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Investigation into the pre-forming's effect during multi-stages of tube hydroforming of aluminum alloy tube by using useful wrinkles

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ABSTRACT

Tube hydroforming is a process for manufacturing of lightweight components, especially automotive parts, with advantages of cost and weight reduction, better structural integrity and increased strength and stiffness over the conventional stamping process. Generally, the hydroformed parts can be obtained by multi-stages made up of bending, pre-forming and finishing. Based on the characters of FEM and using the useful wrinkles, the process of multi-stages was investigated by using an aluminum alloy. For avoiding the typical failure modes such as folding back, wrinkling, buckling and fracture due to unreasonable selection of the internal pressure and the axial punch feeding, the optimization strategy was created and the process parameters were optimized by using "useful" wrinkles instead of "harmful" wrinkles in the pre-forming stage and in the finishing stage. The suitable pre-forming die cavity shape was discussed. The results from simulation keep a reasonable agreement with that from experiment.

1. Introduction

Tube and profile hydroforming, as shown in Fig. 1 has gained increasing interest in the automotive industry after the successful exploration of the breakthrough point of the engine cradle. Dohmann and Hartl (1997) and Vollertsen et al. (1999) gave an overview of the fundamental principles and the applications of tube hydroforming (THF), and the correlations between the workpiece geometry and the design of tooling, process and the results were discussed in details. Hirt and Junk (2001) made a detailed calculation for the calibration stage of hydroforming, by using the theoretical analysis and the numerical simulation method which is very important to predict the accuracy of the hydroformed tubes. Ahmeyoglu et al. (2000) indicated that because this process is a quite new one and no large knowledge base exists until now, many basic experimental and research activities should be finished and training is necessary for the broad application. In recent years, some countries in the world have practiced this technology in the large volume production of automotive parts. Yuan et al. (2001) introduced the application of this process in the aircraft and aerospace industries by using the aluminum alloys and the key process parameters in the aluminum tube hydroforming was investigated in details. Lang (2001) studied and developed the tube hydroforming machine based on the double-action press and some good experimental

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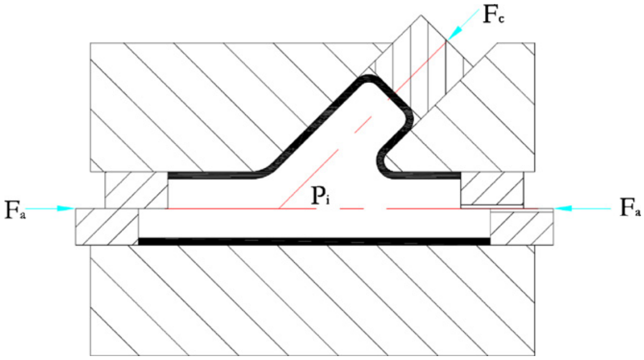

Fig. 1 – Description of tube hydroforming.

results have been obtained, which improves the application of the tube hydroforming in China greatly. Dohmann and Hartl (1996) introduced the volume application of tube hydroforming for forming gear shaft and some locally deformed components, and the process parameters control method was explored. Following the increase use of the tube hydroforming method, Koc and Altan (2001) made a conclusion for the tube hydroforming intensive research and development, and the technology points such as material, tribology, equipment, tooling, etc. was discussed clearly. In general, the liquid pressure for hydroforming is 400 MPa, sometimes a liquid pressure beyond 1000 MPa is needed for manufacturing some special parts with small corner radius, very thick wall or high strength materials, etc. Main applications can be found in the fields of automotive and aerospace industries as well as in sanitary industry. In the aerospace applications, the formed parts can be bellows, variable-diameters tube and joint tube, etc. for transferring the pressurized liquid. Tube hydroforming has several advantages as compared with the conventional manufacturing method which uses the combination of stamping and welding including part integration, weight reduction, improved structural strength and stiffness, lower tooling cost, fewer secondary operations, high accuracy and high materials utilization. Charles and Shah (1997) introduced the hydroforming process including pre-bending, welding, etc. step by step in which some key parameters were discussed in details, and the advantages in the tube hydroforming were described. Lettermann and Zengen (1999) introduced the whole process of tube hydroforming to form the space frame, by which the most advantages of the tube hydroforming was made conclusions.

Many influencing factors exist in tube hydroforming and it is not easy to find the optimum process parameters to control the tube forming process. A lot of experiments must be done to find the suitable process parameters. Nowadays, the numerical simulation provides an effective way to solve this problem. Based on the results from the numerical simulation, it is more convenient to get the optimum experiment parameters. By this means, the optimum parameters can be obtained quickly and economically, so, the numerical simulation method has been widely used in the world. Bobbert (1999) focused on the hydroforming production in the production line to investigate the optimization of the process parameters in tube hydroforming and the key parameters were optimized. Liu and Meuleman (1998) investigated the forming limitation concept in the tube hydroforming based on the FLD curves. Manabe and Nakamura (1999) took consideration of the pre-bending process when making a numerical simulation in the tube hydroforming and accurate results has been obtained by this method. However, it is still difficult to simulate the forming processes with many stages. In this paper, using the birth and death definition in LS-DYNA (Hallquist, 1997), one of the most famous softwares in metal forming organized by Dr. Hallquist in 1997, the forming process of a variable-diameter antirust aluminum alloy tube was investigated based on the useful wrinkles, and the optimized process parameters were obtained finally.

2. Needed part, tool set-up and material properties

The antirust aluminum alloy variable-diameter joint tube which is normally used to deliver pressurized liquid and air conditioner cooling liquid is one important component in the aerospace and automotive products. So, the property of formed part should be very accurate. Especially the mechanical properties including the strength limit and the fatigue limit should be high enough, and the reduction of the wall thickness should be very small to meet the needs of mechanical properties after forming (the limitation of wall thickness reduction ratio must be within ±15% in this case). In conventional stamping, because of the bad cold formability for this material, the hot pipe-expanding process followed by a welding is usually used, by which the technical requirement for some special variable-diameter joint tubes cannot be reached. However, by using multi-stage tube hydroforming process, it is possible to get a uniform wall thickness distribution and the reduction of wall thickness can be decreased.

The part geometrical dimensions are shown in Fig. 2. The diameter of the original tube blank is Ø 65 mm which should be expanded to Ø 88 mm at the most. So, along the circumferential direction in the middle area, the total needed elongation reaches 33.4%. It shows that the deformation ratio is very large in the middle expanding area. The original tube wall thickness is 1.5 mm. The variation of wall thickness must be within ±15% times of the initial tube wall thickness, which means the permitted wall thickness is from 1.275 to 1.725 mm. The material

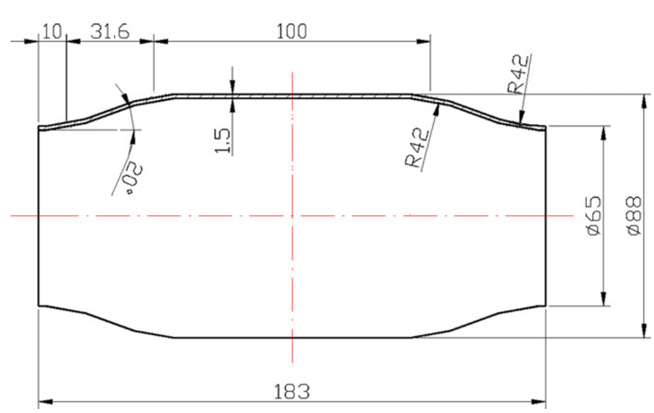

Fig. 2 – Needed part.

Table 1 – Mechanical properties of aluminum alloy LF2M

	Yielding stress, σ_s (MPa)	Tensile strength, σ_b (MPa)	Total elongation, δ (%)	Strain hardening exponent, n
Axial direction	92.3	191.5	18.0	0.232
Circumferential direction	79.2	184.5	17.5	0.236

Table 2 – Chemical compositions of aluminum LF2M

Al	95.5%
Mg	2.21%
Cu	0.02%

of extruded LF2M (China brand) was used in the simulation and in the experiment. Table 1 gives the mechanical properties along the different directions, and Table 2 gives the chemical compositions of this material. For meeting the practical conditions, after the specimens used for the uni-axial tensile test were cut from the tube and then flattened, the annealing process was used to remove the hardening effect. It was found that it is quite difficult to form a satisfactory part in one stage and the pre-forming stage should be used.

3. Finite element analysis

3.1. *Finite element model*

The LS-DYNA is one of the famous softwares which can be used in the research field of sheet metal forming. One characteristic in LS-DYNA for defining the contacting pairs is that the birth time and death time can be determined. Meantime, when defining the death time, the information about the shell wall thickness, geometrical shape and the strain deformation will be inherited to the next stage, which meets the needs of multi-stage forming.

The normally meshed model is shown in Fig. 3. Due to the character of axis-symmetry, only one quarter was selected during the numerical simulation. All the tools were modeled as rigid elements and the tube blank as a four-node quadrilateral, Belytschko–Lin–Tsay element with five integration points through the thickness, and the material was thought to fit von-Mises yielding criterion. The applied material model is elastic–plastic behavior with thickness anisotropic and the plane anisotropy was not considered, and the kinematic hardening was taken into consideration and the Bauschinger effect was not considered. It is assumed that the static friction coefficient equals to the dynamic friction coefficient. Using the Coulomb friction law, the friction coefficients between tools and blank are 0.1. In experiment, no special lubricant but the forming liquid media oil was applied. In simulation, a speeding factor of 100 was used for saving the calculation time. The used tube blank is 250 mm long with a diameter of 65 mm.

3.2. *Key points*

During tube hydroforming, the main failure types are buckling, harmful wrinkles, folding back and fracture. It is important to control the material flow during forming so that the failure types will not emerge and the wall thickness reduction can be kept within limitations.

Many process parameters influence the tube hydroforming, the main parameters are the internal pressure P_s and the punch stroke P_t. How to find the optimum values between internal pressure and the punch stroke is one of the key points. Generally, the process windows should be created in both the pre-forming stage and the calibration stage.

Both in the pre-forming stage and in the calibration stage, the loading path for internal pressure P_s versus punch stroke P_t can normally be divided into the following two types: (1) the first type is named two-steps or multi-steps variation method, as shown in Fig. 4(A). When the punch moves forward, the internal pressure P_f (feeding pressure) keeps no change, which can be called the first step. Then the internal pressure will be increased as high as possible to flatten the useful wrinkles formed in the former period, which can be called calibration pressure P_c in the second step; (2) the second type is named the linear variation method. When the punch moves forward, the internal pressure increases linearly.

Because of the symmetric property, the left punch stroke is always equal to the right punch stroke. For the second method,

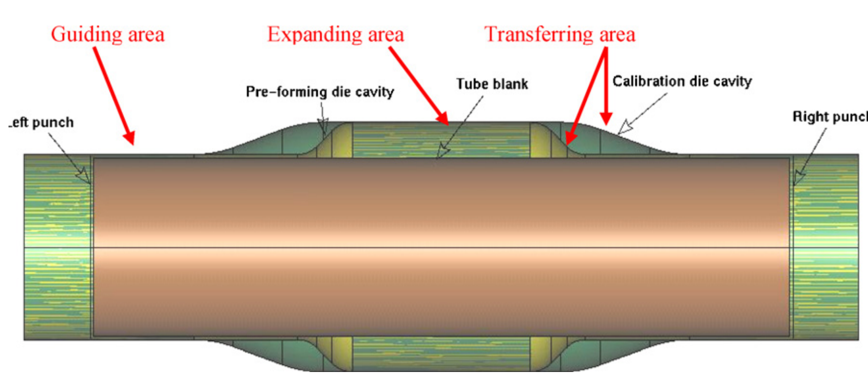

Fig. 3 – Finite element model.

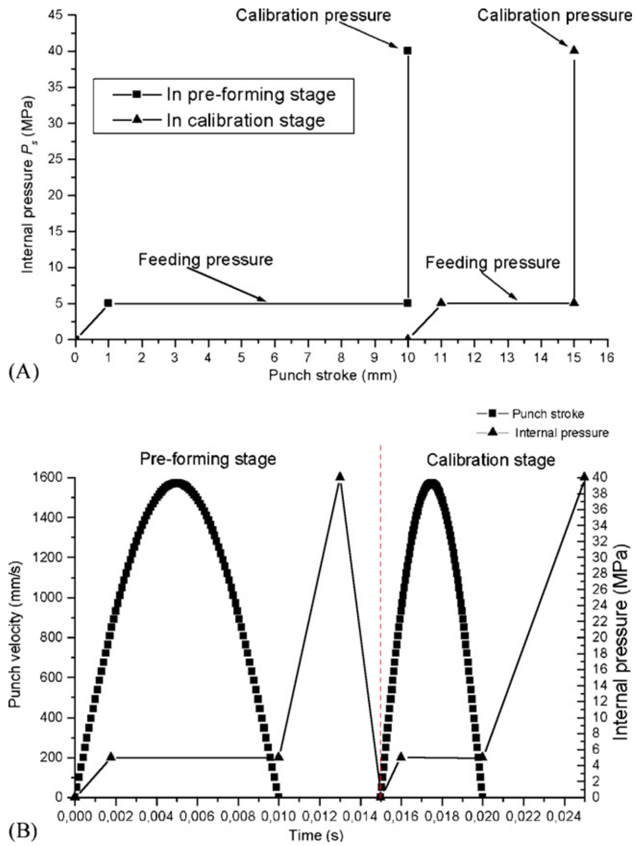

Fig. 4 – Conceptual process parameters versus loading curves used in simulation. (A) Conceptual design for the process parameters; (B) practical usage in simulation.

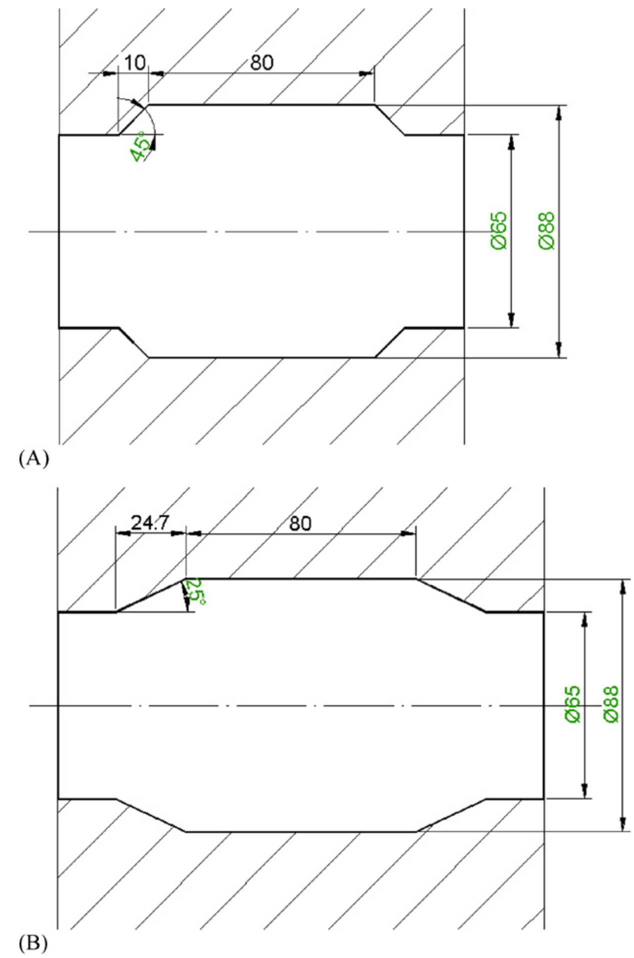

Fig. 5 – Pre-forming die cavities used. (A) 45° pre-forming die cavity; (B) 25° pre-forming die cavity.

the linear variation method, it was found difficult to gain the optimum process parameters because the fracture emerged if the internal pressure became too high. In this paper, only the two-steps variation method will be taken consideration in the pre-forming stage and in the finishing stage.

Finally, the conceptual loading curves for the whole forming period can be determined as shown in Fig. 4(A). In the simulation, the loading curve for the punch stroke speed is sinusoidal variation to avoid the inertia problem, as shown in Fig. 4(B). The shape of the pre-forming die cavity will affect the final results very much. In this paper, two pre-forming die cavities were designed virtually for loading the different boundary conditions, as shown in Fig. 5(A) and (B), which can be called 25° pre-forming die cavity and 45° pre-forming die cavity, respectively.

4. Analysis in simulation based on the useful wrinkles instead of the harmful wrinkles

Just as shown in Fig. 4(B), the two-steps variation method was applied both in the pre-forming stage and in the finishing stage. In both stages, the feeding pressure P_f and the calibration pressure P_c will be used. In simulation, in the pre-forming stage, the process parameters used for the corresponding punch stroke and the feeding pressure were chosen as 8.0, 10.0 and 15.0 mm, and 1.0, 3.0, 5.0, 6.0 and 7.0 MPa, respectively. In the finishing stage, the process parameters used for the corresponding punch stroke and the feeding pressure were chosen as 2.0, 5.0 and 10.0 mm, and 0.0, 3.0, 5.0 and 7.0 MPa, respectively. Two types of pre-forming die cavities were modeled in the simulation, the first one is shown in Fig. 6(A) (45° pre-forming die cavity) and the second one is shown in Fig. 6(B) (25° pre-forming die cavity). In the finishing stage, the die cavity is same as for the needed part, shown in Fig. 6(C).

4.1. *Using 45° pre-forming die cavity*

Figs. 7–11 show the forming processes when using the different process parameters in the pre-forming stage and in the finishing stage. In all cases, the punch strokes were 10.0 mm and the feeding pressures were different in the pre-forming stages and the punch strokes were 5.0 mm under the feeding pressures 5.0 MPa in the finishing stage. The calibration pressures in the pre-forming stage and in the finishing stage were 40.0 MPa.

Obviously, the feeding pressures of 0.0 and 1.0 were not available because the harmful wrinkles are formed in the pre-forming stage, these are quite difficult to be removed by using the calibration pressure. Also, there are very high thin-

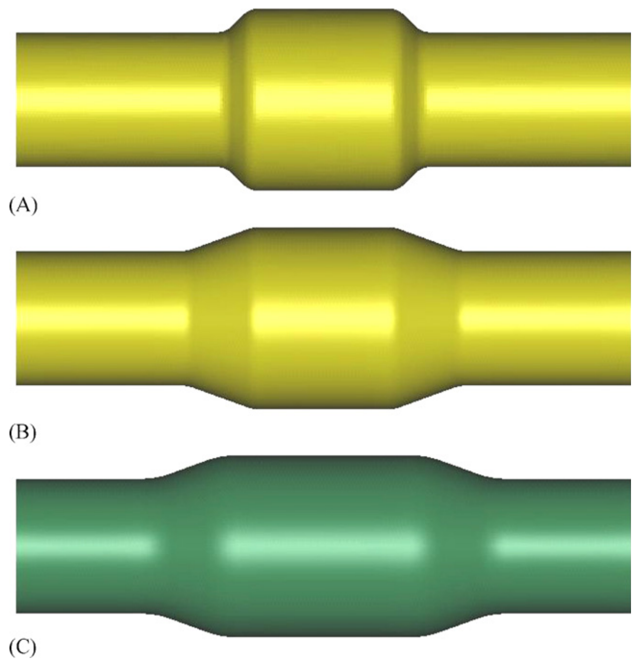

Fig. 6 – Modeled die cavities used in simulation. (A) 45° pre-forming die cavity; (B) 25° pre-forming die cavity; (C) final die cavity.

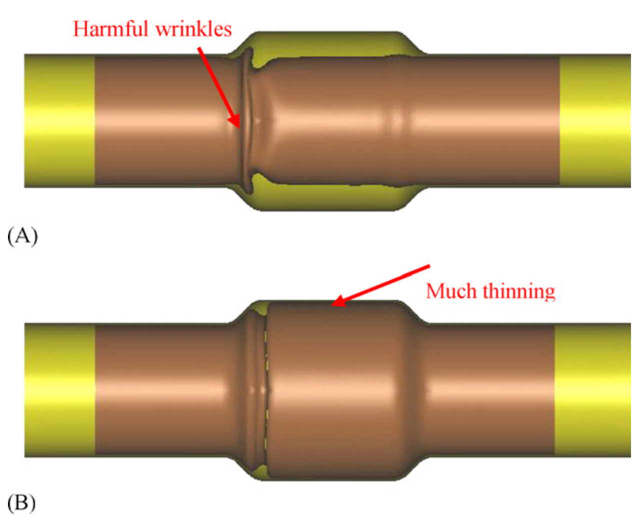

Fig. 7 – Forming processes without feeding pressure in the pre-forming stage. (A) Without the feeding pressure; (B) after the calibration pressure.

ning ratios in the middle of the expanding area. The wrinkles formed under these process parameters are harmful wrinkles compared with those under the other process parameters, which means that these wrinkles will not be flattened under the calibration pressure in the pre-forming stage, as shown in Figs. 7 and 8. In Fig. 9, the formed wrinkles indicated as (A) are not useful to reduce the thinning ratio in the middle of the expanding area. As a result, the wall becomes extremely thin in the middle of the expanding area, and the wall where this type of wrinkles are formed will not be in contact with

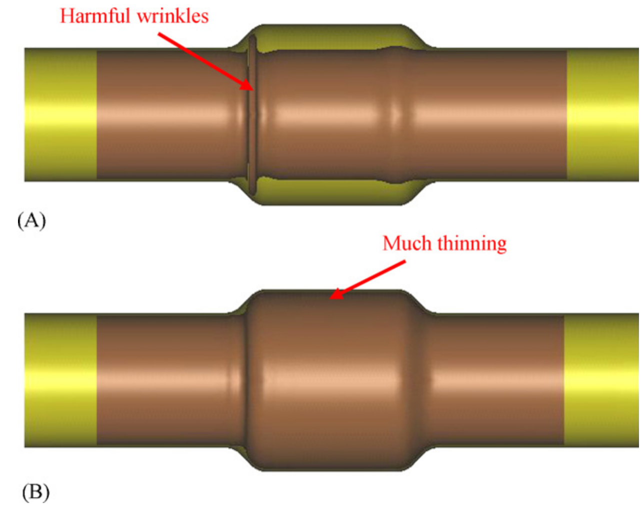

Fig. 8 – Forming processes under 1.0 MPa feeding pressure in the pre-forming stage. (A) After the feeding pressure; (B) after the calibration pressure.

the pre-forming die cavity even under a very high calibration pressure in the pre-forming stage.

Under the feeding pressures of 5.0 and 6.0 MPa in the pre-forming stage, two wrinkles can be formed like the wave-shaped wrinkles in the middle area. These wrinkles can be flattened under the calibration pressure in the pre-forming stage, as shown in Figs. 10 and 11. But still problems exist in the finishing stage whatever process parameters are used for the punch stroke and the feeding pressure, the formed wrinkles cannot be removed even when using a very high calibration pressure. The wrinkles emerge in the transferring area in the finishing die cavity, which suggests that modification should be made in this area. When using 7.0 MPa in the pre-forming stage, the tube blank will fracture in the middle expanding area, as shown in Fig. 12.

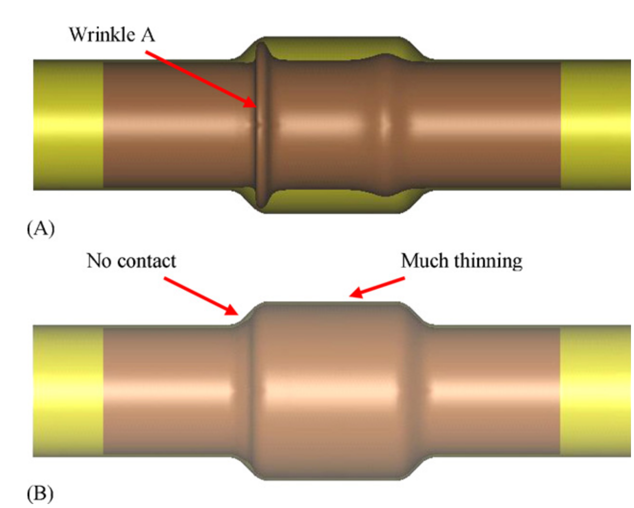

Fig. 9 – Forming processes under 3.0 MPa feeding pressure in the pre-forming stage. (A) After feeding pressure; (B) after calibration pressure.

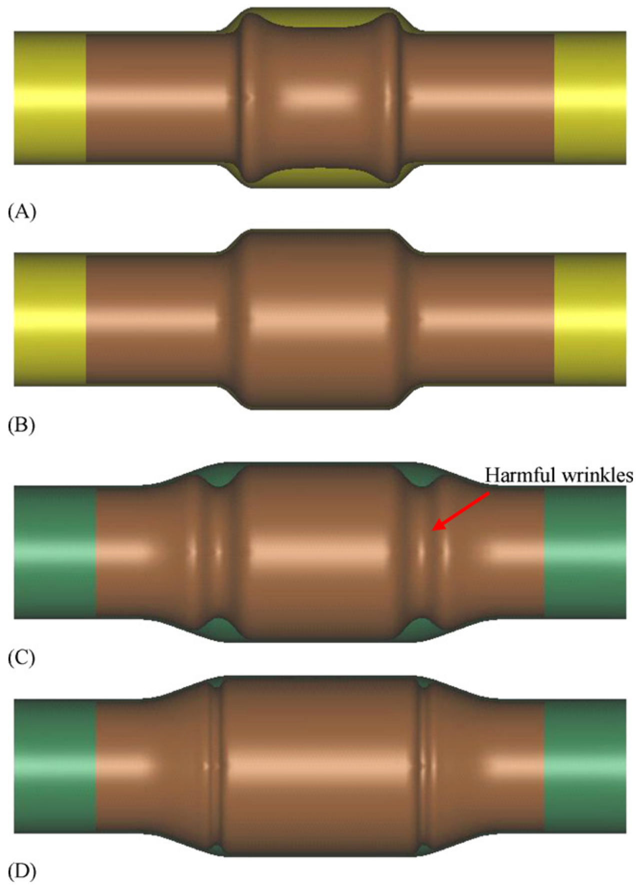

Fig. 10 – Forming processes under 5.0 MPa feeding pressure in the pre-forming stage. (A) After feeding pressure in the pre-forming stage; (B) after calibration pressure in the pre-forming stage; (C) after feeding pressure in the calibration stage; (D) after calibration pressure in the calibration stage.

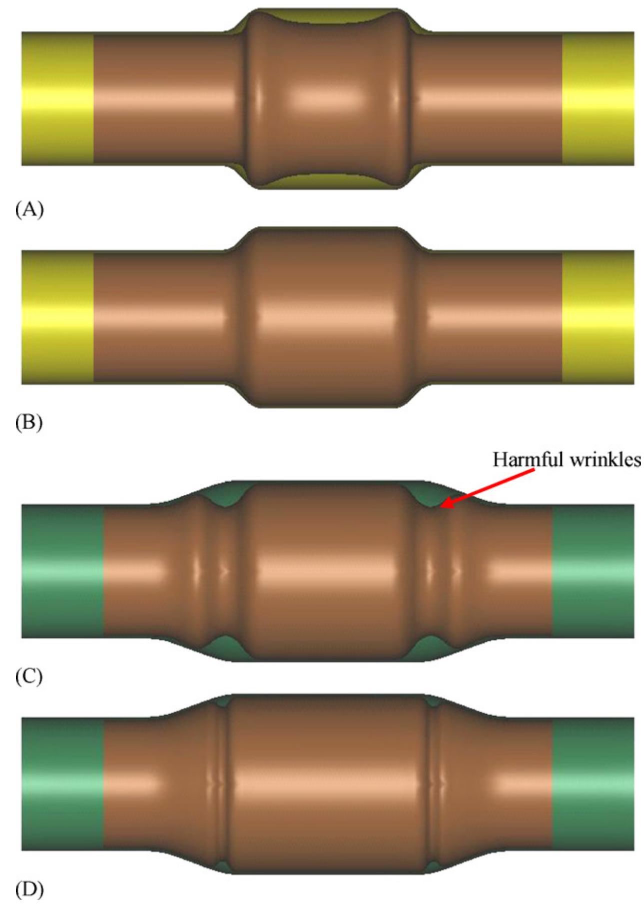

Fig. 11 – Forming processes under 6.0 MPa feeding pressure in the pre-forming stage. (A) After feeding pressure in the pre-forming stage; (B) after calibration pressure in the pre-forming stage; (C) after feeding pressure in the finishing stage; (D) after calibration pressure in the finishing stage.

4.2. *Using 25° pre-forming die cavity*

Based on the above analysis, the transferring area for the pre-forming die cavity was changed as shown in Fig. 5(B). The used process parameters are still 1.0, 3.0, 5.0 and 6.0 MPa for the feeding pressure and 10.0 mm for the punch stroke in the pre-forming stage. Figs. 13–16 show the forming results. The calibration pressures in the pre-forming stage and in the finishing stage are 40.0 MPa.

In the pre-forming stage, it is shown that a different number of wrinkles appear depending on the process parameters. Based on this design, it can be seen that when 1.0 MPa is used for the internal pressure two harmful wrinkles will be formed. At the same time, the sheet located in the middle area will fracture under the calibration pressure. Moreover, when the internal pressure increases to 3.0 MPa, the amount of formed wrinkles changes to three. It seems that the optimized process parameters can be found in Figs. 14–16.

Furthermore, it can be found in Fig. 14(A) and (B), the wave crest in the middle wrinkle is not in contact with the pre-forming die cavity after the feeding pressure. As a result, this wave crest will fracture under the calibration pressure in the pre-forming stage. It can be found that once the sheet contacts with the die cavity, it will not fracture here. Still in the calibration stage shown in Fig. 14(C) and (D), wrinkles exist in the transferring area under the calibration pressure of 40.0 MPa, which seems harmful. In Figs. 15 and 16, the

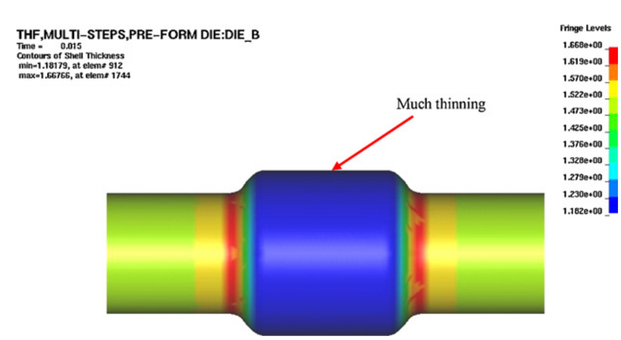

Fig. 12 – Thickness distribution when using 7.0 MPa feeding pressure in the pre-forming stage.

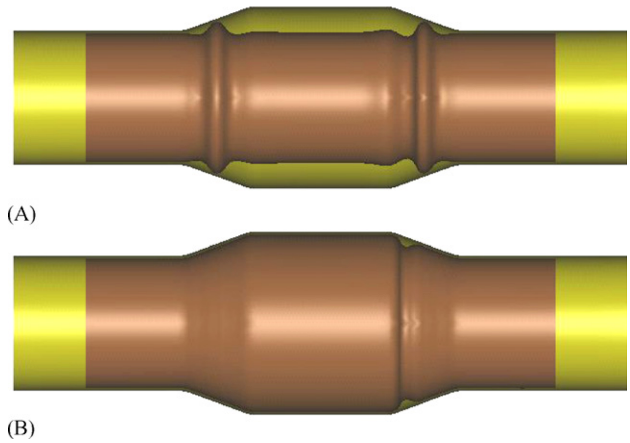

Fig. 13 – Formed forming processes under 1.0 MPa internal pressure in the pre-forming stage. (A) After feeding pressure; (B) after calibration pressure.

non-flattened wrinkles are also kept in the transferring area, but the obtained final parts are better than those in Fig. 14, which indicates that the optimized results can be found in Figs. 15 and 16.

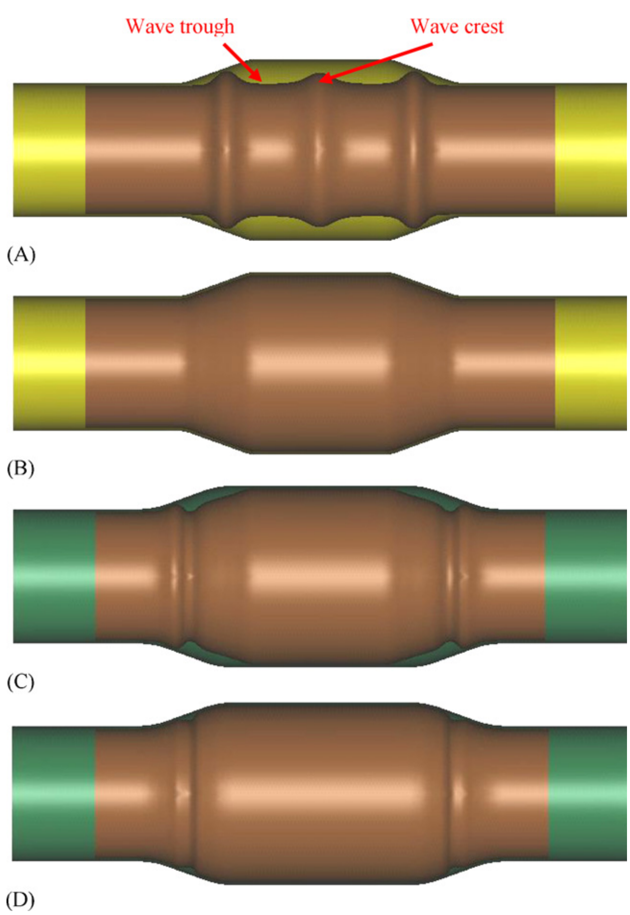

Fig. 14 – Forming processes under 3.0 MPa internal pressure in the pre-forming stage. (A) After feeding pressure in the pre-forming stage; (B) after calibration pressure in the pre-forming stage; (C) after feeding pressure in the finishing stage; (D) after calibration pressure in the finishing stage.

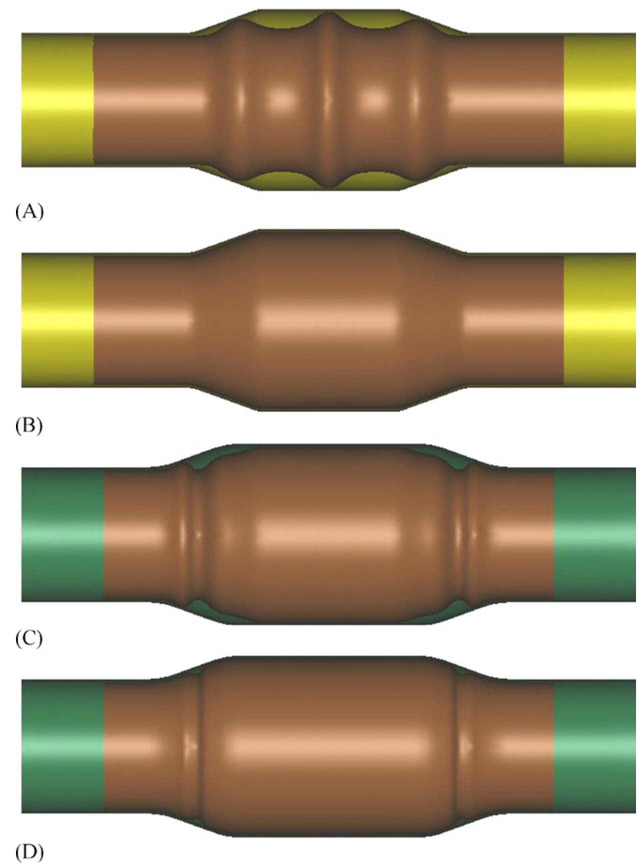

Fig. 15 – Forming processes under 5.0 MPa internal pressure in the pre-forming stage. (A) After feeding pressure in the pre-forming stage; (B) after calibration pressure in the pre-forming stage; (C) after feeding pressure in the finishing stage; (D) after calibration pressure in the finishing stage.

4.3. *Discussion*

As described above, the 25° pre-forming die cavity performs better than the 45° pre-forming die cavity and can form the useful wrinkles in both the pre-forming stage and the finishing stage. Also, it can be found that in these cases it is quite important to avoid the fracture in the pre-forming stage and to avoid the dead wrinkles in the finishing stage. Both using 25° pre-forming die cavity and 45° pre-forming die cavity, the fracture can be controlled and the harmful wrinkles can be avoided under the feeding pressure of around 5.0 MPa in the pre-forming stage. But when using 45° pre-forming die cavity, the harmful wrinkles will be formed in the transferring area in the finishing stage. When using the 25° pre-forming die cavity, wrinkles are also formed in the transferring area in the calibration stage, these can be flattened by adjusting the process parameters. Figs. 17 and 18 show the formed parts by use of the very high internal pressure or shortening the punch strokes to remove the formed wrinkles in the transferring area. It can be found that these methods are quite effective.

With consideration to the tube wall thickness, when using 25° pre-forming die cavity, Figs. 19–21 show the thickness distributions under different process parameters. In all these

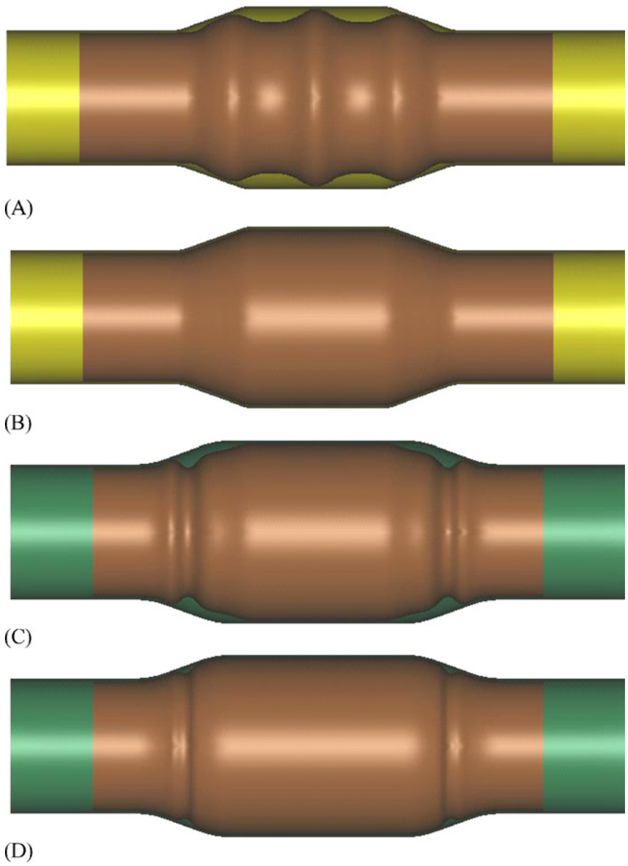

Fig. 16 – **Forming processes under 6.0 MPa internal pressure in the pre-forming stage. (A) After feeding pressure in the pre-forming stage; (B) after calibration pressure in the pre-forming stage; (C) after feeding pressure in the finishing stage; (D) after calibration pressure in the finishing stage.**

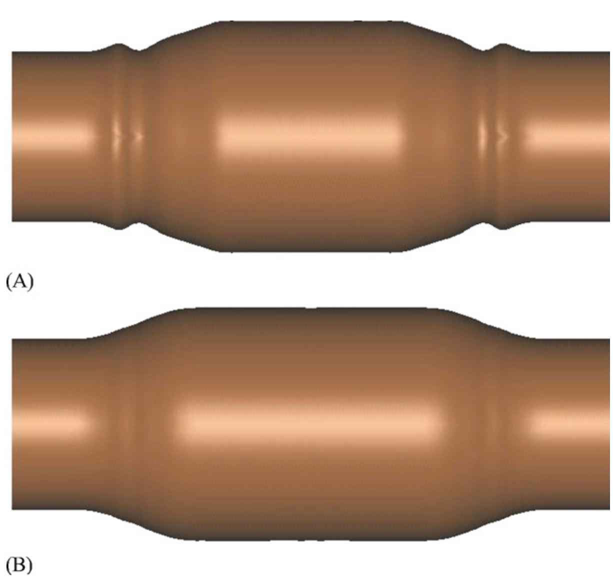

Fig. 17 – **Final part by using very high calibration pressure 80.0 MPa in the finishing stage. (A) After feeding pressure; (B) after calibration pressure.**

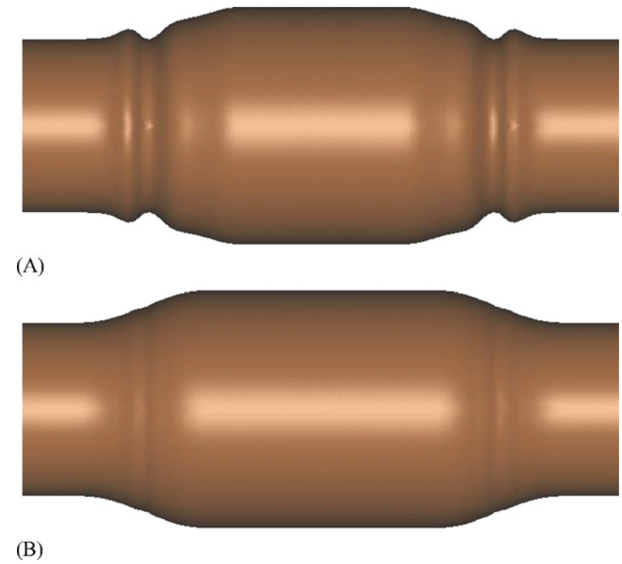

Fig. 18 – **Final part by shortening the punch strokes to 3.0 mm in the finishing stage. (A) After feeding pressure; (B) after calibration pressure.**

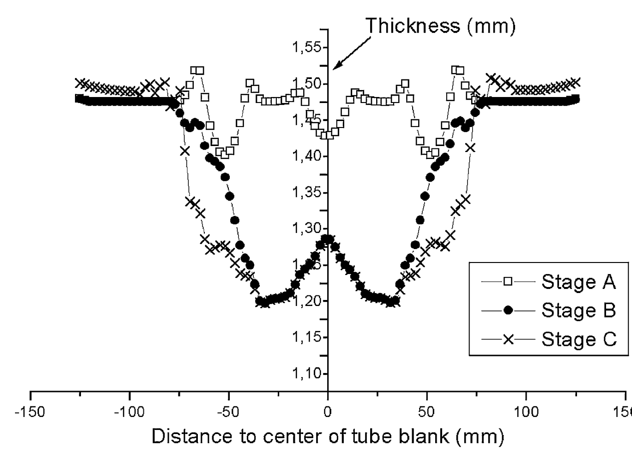

Fig. 19 – **Wall thickness distributions in different stages under feeding pressure of 3.0 MPa in the pre-forming stage.**

cases, except for the different feeding pressures 3.0, 5.0 and 6.0 MPa in the pre-forming stage, the other parameters are the same: in the pre-forming stage, the punch stroke is 10.0 mm and the calibration pressure is 40 MPa. In the finishing stage, the punch stroke is 5.0 mm under the feeding pressure 5.0 MPa and the calibration pressure is 40 MPa. Stage A means that the useful wrinkles are formed in the pre-forming stage; stage B means that the useful wrinkles are flattened in the pre-forming stage; stage C means that the final parts are formed after the calibration pressure in the finishing stage. It can be seen that although the thickness is more uniform in stage A in Fig. 19 than in the other cases, the thickness decreases sharply after stage B. It can be seen from Fig. 14(A) that the wave crest in the formed middle wrinkle is not in contact with the die cavity at all. The thickness distribution in the middle expanding area in Fig. 20 is larger than the others, therefore, the opti-

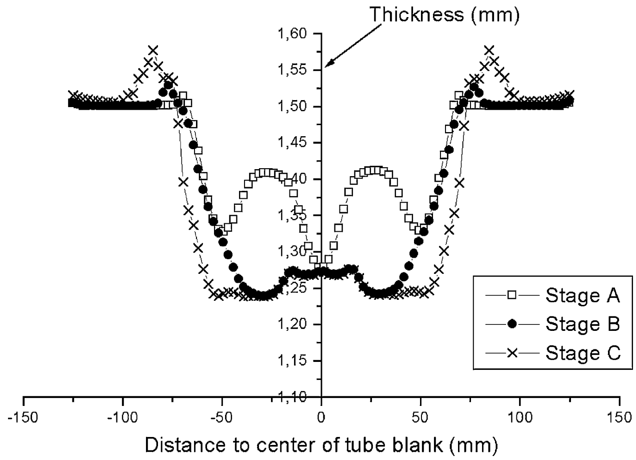

Fig. 20 – Wall thickness distributions in different stages under feeding pressure of 5.0 MPa in the pre-forming stage.

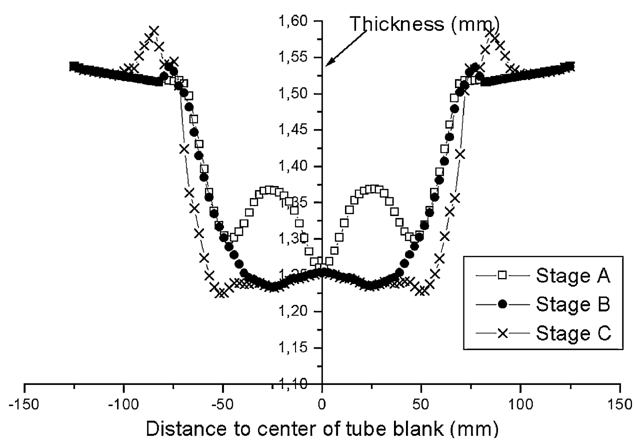

Fig. 21 – Wall thickness distributions in different stages under feeding pressure of 6.0 MPa in the pre-forming stage.

mized value for the feeding pressure in the pre-forming stage can be assumed to be around 5.0 MPa. Because of the use of useful wrinkles, the thinnest point is not located at the wave crest but at the wave trough.

Moreover, from Figs 14 to 16, the wave trough increases with the feeding pressure in the pre-forming stage. Meantime, the sheet in the wave trough becomes thinner.

When the punch stroke moves forward more than 15.0 mm in the pre-forming stage, harmful wrinkles will be formed in the middle expanding area. And in the finishing stage, if the punch stroke exceeds 5.0 mm, more harmful wrinkles will be formed in the transferring area. Depending on the above analysis, the total process windows between the feeding pressure and the punch stroke can be drawn virtually in Fig. 22. In the pre-forming stage, the feeding pressure is within 4.0 and 7.0 MPa, and the punch stroke is within 8.0 and 15.0 mm; in the finishing stage, the feeding pressure is within 4.0 and 7.0 MPa, and the punch stroke is within 3.0 and 8.0 mm, the corresponding minimum calibration pressures of which are between 40 and 80 MPa. It can be found that the forming strip is quite narrow and a very accurate control system must firstly be designed. Also, it can be found that whatever in the pre-forming stage and the finishing stage, the needed pre-forming pressures are almost the same, but compared to the pre-forming pressure, the calibration pressure should be increased very high to flatten the formed wrinkles.

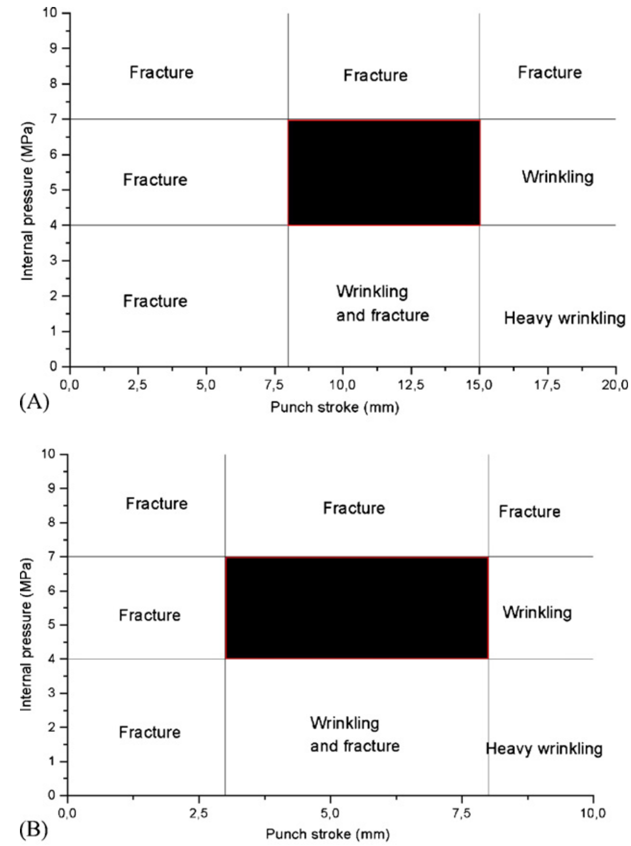

Fig. 22 – Process windows for the feeding pressure and the punch stroke. (A) In the pre-forming stage; (B) in the finishing stage.

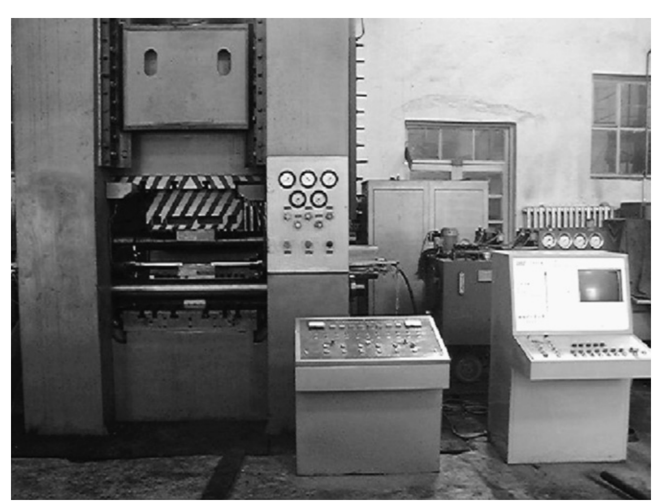

Fig. 23 – Photograph of tube hydroforming equipment.

5. Experimental verification

The equipment is the base of the experiment. Fig. 23 shows a picture of this equipment which was studied and developed. The equipment is mounted on a general double-actions press in which the total clamping force can reach 10,000 kN. The maximum punch force can reach 1500 kN, and the maximum punch stroke is 150.0 mm. The internal pressure can be adjusted by two ranges: from 0 to 150 MPa or from 150 to 400 MPa, by using different intensifiers. For aluminum alloy tube hydroforming, the intensifier with internal pressure of 150.0 MPa was used because the needed internal pressure was low for the hydroforming of aluminum tube.

Based on the results from simulation, the experiment was carried out. All the applied parameters including the material and the tools are the same as in the simulation. The machine oil used as forming media was used as lubricant in the guiding area. According to the results obtained from simulation, the selected parameters were that the punch strokes should be 15.0 mm under the feeding pressure of 5.5 MPa in the pre-forming stage and then in the finishing stage, the punches moved forward again 3.0 mm under the feeding pressure of 5.0 MPa. The calibration pressure in the finishing stage was 80.0 MPa. Fig. 24 shows the forming processes, and Figs. 25 and 26 show comparison between the measurements and the predicted wall thickness distributions in the performing and the finishing stages. The predictions are similar to the measurements.

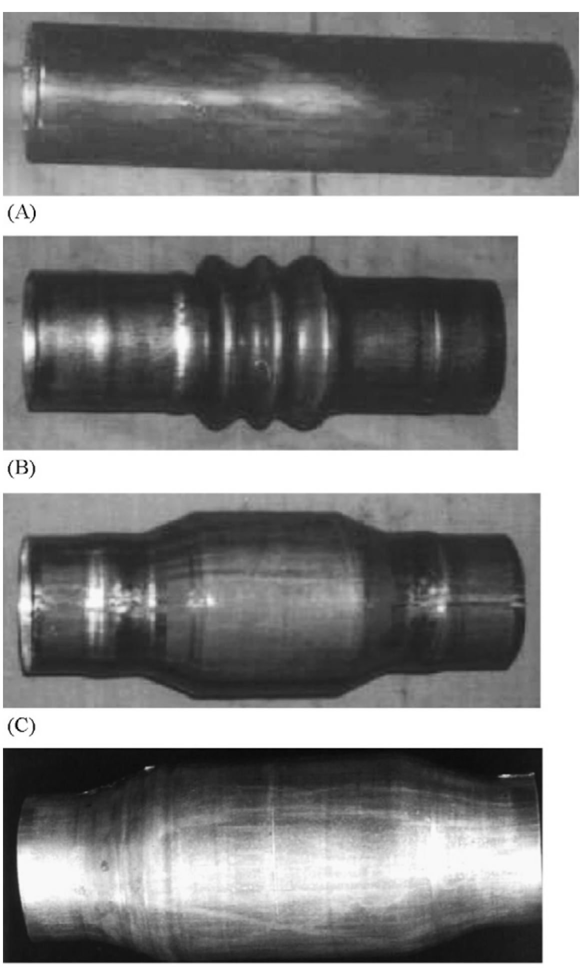

Fig. 24 – Different forming stages. (A) Tube blank; (B) useful wrinkles in pre-forming stage; (C) pre-formed part; (D) finally formed part.

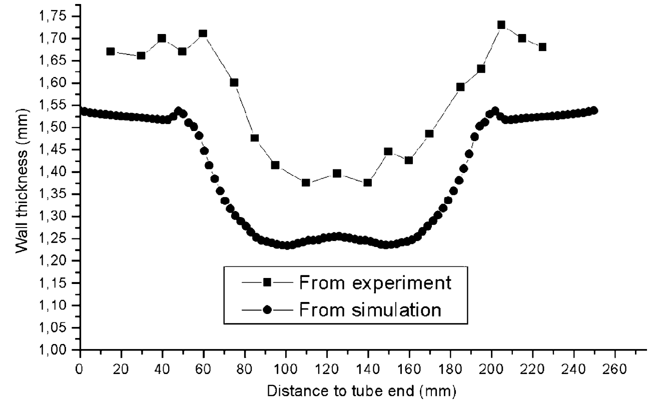

Fig. 25 – Wall thickness distributions along axial direction profile between simulation and experiment after the pre-forming stage.

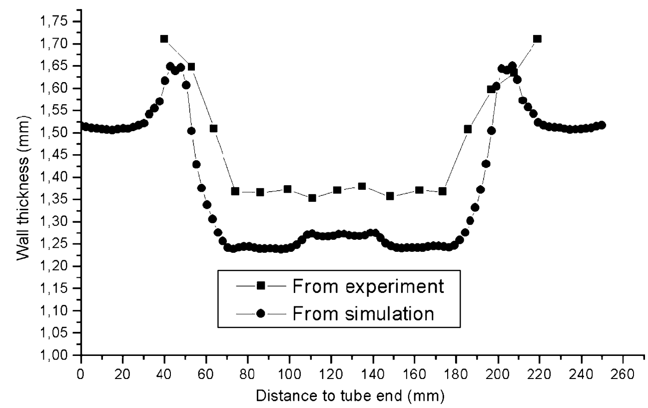

Fig. 26 – Wall thickness distributions along axial direction profile between simulation and experiment after finishing stage.

6. Conclusions

Useful wrinkles instead of the harmful wrinkles should be formed under the two-step variation method in both the pre-forming stage and the finishing stage. By using the useful wrinkles, the quantity of the pre-forming dies can be decreased and the cost of the tooling can be reduced. Based on the useful wrinkles and using aluminum alloy with a bad cold formability and the concept of the useful wrinkles, multi-stages tube hydroforming can be done by controlling birth time and dead time for all the contact pairs in simulation. All the tools including the pre-forming die cavity and the calibration die cavity can be built in one simulation, which will make the operation more simple and the obtained results more accurate.

The pre-forming pressures in both the pre-forming stage and the calibration stage are almost the same, and compared the pre-forming pressures, the needed calibration pressures are needed quite high. Pre-forming plays an important role in tube internal high pressure forming and affects the forming of the useful wrinkles very much, and the optimized process parameters firstly have to be found in the pre-forming stage to obtain a successfully formed part. The designed 25° pre-forming die can be more useful to form the useful uniform wrinkles successfully than the 45° pre-forming die, and it shows that the suitable boundary conditions must be selected to obtain the useful wrinkles.

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