

Effects of mandrel shape on deformation behavior for hot mandrel bending of elbows

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Elbows of steel pipe joints are used in the industrial plants and are mainly manufactured by the hot mandrel bending from raw material of straight steel pipe. Elbows are generally manufactured at elevated temperature by means of pushing, expanding and bending of pipes simultaneously, using the inner tool of mandrel. Characteristics of mandrel bending strongly depend on the integrated shape and dimensions of the mandrel. We investigate the effects of shape and dimension of mandrel on deformation behaviors for hot mandrel bending of elbows, conducting experimental test and numerical analysis. We clarify the effects of bending radius ratio R_{out}/D_{out} , expansion ratio D_{out}/D_{in} , mandrel length ratio L/D_{out} and other items of mandrel shape. And optimum conditions of mandrel are estimated as conclusion.

KEYWORDS: hot mandrel bending, elbow, pipe, bending radius ratio, expansion ratio, mandrel length ratio, bending direction ratio, deformation, finite element analysis, pushing load

INTRODUCTION

In various plants, a lot of elbows are used for curve parts of piping. The dimension and shape of elbows are prescribed in Japanese Industrial Standard (JIS), being termed as joints of butt-welded steel pipe. This joint has a round section with uniform thickness, same as the standard of a straight pipe. Mandrel bending and cold dice bending of steel pipes, and press forming of a steel plate are used as a manufacturing process of elbows, however the mainstream is hot mandrel bending which is so called Hamburg bending.

Elbows manufactured by using hot mandrel bending have advantages of small thickness deviation and shorter bending radius than those of any other bending method type. However, improvement of quality and productivity for elbows by using the hot mandrel bending has been requested. We have been investigated to clarify mechanism of hot mandrel bending by conducting experimental mandrel bending tests of hot steel pipes [1,2] and cold aluminum pipes [3,5], and numerical analysis simulation [1,7]. The purposes of this study are to clarify the effects of bending radius ratio R_{out}/D_{out} , expansion ratio D_{out}/D_{in} , mandrel length ratio L/D_{out} and bending direction ratio of mandrel shape, to confirm deformation behavior of the pipe, to investigate of change of thickness distribution and to analyze bending moment and pushing load. And optimum conditions of mandrel are estimated as conclusion.

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EXPERIMENTAL PROCEDURE

Hot mandrel bending

Hot mandrel bending is conducted as follows. As shown in Fig.1, firstly, specimens with short length are cut off from straight long pipe and they are inserted into a mandrel, which has a sophisticated shape. Secondly, the specimen are compressed by the pusher at the designated velocity, being expanded and bent through the mandrel, while at the bending part of mandrel they are heated at about 800C by using a burner in a heating furnace. Finally, elbows are manufactured from the specimens.

Shape and dimension of mandrel

Experimental mandrel is designed by technology of plastic deformation as shown in Fig.2. Functions of mandrel shapes are classified three zones and named as follows. In zone 1 of expanding part, short straight pipes are inserted into the mandrel and are supported in the center of the axis. In zone 2 of holding part, pipes are compressed, bent and expanded to make wall thickness uniform. And in zone 3 of finishing part, elbows are finished the forming. Expansion ratio and bending radius ratio

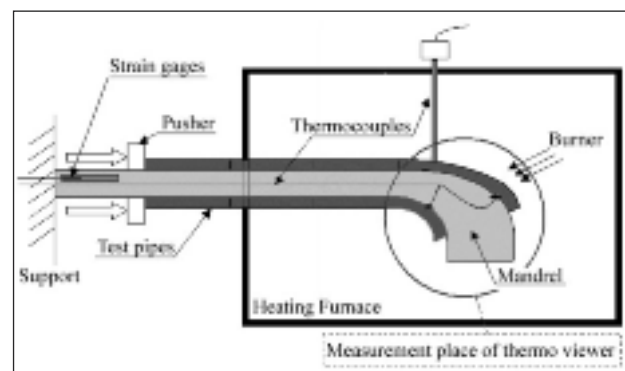


FIG. 1 Hot mandrel bending.

Piegatura a caldo mediante mandrino.

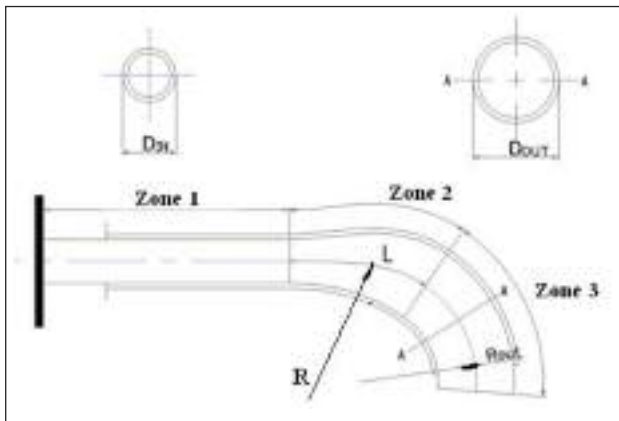


FIG. 2 Shape and dimension of mandrel.

Forma e dimensioni del mandrino.

are important factors in mandrel shape. Expansion ratio is defined as D_{OUT}/D_{IN} and bending radius ratio is defined as R_{OUT}/D_{OUT} , where outer diameter of elbows, bending radius ratio of elbows and outer diameter of straight pipes are termed D_{OUT} , R_{OUT} and D_{IN} respectively. As shown in Fig.2, the mandrel length along the central line in the zone 2 is termed L.

Design concepts of experimental mandrel are decided as follows. Cross-sectional shape of each zone in experimental mandrel is designed to be round. Expansion ratio D_{OUT}/D_{IN} is optimized in order to equalize thickness of elbow. Curvature in zone 2 of expanding part increases gradually from inlet to outlet in order to equalize load distribution in mandrel bending. Expansion ratio D_{OUT}/D_{IN} is calculated eqn (1) and curve of zone 2 is consisted of straight line and transition curve of trigonometric function.

$$\frac{D_{OUT}}{D_{IN}} = \frac{2 \left(1 + \frac{D_{IN}}{2R_{OUT}} \right)}{\sqrt{1 - \left(\frac{D_{IN}}{2R_{OUT}} \right)^2}} \left[\arcsin \left(\frac{1 + \frac{D_{IN}}{2R_{OUT}}}{\sqrt{1 - \left(\frac{D_{IN}}{2R_{OUT}} \right)^2}} \right) - \arcsin \left(\frac{-1 + \frac{D_{IN}}{2R_{OUT}}}{\sqrt{1 - \left(\frac{D_{IN}}{2R_{OUT}} \right)^2}} \right) \right] \quad (1)$$

Zone 2 of expanding part is an important part that conducts the majority of the forming.

The shape of zone 2 of expanding part is decided as follows. In the forming process, the increment of curvature is basically designed to be proportional to the expansion ratio D_{OUT}/D_{IN} for diameter of pipe, because the curvature increment means the increment of the bend moment to be necessary for the processing. On the other hand, when the increment of the curvature of the expansion part is constant, singular points appear at the boundary of zone 1 and zone 2, and zone 2 and zone 3, as shown in Fig.3. When there are singular points in the curvature, the concentration of the stress and the strain is caused in the process of plastic deformation. A trigonometric transition of curvature is adopted at the boundary neighborhood in each zone of the mandrel, as shown in Fig.3.

The design of the mandrel at zone 2 of expanding part is as follows. Zone 2 is divided into N step. It is $i=0, 1, \dots, N$ as for the number of steps. $D(0)$ is a diameter of the mandrel in the zone 1, and $D(N)$ is a diameter of the mandrel in the zone 3. The curvature increment is assumed to be a proportion to the expansion ratio in each step, as shown eqn (2). Thereby, is constant value.

$$\frac{d\rho_{(i)}}{di} = a \frac{dD_{(i)}}{di} \quad (2)$$

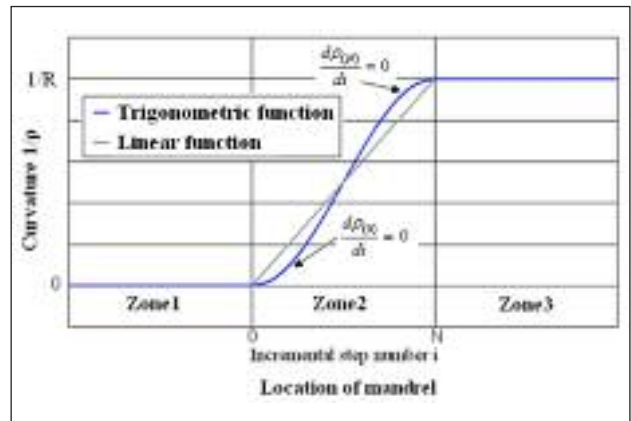


FIG. 3 Transition of curvature for each zone of mandrel.

Variatione della curvatura per ciascuna zona del mandrino.

As results, relationship between bending radius ratio R_{OUT}/D_{OUT} and expansion ratio D_{OUT}/D_{IN} is designed appropriately in order to equalize wall thickness of elbow and curvature in zone 2 increases gradually in order to equalize load distribution. Therefore, there are little singular points in shape of mandrel. And cross sectional shapes are true round in all zones, as shown in Fig.2. We define the ratio of the displacement toward extrados and intrados from the base line of expansion as 'expanding direction ratio', as shown in Fig.8.

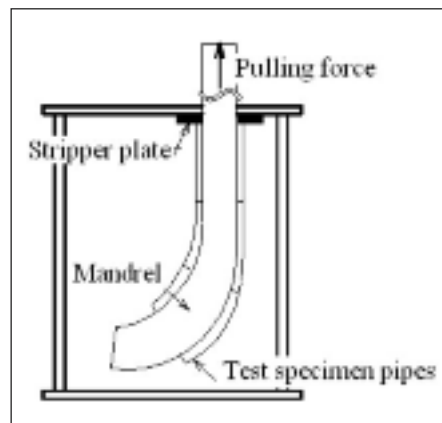


FIG. 4

Experimental method for mandrel bending by aluminum pipe.

Metodo sperimentale per piegatura mandrino da tubo di alluminio del mandrino.

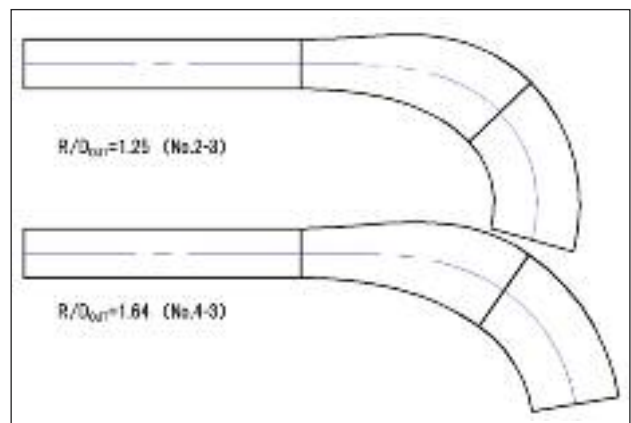


FIG. 5 Mandrel shape for bending radius ratio R_{OUT}/D_{OUT} of 1.25 and 1.64.

Forma del mandrino per rapporti di raggio di piegatura R_{OUT}/D_{OUT} di 1.25 e 1.64.

Experimental method

It is difficult to keep the temperature to be uniform in the furnace heating of the hot mandrel bending. Therefore, aluminum pipes are used in the room temperature for specimen instead of steel pipes in the elevated temperature, because of its almost similar plastic metal flow. Aluminum pipes are machined from round rods whose grade is A11070BE-F. Aluminum pipes are inserted into the mandrel and the mandrel is pull up by tensile test machine, restricting the aluminum pipes by stripper plate, as shown in Fig.4. The pulling speed is set at 20mm/min. The disulfide molybdenum grease is used as lubricant. Mandrel shape is calculated by eqn (1) and (2). The effect of expansion ratio D_{out}/D_{in} , bend radius ratio R_{out}/D_{out} , mandrel length ratio L/D_{out} and expanding direction ratio on the deformation behavior is examined. Experimental conditions and test specimens are shown in Table 1. Bending radius is 90 degree and the length of the test specimen is 105mm. Bending radius ratio R_{out}/D_{out} for experimental conditions is set at 1.25 and 1.64, as shown in Fig.5. Mandrel length ratio L/D_{out} changes at 1.50, 2.00 and 2.50.

Numerical simulation analysis

Numerical simulation analysis is conducted by finite element analysis software MARC/MENTAT. Mandrel, pusher, and stripper are made a solid body. Frictional coefficient is set at 0.1. Material of pipes is assumed to be 1/2 models for the plane symmetry. Fig.6 shows the general view of numerical analysis for hot mandrel bending.

Conditions of numerical simulation are shown in Table 2. Mandrel length ratio L/D_{out} changes at 1.50, 2.00 and 2.50, as shown in Fig. 7. The values of 0:100, 50:50 and 100:0 for the expanding direction ratio are shown in Fig.8 (a), (b) and (c), respectively.

RESULT AND DISCUSSION

Bending radius ratio R_{out}/D_{out} and expansion ratio D_{out}/D_{in}

In the past we reported[4,6] the relation between bending radius ratio R_{out}/D_{out} and expansion ratio D_{out}/D_{in} for practical mandrel shape by hot mandrel bending of steel pipes and by cold mandrel bending of aluminum pipes, comparing with experimental mandrel shape by cold mandrel bending, as shown in Fig.9. When the relation between bending radius ratio R_{out}/D_{out} and expansion ratio D_{out}/D_{in} is on the curved line calculated by eqn (1), wall thickness deviation at intrados is very small. However when the relation of bending radius ratio R_{out}/D_{out} and expansion ratio D_{out}/D_{in} is set at over or under the curved line, the deviation of the wall thickness increases. On the curved line, changes of wall thickness are -1.63, 3.39, 1.66 and 0.89%. Out of the curved line, they are 11.47 and -12.29%.

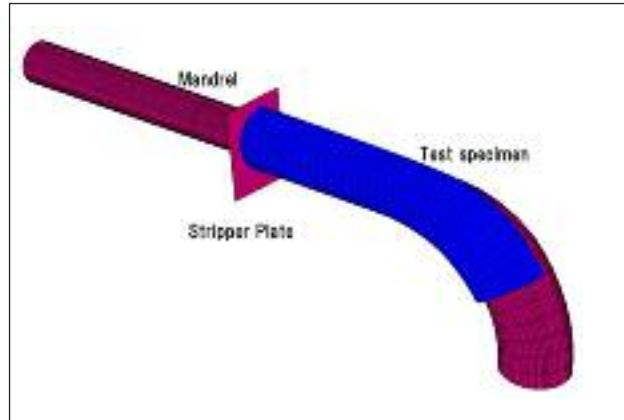


FIG. 6 General view of numerical analysis for hot mandrel bending.

Vista generale del risultato dell'analisi numerica per la piegatura a caldo mediante mandrino.

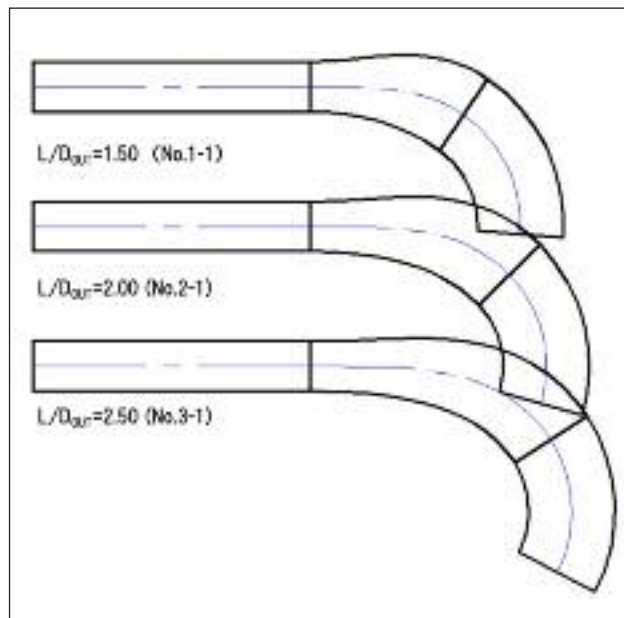


FIG. 7 Mandrel shape for mandrel length ratio of L/D_{out} of 1.5, 2.0 and 2.5.

Forma del mandrino per rapporti L/D_{out} delle dimensioni del mandrino di 1.5 e 2.5.

No	Mandrel			Expanding direction ratio	Test specimen	Bent pipe Elbow
	Expansion ratio D_{OUT}/D_{IN}	Bending Radius ratio R_{OUT}/D_{OUT}	Mandrel length ratio L/D_{OUT}		$D_{IN} \times t_{IN}$ [mm]	$R_{OUT} \times D_{OUT} \times t_{OUT}$ [mm]
1-1	1.36		1.50		28.0×3.5	47.5×38.0×3.5
2-1	1.36				28.0×3.5	
2-2	1.32		2.00		28.8×3.4	
2-3	1.28	1.25		50:50	29.8×3.2	
3-1	1.36		2.50		28.0×3.5	
4-3	1.28	1.64	2.00		29.8×3.2	62.4×38.0×3.2

TAB. 1 Experimental condition and test specimen.

Condizioni sperimentali e dimensioni dei provini.

No	Mandrel shape and dimension			Bending direction ratio extrados: intrados	Specimen Diameter x thickness $D_{IN} \times t_{IN}$ [mm]	Bent pipe Bending radius x diameter x thickness $R_{OUT} \times D_{OUT} \times t_{OUT}$ [mm]
	Bending radius ratio R_{OUT}/D_{OUT}	Expansion ratio D_{OUT}/D_{IN}	Mandrel length ratio L/D_{OUT}			
2-1	1.25	1.36	1.50	50:50	28.0×3.5	47.5×38.0×3.5
2-2			2.00			
2-3			2.50			
2-4			1.50			
2-5			50:50			
2-6			100:0			
3-1	1.26	1.42	1.50	50:50	47.2×42	76.2×60.5×3.9
3-2			2.00			
3-3			2.50			
3-4			1.50			
3-5			2.00			
3-6			2.50			

TAB. 2 Main conditions of numerical simulation.

Principali condizioni della simulazione numerica.

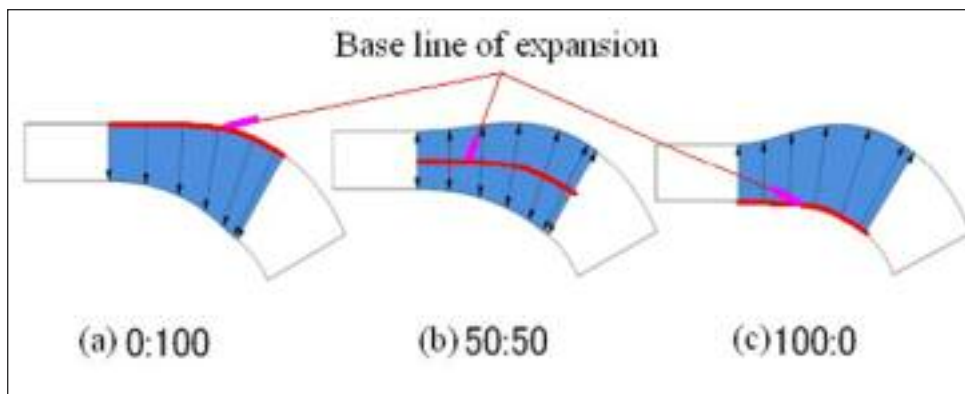


FIG. 8 Mandrel shape for expanding direction ratio of 0:100, 50:50 and 100:0.

Forma del mandrino per rapporti della direzione di espansione pari a 0:100, 50:50 e 100:0.

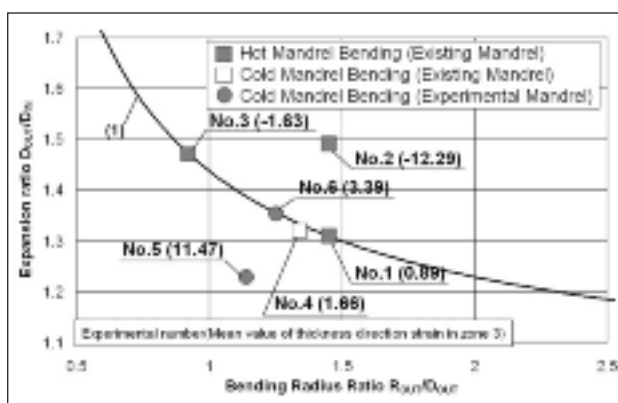


FIG. 9 Changes in wall thickness at intrados by expansion ratio D_{OUT}/D_{IN} and bending radius ratio R_{OUT}/D_{OUT} .
Cambiamento dello spessore della parete all'intradosso in funzione del rapporto di espansione D_{OUT}/D_{IN} e del rapporto del raggio di piegatura R_{OUT}/D_{OUT} .

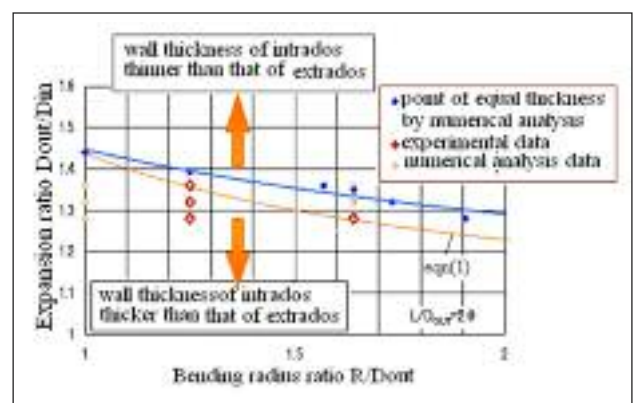


FIG. 10 Effect of expansion ratio D_{OUT}/D_{IN} and bending radius ratio R_{OUT}/D_{OUT} .

Effetto del rapporto di espansione D_{OUT}/D_{IN} e del rapporto tra le misure di piegatura R_{OUT}/D_{OUT} .

The effect of the expansion ratio D_{out}/D_{in} and the bending radius ratio R_{out}/D_{out} on the wall thickness distribution is confirmed in this study by experiment and numerical analysis, as shown in Fig.10. The blue color curved line is calculated by numerical analysis, where the wall thickness t_1 at extrados is equal to the wall

thickness t_2 at intrados. Upper the blue line, the wall thickness t_2 at intrados is smaller than the wall thickness t_1 at extrados. And under the blue line, the wall thickness t_2 at intrados is bigger than the wall thickness t_1 at extrados. The phenomena are same as the data which were reported in the past. Namely, the

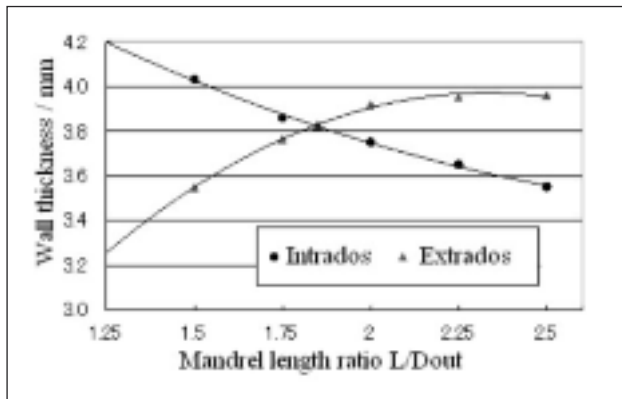


FIG. 11 Mandrel length ratio L/D_{out} vs. the wall thickness at intrados and extrados.

Relazione tra il rapporto delle misure del mandrino L/D_{out} e lo spessore della parete all' intradosso e all'extradosso.

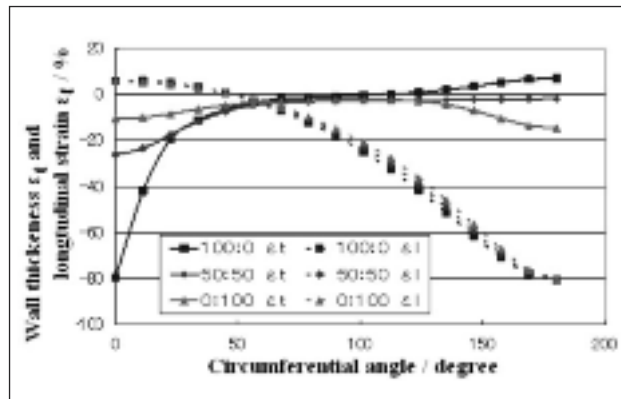


FIG. 13 Effect of expanding direction ratio on wall thickness and longitudinal strain.

Effetto della direzione di espansione sul rapporto tra spessore di parete e allungamento longitudinale.

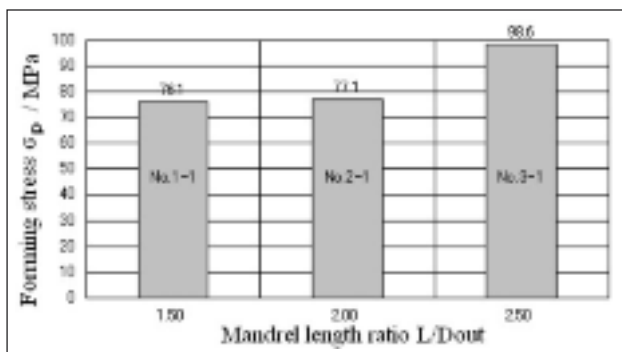


Fig. 12 Effect of the mandrel length ratio L/D_{out} on the forming stress σ_p .

Effetto del rapporto delle misure del mandrino L/D_{out} sul carico di formatura σ_p .

relation between expansion ratio D_{out}/D_{in} and bending radius ratio R_{out}/D_{out} is important factor in order to manufacture elbows whose distribution of wall thickness is uniform. The eqn (1) will be effective for the uniformity of wall thickness.

Mandrel length ratio of L/D_{out}

Effect of the mandrel length ratio L/D_{out} on the wall thickness at the intrados and the extrados is estimated by numerical analysis simulation, as shown in Fig.11. The bending direction ratio is set at 50:50. As the mandrel length ratio L/D_{out} increases, the wall thickness at extrados increases and the wall thickness at intrados decreases. At the mandrel length ratio L/D_{out} of 1.85, the wall thickness at intrados is equal to that at extrados. We measure the pushing load by load cell and defined the forming stress in which the pushing load is divided by the cross section area of the specimen pipe. Fig.12 shows the effect of the mandrel length ratio L/D_{out} obtained from the experiment on the forming stress. As the mandrel length ratio L/D_{out} increases, the forming stress ϵ_p increases. As for the mandrel length ratio L/D_{out} of 1.50, 2.00 and 2.50, the forming stress is 76.1, 77.1 and 98.6MPa, respectively. The reason is estimated that frictional force increases as the mandrel length ratio L/D_{out} increases.

Expanding direction ratio

The numerical analysis is conducted by changing the expanding direction ratio as 0:100, 50:50 and 100:0. The longitudinal di-

rection strain ϵ and the wall thickness direction strain ϵ_t distribution along the circumferential angle are calculated, as shown in Fig.13.

The circumferential angle is defined as the angle 0 degree is at extrados and 180 degree is at intrados. There is little effect of the expanding direction ratio on the longitudinal direction strain. However there is great effect on the wall thickness strain distribution along the circumferential angle. When the expanding direction ratio is 100:0, the wall thickness strain is ununiformly distributed along the circumferential angle. It seems that wall thickness distribution at the expanding direction ratio of 0:100 or 50:50 will be more uniform along the circumferential angle than that at the expanding direction ratio of 100:0.

CONCLUSION

The effect of mandrel shape on deformation behavior for hot mandrel bending of elbows is clarified as follows.

1. Relation between expansion ratio D_{out}/D_{in} and bending radius ratio R_{out}/D_{out} is important factor to manufacture elbows whose wall thickness is uniform.
2. Effect of mandrel length ratio L/D_{out} on the wall thickness and pushing load is clarified. At the mandrel length ratio L/D_{out} of 1.85, the wall thickness at intrados will be equal to that at extrados.
3. It seems that wall thickness distribution at the expanding direction ratio of 0:100 or 50:50 will be more uniform along the circumferential angle than that at the expanding direction ratio of 100:0.

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Abstract**Influenza della forma mandrino sul comportamento a deformazione sulla piegatura di gomiti con mandrino a caldo**

Parole chiave: acciaio - lavorazioni plastiche a caldo

I gomiti dei giunti dei tubi d'acciaio sono utilizzati negli impianti industriali e sono principalmente prodotti mediante piegatura a caldo con mandrino partendo da tubi dritti di acciaio come materiale di partenza. I gomiti vengono generalmente prodotti a temperatura elevata mediante contemporanea spinta-espansione-piegatura dei tubi, utilizzando lo strumento interno del mandrino. Le caratteristiche della piegatura dipendono fortemente dalla forma integrata e dalle dimensioni del mandrino. Nel presente lavoro sono stati studiati gli effetti di forma e dimensione del mandrino sul comportamento a deformazione nella piegatura a caldo di gomiti mediante mandrino, conducendo prove sperimentali e analisi numeriche. Sono stati chiariti gli effetti del rapporto del raggio di curvatura R_{OUT} / D_{OUT} , del rapporto di espansione D_{OUT} / D_{IN} , del rapporto della lunghezza del mandrino L / D_{OUT} e altri elementi relativi alla forma del mandrino. Infine sono state valutate le condizioni ottimali del mandrino.