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Effect Study and Better Combination of Process Parameters for Tube Forming by a New Processing Technique of Bending and Hydroforming

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Keywords： subsequent technique, bending, hydroforming bulging, Taguchi method.

ABSTRACT

This work presents a new forming processing technique for tubular forming which the bending and hydroforming bulging are completed subsequently by a die set. The FEM is applied to simulate the entire forming processes for producing a bending and bulging tube. The effects of such process parameters as bending angle, bending radius, bending velocity, punch velocity and internal pressure on distributions of wall thickness, effective stress, effective strain and formability of the tube are investigated. Furthermore, the orthogonal array and factor response in the Taguchi method are applied together to determine the optimal process conditions. Because possible forming defects are not considered as a constraint when determining the optimal process conditions, analysis of variance for factor contribution is applied to adjust the obtained optimal process conditions. A better process condition is thus ascertained such that the finished tube is free of forming defects and has a thicker tube wall thickness.

INTRODUCTION

Bending tubes can guide or alter the direction of a flowing fluid via their geometrical shape. Hence, bent tubes are commonly utilized in transportation pipelines, electrical power systems and as vehicle components.

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When the shape of a finished tube is a primary concern, treatments in addition to bending are required. Among these treatments, the hydroforming process is considered the most efficient, and a wide variety of geometrical contours can be formed using bulging via hydraulic pressure. The conventional approach for this complex task is to use two processes performed in sequence, i.e., a straight tube billet is first bent and this bent tube is then bulged by hydroforming. However, cost of this approach is relatively high because forming processes need two sets of dies and apparatuses.

Gao and Strano (2004) applied FEM simulations on tube pre-bending and subsequent hydroforming for a given hydroforming tool and to make modifications possible in process planning to successfully form a given part. Three process variables that affect tube wall thickness thinning, tube material, the frictional coefficient and pre-bent tube radius, were analyzed. Analytical results indicated that SS304 is more favorable for forming the tubular part than SS409. Moreover, reducing the frictional coefficient and increasing the pre-bent tube radius markedly reduce thinning of the tube wall thickness during subsequent hydroforming. Lee et al. (2005) conducted parametric studies on the bending of oval tubes without a mandrel. The finite element modeling technique was applied to examine such deformation characteristics as wall thinning, strain, side bulge, flattening, and hoop buckling for circular and oval tubes. The bending process parameters, bending radius, geometrical aspect ratio of the oval tube, and wall thickness, were varied in simulations. Observations were made to acquire a hoop-buckle limit diagram, as well as to identify acceptable conditions for bending a tube, which may be suitable for tubular hydroforming without a preforming step. Yang et al. (2001) presented simulation results for the pre-bending and hydroforming processes used to form an automotive part. Two pre-bending simulations, with a rotary draw bending machine and a bend die, were carried out to identify shape changes to the tube cross section and thinning. Analytical results were compared. To avoid wrinkling in a compressive area of the tube during bending, a wiper die was applied. Trana (2002) conducted finite element simulations of the complete hydroforming process for the lower part of an A-pillar for an automobile. Bending, preforming and hydroforming processes were simulated using the explicit code of FEM. The work developed a practical simulation procedure for the entire hydroforming process and determined how bending and preforming operations influence hydroforming results. The work demonstrated that the bending operation must be considered when simulating hydroforming. Kim et al. (2002) developed a three-dimensional finite element program based on a rigid plastic model for analyzing and designing a tube hydroforming process for the lower arm of an automobile. A concept for die contact and non-contact to workpiece and an algorithm for calculating friction during tube hydroforming were implemented in the developed program. The work investigated the influences of forming conditions on hydroforming of the lower arm via simulations to predict strain and tube shape during bending, preforming, and final hydroforming processes. Gantner et al. (2005) developed free bending, a novel bending technique, for bending profiles and tube cross sections. A FEM simulation model of the free bending process was developed and verified via bending tests. Free bending can be used in feasibility studies for new applications and for the hydroforming process chain to reduce time and cost associate with the physical tryouts and improve quality. Baudin et al. (2004) developed a novel tube bending method for an elbow section formed from a straight tube using internal pressure and a rigid die. The rigid die guides the tube into the elbow when pushed by a punch; internal pressure prevents wrinkling and buckling. Finite element simulation results validated this concept and design. Internal hydraulic pressure via a liquid and a urethane rod was compared. Lee et al. (2002) conducted hydroforming experiments and described this process for manufacturing automotive radiator supports, including a new tool design concept, in which a mechanical cam sliding system was introduced into the preforming process. A start tube was pre-bended and narrowed simultaneously under an internal pressure of 150 bar to approximately fit the part shape. Via this method, annealed start tubes were successfully and safely hydroformed at an internal pressure of 430 bar. Tensile tests demonstrated that the tensile stress of hydroformed parts was increased by an expected percentage as compared with that of start tubes. Lei et al. (2000) analyzed the hydroforming process for an automotive rear axle housing via the finite element approach using a rigid plastic model. The effects of process parameters and process layout on metal deformation flow were discussed and compared with experimental data. An optimum process layout was proposed using numerical simulation to meet practical requirements, demonstrating the efficiency of numerical simulation.

A newly-developed tube forming technique for bending and hydroforming bulging continuously is proposed in this work. This technique significantly reduces operation cost and forming time, which are desirable industry goals. The FEM is applied to simulate bending and bulging processes of tube forming subsequently. Change in tube wall-thickness, equivalent stress and strain distributions, and the quality of the finished geometrical contour of the tube cross section are investigated. Furthermore, the orthogonal array, factor response and analysis of variance for factor contribution via the Taguchi method (1993) are combined together to establish a workable range for optimal or better process parameter combinations without forming defects.

TAGUCHI'S DEFINITION OF QUALITY

The concept of the orthogonal arrays from the Taguchi method is adopted to acquire available statistical information by less number of experiments. Although the corresponding accuracy will be sacrificed theoretically, the results are accurate enough to solve the quality problems of engineering. Hence using the orthogonal arrays has become an important technique for process planning of product manufacturing. While *S/N* ratio is an index containing mean value and standard deviation. The higher *S/N* ratio is the less quality loss of product and the higher product quality is. The transformation mode of the *S/N* ratio is mainly related to the quality characteristics of the product. In this paper, the quality characteristics of a tube product are nominal-the-best (NTB). As the quality characteristics get closer to the target value, its corresponding quality turns out to be better. This is defined as the characteristics of NTB, and the corresponding conversion equation for *S/N* ratio is

$$S/N_{NTB} = -10\log\left[\left(\bar{y} - m^2\right) + s^2\right] = -10\log\frac{\sum_{i=1}^{n}\left(y_i - m\right)^2}{n} \qquad (1)$$

where y_i is the observations, m is the target, n is the total number of observations, $\bar{y}$ is the average of the all observations and s is the standard deviations.

Since this study considers not only the minimum tube wall thickness as quality characteristics but also free of forming defects, analysis of variance for factor contribution is further adopted to evaluate the contribution rate of each factor upon quality characteristics. The purpose is to adjust the process parameters for achieving a favorable product with larger minimum tube wall thickness and excellent formability (free of forming defects). The related equations such as total sum of square, factor sum of square and factor contribution rate are described, respectively as below:

$$SS_T = \left(\sum_{i=1}^{n} \sum_{j=1}^{r} y_{ij}^2 \right) - n \times r \times \bar{y}^2 \tag{2}$$

$$SS_p = \left(\sum_{j=1}^{r} \frac{y_{pj}^2}{n_j} \right) - n \times \bar{y}^2 \tag{3}$$

$$\rho_p = \frac{SS_p}{SS_T} \times 100\% \tag{4}$$

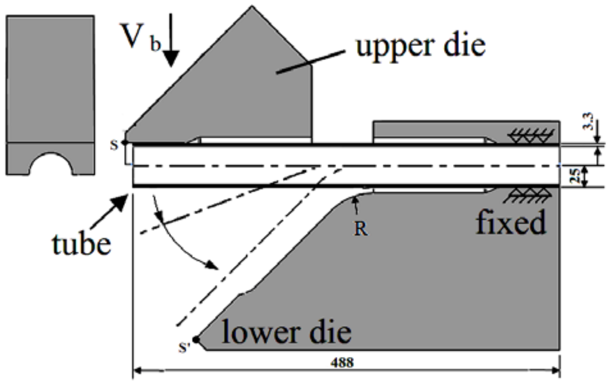
Where n is total number of observations, r is number of replications.

PROBLEM STATEMENT AND METHOD OF APPROACH

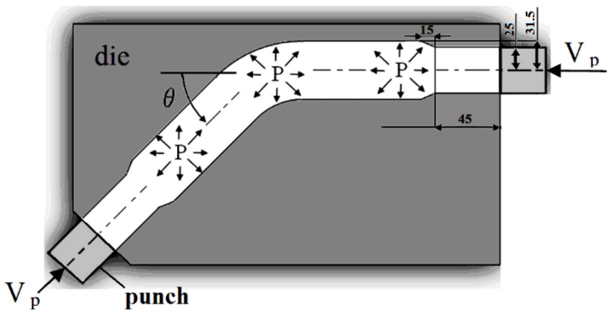
To investigate the effects of process parameters on tube forming characteristics by the proposed technique, this work focused on process simulations for tube forming via the finite element method (DEFORM-3D), in which the tetrahedron element of four nodes is applied to generate a grid pattern of the tube billet. The process parameters selected are bending angle, bending velocity, and bending radius for tube pre-bending, and internal pressure and punch velocity for hydroforming bulging. Each parameter has two or three levels, such that 72 combination sets exist (Table 1). The tube billet used in simulations is a round straight tube with an outer radius of 25mm, length of 488mm, and initial tube wall-thickness of 3.3mm. Figures. 1(a) and 1(b) show the geometrical dimensions and configuration of the die and tube for pre-bending and hydroforming bulging, respectively. Notably, pre-bending was performed by driving the upper die to move along straight and angular rotation paths simultaneously. A specific point on the upper die is selected (Fig. 1(a)), and linear displacement (connection distance) of this point between the start location (S) and finish location (S') in pre-bending can be measured when the upper and lower dies are closed coincidently. Forming time for tube pre-bending was determined by dividing the vertical component of this linear displacement by bending velocity, V_b. Rotational velocity, which was derived by dividing total bending angle by forming time, was set in the simulation software in addition to V_b.

Table 1 Level setting for process parameters.

Process parameter	Level		
	1	2	3
Bending angle, θ(degree)	45	90	
Bending radius, R(mm)	100	150	
Bending velocity, V_b(mm/s)	1	2	
Punch velocity, V_p(mm/s)	0.9	1.2	1.5
Internal pressure, p(MPa)	120	130	140



(a) pre-bending

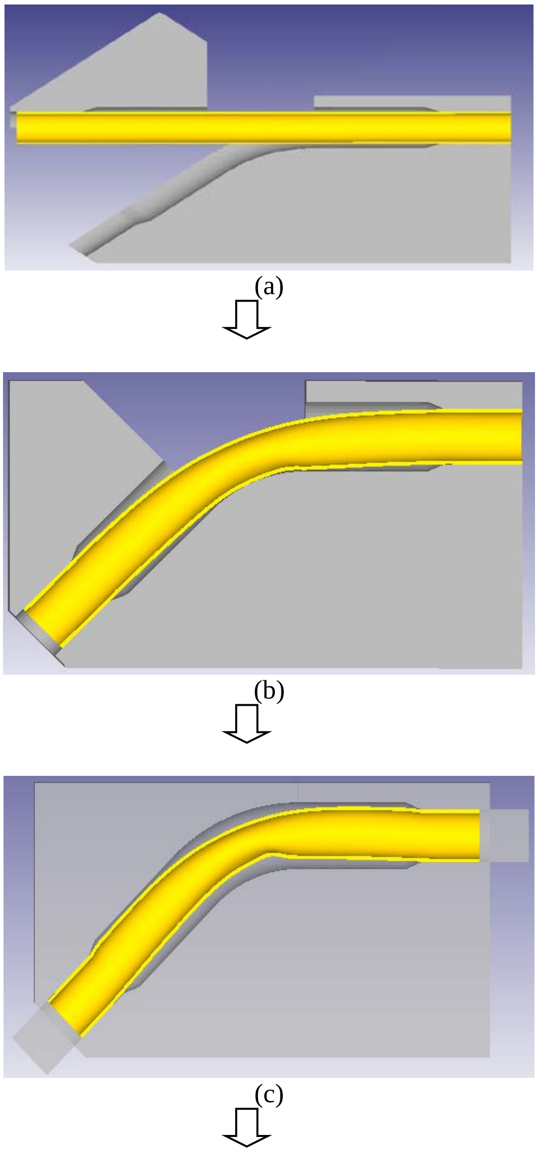


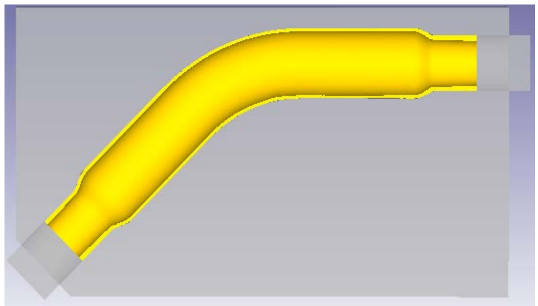
(b) hydroforming

Fig. 1. The geometrical conditions, and configuration of the die and tube for subsequent tube forming of bending and hydroforming bulging.

Stainless steel SUS-304, the tube billet material, has flow stress of $\sigma = 1392\varepsilon^{0.3792}$ MPa. Three loading paths were arranged such that their internal pressures are initially from zero raised to a designated level and were linearly proportional at 10 seconds during the early deformation stage, and then remained constant until final forming was completed. Constant shear frictional theory is applied; the shear frictional factor was set as 0.1 at all interfaces. Supplementary feeding via punch for this tube forming at one end-side was set as 10mm in the early punch feed stage, and 15mm in the succeeding stage of hydroforming, total feed supply was 25mm. As the workpiece had bilateral symmetry, simulation was performed for half of the entire model to increase calculation speed.

The simulation steps for the proposed technique are briefly described as follows. A round straight tube of stainless steel is placed on the lower die (Figure. 2(a)). Bending of the tube is then started by moving the upper die downwards combined with angular rotation (Fig. 2(b)) until the upper die and lower die are closed coincidently. The remaining dies are then attached to the entire tool set, and the tube billet is compressed with a 10mm punch feed, such that the tube billet can fit tightly to the punch to prevent internal high-pressure fluid from leaking. The tube billet must be properly contacted to the lower die; if this joint is too tight and detrimental, the succeeding hydroforming operation will be adversely affected (Fig. 2(c)). Finally, during the hydroforming stage, bulging is initiated by raising the hydraulic pressure of the internal fluid; the punch is operated on both end-side of the tube while feeding movements with a punch feed of 15mm is proceeded until forming ends (Fig. 2(d)).





(d)

Fig. 2. Processing steps for subsequent tube bending and hydroforming bulging.

In this work, the orthogonal array and factor response from the Taguchi method are applied together to determine optimal process conditions. Additionally, analysis of variance for factor contribution is used to adjust the optimal process conditions obtained. The L9 orthogonal array based on the Taguchi method is first adopted to define some combinations of process parameters (Table 2). Figure 3 shows a complete flow chart for determining the optimal or better T_{min} without forming defects.

Table 2 L9 orthogonal array.

Set number	R (mm)	V_b(mm/s)	V_p(mm/s)	p(MPa)
1	1	1	1	1
2	1	2	2	2
3	1	1	3	3
4	2	1	2	3
5	2	2	3	1
6	2	1	1	2
7	1	1	3	2
8	1	2	1	3
9	1	1	2	1

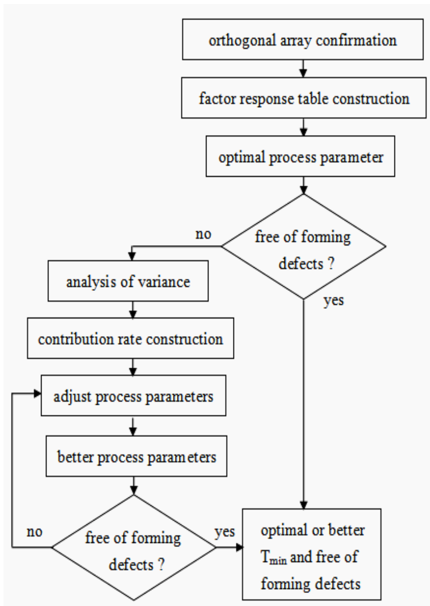
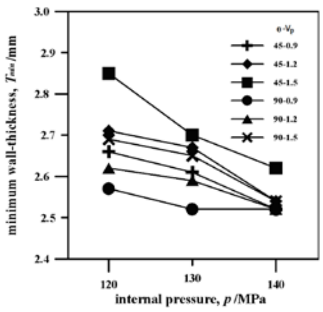


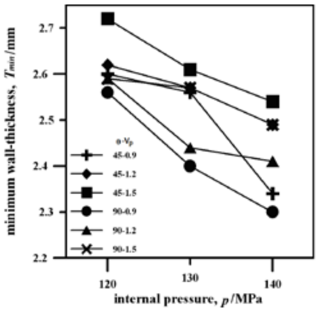
Fig. 3. Flow chart for optimal or better T_{min} determination without the existing of forming defects.

RESULTS AND DISCUSSIONS

Within the designated range of process parameters and under the same bending radius and bending velocity, the tube wall thins as internal pressure increases (Fig. 4). Additionally, as internal pressure increases, bulging speed increases. Consequently, punch velocity can not accord with bulging speed that there is not sufficient time for material to flow from both tube ends into the curved region for material feeding supplement. This causes the tube wall-thickness to thin and even fractured. However, using an internal pressure that is as low as possible is not always beneficial because a low internal pressure will cause failure during the bulging process and eventually generated defects. If punch velocity is adjusted to a higher level, the bulging speed may not accord with this increased punch velocity. This leads to undesirable material accumulation that forms obstacles, interfering with subsequent material inflow finally generating folding defects. Within the selected ranges of process parameters, tube wall thickness decreases as punch velocity slows (Fig. 4). Figure 4 also shows the effects of the bending angle. Under the same bending velocity and bending radius, tube wall-thickness with a bending angle of 90° is thinner than that with a bending angle of 45°. That is, under the same tube billet length, a larger bending angle results in severe tensile stresses at the curved region and, thereby, a thin tube wall. Similar reasoning can explain the effects of bending radius. The tube wall-thickness with a bending radius of 150mm is less than that with a bending radius of 100mm under the same bending angle. In other words, under the same tube billet length, a large bending radius causes severe tensile stresses and consequently thinning the tube wall. However, one trade-off to consider is that decreasing the bending radius may generate defects during the subsequent hydroforming process. In terms of bending velocity, a fast speed will generate a thin tube wall, since a fast bending velocity cannot provide sufficient time for flow response among materials as well as forming. Therefore, tube wall thickness around the curved region becomes markedly thinner, and *vice versa*.



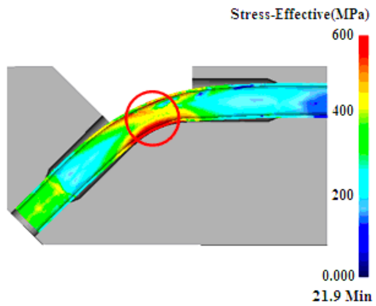
(a) R=100mm, V_b=1mm/s



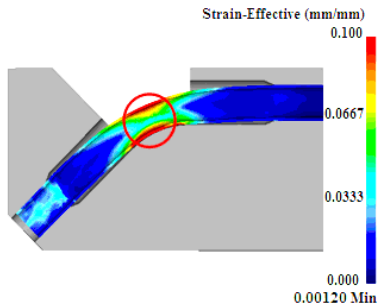
(b) R=150mm, V_b=1mm/s

Fig. 4. Comparison of the effects of various process parameters on minimum tube wall thickness.

The location with a distribution of high equivalent stresses is the inner side of the curved region of the tube, which is subjected to intense compressive loading (Figures. 5(a) and 6(a)). Furthermore, this location is the major contact points for the tube billet and die, and is exposed to the influence of both compression and friction, such that higher equivalent stresses are generated. Investigation results (Figs. 5(b) and 6(b)) indicate that the location with distribution of high equivalent strains after bending is also at the curved region of the tube, since severe deformation is generated under excessive tension and compression in both the outer and inner parts of the curved region.

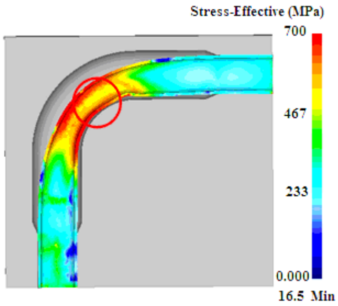


(a) Equivalent stress

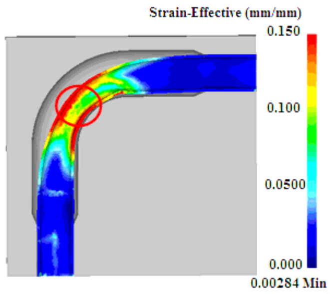


(b) Equivalent strain

Fig. 5. Distribution of equivalent stress and strain for 45° tube bending after bending operation (R=150mm, V_b=1mm/s).



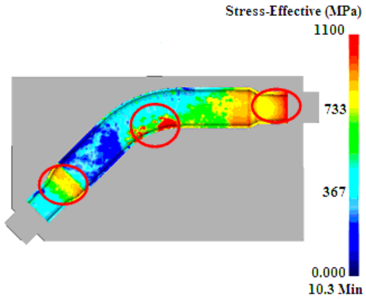
(a)Equivalent stress



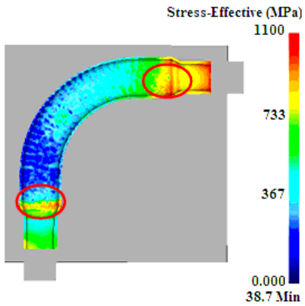
(b) Equivalent strain

Fig. 6. Distribution of equivalent stress and strain for 90° tube bending after bending operation (R=100mm, V_b=2mm/s).

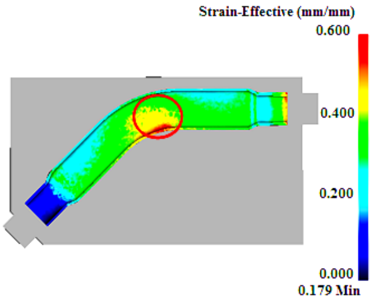
Figure 7(a) shows a 45° bent tube after hydroforming. Regions with high equivalent stresses are at the inner side of the curved region and both tube ends which are close to punch. During the bending process, the inner side of the curved region is subjected to severe compression and is influenced by both compression and friction due to contact between the tube billet and die, resulting in high equivalent stresses. The tube ends are also subjected to high equivalent stresses; however, the cause is high compressive force by the punch. For the 90° bent tube (Fig. 7(b)), the regions with high equivalent stresses are located at both tube ends which are close to punch. However, high stresses may develop on the inner side of the curved region during the initial forming stage, *i.e.*, bending. Stresses decrease during the subsequent hydroforming stage due to particular geometric characteristics, *i.e.*, both ends of the punch are aligned perpendicularly. The location with the highest equivalent strain distribution remains the curved region for 45° tube bending (Fig. 7(c)). This is because the inner and outer sides of the curved region are subjected to severe compression and tension during bending, resulting in enormous deformation that generates high strains during hydroforming. The 90° tube bending has the same strain distribution.



(a) Equivalent stress



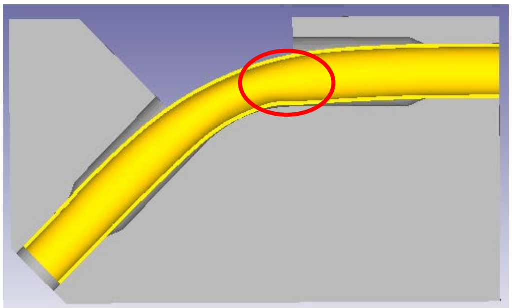
(b) Equivalent stress



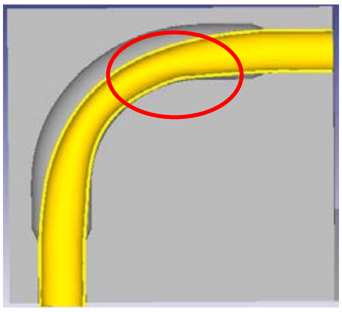
(c) Equivalent strain

Fig. 7. Distribution of equivalent stress and strain after hydroforming operation under the conditions of R=150mm, V_b=1mm/s, p=120MPa and V_p=1.5mm/s for 45° and 90° tube bending.

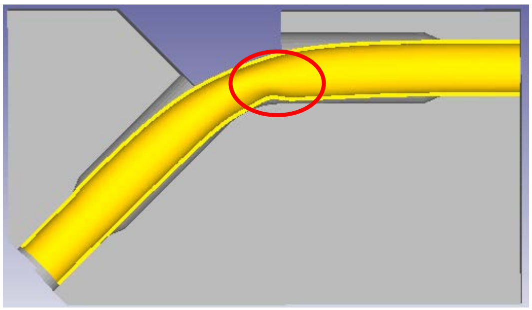
Simulation results indicate that the most important process parameter related to buckling defects is bending radius, because the tube billet is bent by closely contacting against the curved region of the lower die. Comparison of bucking defects in Figs. 8(a) and 8(b) with buckling defects in Figs. 8(c) and 8(d) reveals that, under the same bending velocity, larger bending radius has a smooth bending curve, which causes the tube billet to bend easily, resulting in good formability during the succeeding hydroforming stage. Conversely, smaller bending radius may generate undesired concave spots that easily form defects during the succeeding hydroforming process, resulting in poor formability.



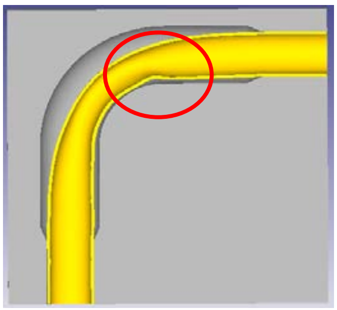
(a) θ=45°, R=150mm



(b) θ=90°, R=150mm



(c) θ=45°, R=100mm



(d) θ=90°, R=100mm

Fig. 8. Buckling defects occurred around the inner-side of the curved region for V_b=1mm/s.

In this work, the orthogonal array from the Taguchi method is applied to define partial combinations of process parameters (Table 2). The minimum wall thickness of the finished tube is expected to approach that of the original tube. The calculated data of minimum tube wall thickness from finite element simulation are transformed to *S/N* ratio using the characteristics of nominal-the-best in Eq. (1). The results of *S/N* ratio are shown in Table 3, which in turn are used to construct the factor response table (Table 4). Finally, the most important process parameter for the proposed tube forming process can be found, and, the optimal combination of process parameters can be determined.

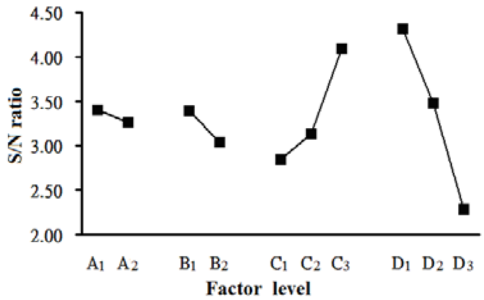
Table 3 T_{min} and *S/N* ratio.

Set number	T_{min}(mm)		*S/N* ratio	
	45°	90°	45°	90°
1	2.66	2.57	3.804	2.694
2	2.59	2.52	2.916	2.123
3	2.62	2.54	3.286	3.347
4	2.51	2.42	2.00	1.083
5	2.72	2.59	4.643	2.933
6	2.61	2.50	3.161	1.905
7	2.7	2.65	4.355	3.692
8	2.47	2.46	1.575	1.484
9	2.71	2.62	4.498	3.304
Average	2.62	2.54	3.36	2.507

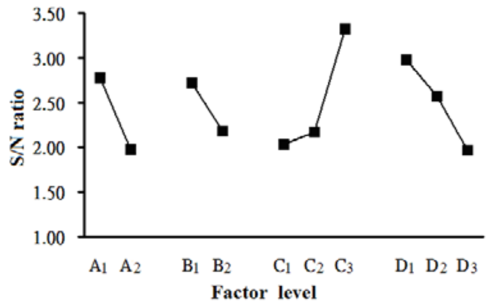
Table 4 and Fig. 9 show the *S/N* response table and *S/N* response graph for minimum tube wall thickness, respectively. Symbols A, B, C, and D in Fig. 9 represent the process parameters of R, V_b, V_p and p, respectively. Regardless of the-lower-the-better or the-higher-the-better quality characteristic, the greater *S/N* ratio corresponds to the smaller variance of the output characteristic around the desired value. Based on this criterion, the optimal combination of the process parameters for a 45° bending tube is $A_1B_1C_3D_1$, *i.e.*, bending radius of 100mm, bending velocity of 1mm/s, punch velocity of 1.5mm/s, and internal pressure of 120MPa; this combination generates the largest minimum tube wall thickness. The maximum value of the minimum tube wall thickness for the 45° bending tube is 2.85mm from simulation. Similarly, the optimal combination of process parameters for the 90° bending tube is $A_1B_1C_3D_1$, *i.e.*, bending radius of 100mm, bending velocity of 1mm/s, punch velocity of 1.5mm/s, and internal pressure of 120MPa, yielding the maximum simulation Tmin value of 2.69mm.

Table 4 Factor response table.

Level	R		V_b		V_p		p	
	45°	90°	45°	90°	45°	90°	45°	90°
1	3.406	2.774	3.397	2.716	2.847	2.028	4.315	2.977
2	3.268	1.974	3.045	2.18	3.138	2.17	3.477	2.573
3	/	/	/	/	4.095	3.324	2.287	1.971



(a) 45° tube bending



(b) 90° tube bending

Fig. 9. *S/N* response graph for minimum tube wall thickness.

Parameter conditions in the factor response table (Table 4) are acquired by considering the minimum tube wall thickness as the only object function while forming defect constraint is not accounted for simultaneously. Consequently, an undesirable buckling defect may form within the tube product. Hence, the factor contribution rate from variance analysis is introduced and constructed into a table (Table 5) to adjust process parameters finely and obtain a better result in terms of a thick tube wall free of forming defects.

Table 5 Analysis of variance.

	SS_T		ρ (%)	
	45°	90°	45°	90°
R	0.067	1.337	0.71	20.39
V_b	0.477	0.538	5.08	8.21
V_p	2.587	3.088	27.54	47.1
p	6.262	1.593	66.67	24.3
Total	9.393	6.556	100	100

The most important parameters affecting minimum tube wall thickness are punch velocity and internal pressure (Table 5). The expected adjustment with the smallest variation of the previous outcome by the Taguchi optimization algorithm is conducted by first selecting the process parameter with a minor contribution to be adjusted by the variance analysis. For the 45° bending tube, the least significant parameter is bending radius which is selected to be adjusted first from 100mm to 150mm while the rest ones remaining the same as those obtained from the optimization procedure. The resulting minimum tube wall thickness is 2.79mm ranks second without undesirable buckling defects. Following the same approach for the 90° bending tube, bending velocity is the minor contribution parameter to be selected first and adjusted varying from 1 to 2mm/s. Similarly, the resulting minimum tube wall thickness is 2.65mm; however a buckling defect still exists. By the same method, the second minor contribution parameter, bending radius, is selected to be adjusted once again from 100 to 150mm while the rest ones remaining the same as those obtained from the optimization procedure. The resulting minimum tube wall-thickness is 2.66mm, with desirable vanish of buckling defects at this time.

By summarizing all the results in this work, it is found that the most important process parameters affecting minimum tube wall thickness are punch velocity and internal pressure, while those influencing the distribution of equivalent stress and strain as well as formability of a tubular product are bending velocity and bending radius. Moreover, under a thicker minimum tube wall thickness and free of forming defects, the better combination of the process conditions for the 45° and 90° bending tubes is bending radius of 150mm, bending velocity of 1mm/s, punch velocity of 1.5mm/s and internal pressure of 120MPa; the corresponding minimum tube wall thicknesses of the product are 2.79 and 2.66mm, respectively. These minimum tube wall thicknesses deviate slightly from those obtained by the Taguchi optimization algorithm. However, differences between them are merely 0.06 and 0.03mm, respectively.

CONCLUSIONS

This work investigated how various process parameter conditions affect minimum tube wall thickness, stress and strain distributions, and formability of a newly-developed tube forming processes via FEM-based simulations. Furthermore, the orthogonal array and factor response from the Taguchi method are applied together to determine the optimal process conditions. Additionally, the factor contribution rate from analysis of variance is supplementary to adjust the obtained optimal process conditions, in which possible forming defects may occur. Finally, the better process conditions are thus ascertained. The following conclusions are based on analytical results.

1. In consideration of subsequent tubular bending and hydroforming bulging, the curved region, especially its outer area, which is subjected to tension during bending, comes up with thinner

wall thickness, because considerable tensile loading takes place there.

2. The most important process parameters affecting minimum tube wall thickness are punch velocity and internal pressure; that influencing formability of the tube product is bending radius.
3. Bending radius has the greatest influence upon formability of the tube during bending process. With larger bending radius for bending, it is easier to give satisfactory results in succeeding hydroforming bulging.
4. Under a thicker minimum tube wall thickness without forming defects, the better combination of the process conditions for both the 45° and 90° bending tubes are a bending radius of 150mm, bending velocity of 1mm/s, punch velocity of 1.5mm/s, and internal pressure of 120MPa; the corresponding minimum tube wall thicknesses without buckling defect are 2.79mm and 2.66mm, respectively. These minimum tube wall thicknesses deviate slightly from those obtained by the Taguchi optimization algorithm. However, differences between them are merely 0.06 and 0.03mm, respectively.

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新的彎曲及液壓管件成形製程技術較佳製程參數組合及影響效應之研究

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摘　要

本文提出一新的管件成形製程技術，藉由一組模具依序完成彎曲與液壓成形鼓脹。使用有限元素法模擬整個管件彎曲與鼓脹成形製程。研究製程參數，例如彎曲角、彎曲半徑、彎曲速度、冲頭速度及內壓力，對於壁厚分布、有效應力、有效應變、及管件成形性的影響效應。再者，結合田口法的直交表及因子反應表加以應用，以求取最佳的製程條件。因最佳製程條件求取過程中可能的成形缺陷沒有被考慮為拘束條件，故使用因子貢獻率的變異數分析來調整所求得最佳的製程條件。最後，一較佳製程條件被確立，使得完成的管件沒有成形缺陷，且具有較厚的管壁厚度。