process-induced defects. Due to the incompressibility of lead on the tube surface, the tube expansion was locally restricted, and the resultant strain gradient was reduced and spread to adjacent regions of the tube. These results strongly confirm that the proposed method is viable and can be successfully applied in the fabrication of complex shape parts that fail when hydroformed by traditional methods. In a typical tube hydroforming process, the tube and the die are in full

Fig. 13. Cracking in hydroformed trailing arm.

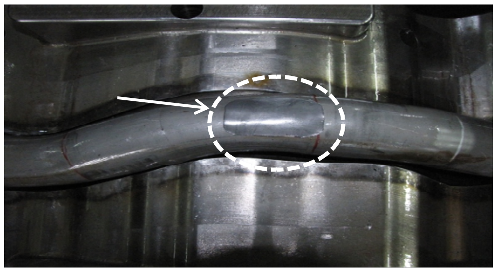
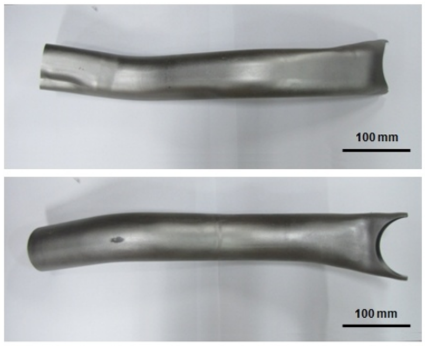


Fig. 14. Lead patch attached at potential necking position.

(a)



(b)

Fig. 15. (a) Hydroformed trailing arm; (b) trimmed/cleaned trailing arm.

contact during the process and material is pushed into the deformation zone by axial feeding cylinders.

As axial feeding is not applied in this study, the friction effect exists only in expansion zone where deforming material at the die-material interface undergoes surface expansion.

The tube was expanded by an internal pressure against the tool wall. By pushing the tube through the tool, a friction force at the contact surface between the tube and the tool occurs. Therefore, friction at the die-tube interface may affect the formability in tube hydroforming. To reduce the variability of frictional effects, sufficient lubrication has been maintained during hydroforming of trailing arm.

5. Conclusions

The improvement of formability during hydroforming by decreasing the local strain gradient at potential necking sites during tube bulging was evaluated, using both finite element simulations and experiments. To reduce the strain gradient at a potential necking point, the expansion at these points was intentionally restricted. The proposed method was demonstrated through a restrictive ring bulging test and the fabrication of a trailing arm without any process-induced defects. The proposed method has been proven to be successful with respect to effectiveness and feasibility through the restrictive ring bulging test and fabrication of the trailing arm. Consequently, it has been shown that the approach proposed in this study provides a valuable method to satisfy the increasing practical demands for the enhanced hydroformability of tubes.

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