FE ANALYSIS ON TUBE HYDROFORMING OF SMALL DIAMETR ZM21 MAGNESIUM ALLOY TUBE

H. Yasui*, T. Miyagawa†, S. Yoshihara††, T. Furushima†††, R. Yamada†††† and Y. Ito†††††

*, †Faculty of Engineering, Integrated Graduate School of
Medical, Engineering, and Agricultural Sciences, University of Yamanashi,
4-3-11 Takeda Kofu-shi, Yamanashi, 400-8511, Japan.
*E-mail: g18tma01@yamanashi.ac.jp
†E-mail: g18tm029@yamanashi.ac.jp

††Department of Engineering and Design, Shibaura Institute of Technology,
3-9-14 Minato-ku, Tokyo, 108-8548, Japan.
Email: yoshi@shibaura-it.ac.jp

†††Institute industrial science, The University of Tokyo,
4-6-1 Komaba Megro-ku, Tokyo, 153-8505, Japan.
Email: tsuyoful@iis.u-tokyo.ac.jp

††††, †††††Graduate Faculty of Interdisciplinary Research Faculty of Engineering,
Mechanical Engineering (Mechanical Engineering), University of Yamanashi.
4-3-11 Takeda Kofu-shi, Yamanashi, 400-8511, Japan.
††††Email: ryamada@yamanashi.ac.jp
†††††Email: yasumii@yamanashi.ac.jp

Key words: Tube Hydroforming, Warm forming, Small diameter tube, Magnesium alloy tube.

Abstract. Tube hydroforming (THF) is one of the plasticity processing methods. Tubular parts, for instance automotive components are expanded by forces such as internal pressure and axial compression in order to deform an objective shape. THF has less restriction on shape and size of workpieces owing to adopting the liquid tool. The demand of a small diameter magnesium alloy tubular parts have been increased for applying small medical and electronic devices. In this study, it was investigated that influence of process conditions such as processing temperature, internal pressure and axial feeding amount on formability of small diameter ZM21 magnesium alloy tube with outer diameter of 2.0mm and thickness of 0.20mm. Furthermore, the processing conditions for improving the formability of material in THF were examined. For prior evaluation of deformation characteristics in the warm THF of small diameter ZM21 magnesium alloy tube, a finite element (FE) simulation was conducted. The FE method (FEM) code was used LS-DYNA 3D for analysis of the FE model of the tube and the dies. The material characteristics were obtained by tensile test and fracture test. From FE analysis results, it was elucidated that effect of the processing temperature, the variable internal pressure and the axial feeding amount on deformation behavior. The formability of

ZM21 magnesium alloy tube was improved by processing at 250 ℃. The difference of deformation characteristic between FE results and experimental results was compared. As the results, the processing condition which could improve the formability of ZM21 tube was clarified using this FE model. The effect of adding the straightening stage in the loading path after the preform on formability was investigated. The thinning of the wall thickness of the tube was inhibited by calibration after the axial feeding.

1 INTRODUCTION

Magnesium and its alloys have excellent strength and low density against weight ratio. These materials are widely applied for parts of the automotive, aircraft and telecommunications products. In addition, magnesium is suitable for medical devices because of the essential element for human health [1]. Recent developments in the bioabsorbable implant industry include magnesium alloys [2]. In recent years, the miniaturizations of electronic and medical devices have been required. The demand for manufacturing of small diameter tubular products has been increasing. Tube hydroforming (THF) is a plastic processing method which could expand the tube by loaded the internal pressure and axial compression force during the process. Loaded pressure and axial direction force deform the tubes having complex cross-section shape integrally. This characteristic leads to weight reduction and high strength of the product. THF has less restriction on the shape and size of the workpieces owing to using liquid tools. Therefore, it is expected to manufacture small diameter tube parts made of magnesium alloy by THF [3]. However, it is difficult to deform the magnesium alloy tubes because of low ductility at room temperature (RT). Warm processing is generally applied for improving of formability on magnesium. In previous studies, improvement of formability on AZ31 magnesium alloy tubes with an outer diameter of 22mm was investigated on warm THF. It had succeeded that expanding of the tube with approximately 1.5 times bulge height against the outer diameter of original tube from experiment and FE analysis [4]. The T-shaped AZ31 magnesium alloy tube with an outer diameter of 42.7mm had deformed by FE analysis and experiment at 250℃. The characteristics of fracture and buckling were evaluated by valid FE model [5]. Furthermore, the wall thickness uniforming had studied by setting the temperature distribution in the die cavity [6]. However, applying the process of these studies for small diameter tube less than 10mm of outer diameter is impossible. There are problems such as size effect, accuracy of tool and friction between die and tube materials, these effect the formability of tube. In small diameter tubes, there is a critical problem that is the number of crystal grains relative to the thickness of the material [7]. This problem makes the prediction result of deformation behavior unstable. It is necessary to clarify the formability and deformation characteristics of the small diameter magnesium alloy tube in THF. In this study, the suitable processing conditions and deforming behavior were investigated by FEM for ZM21 magnesium alloy tube with an outer diameter of 2.0mm and a thickness of 0.20mm in order to achieve THF for small diameter tube in warm temperature. The effects of processing temperature, internal pressure and axial feeding amount on the formability and deformation characteristic of tube were investigated. Moreover, the processing conditions which could improve the formability of tube are considered.

2 EXPERIMENTAL SETUP AND FE MODEL

2.1 Material characteristic and results of tensile test and bursting test

Mechanical properties were investigated by tensile test and bursting. The specimens were annealed at 300℃ for 24 hours. ZM21 magnesium alloy bars with an outer diameter of 6.0mm manufactured by hot extrusion and used for tensile tests. **Table1** shows the chemical composition of the rod material. **Table2** shows the tensile test conditions of ZM21. The nominal stress-nominal strain diagram which obtained from the tensile test of the ZM21 rod is shown in **Fig.1**. As the result, it was confirmed that deformation resistance decrease and ductility increase as test temperature increase. It is easy to deform ZM21 at 250℃ because it had excellent ductility. ZM21 magnesium alloy tubes with an outer diameter of 2.0mm and a wall thickness of 0.2mm were tested for tensile test. **Table3** shows the chemical composition of the tube material. The materials were manufactured by drawing process. The tensile speed was set on 0.6mm/min and temperature at RT and 250 ℃. **Fig.2** shows the nominal stress-nominal strain diagram of the ZM21 tube. The comparison of Fig.1 and Fig.2, there is a correlation between ZM21 bar and ZM21 tube for change in the deformation resistance and ductility at warm area. Furthermore, the fracture pressure of tube was measured by bursting test. The internal pressure was loaded as speed of 1.0MPa/s until rupturing. **Fig.3** shows the result of bursting test of ZM21 tube.

Table1 Composition of specimens (ZM21 magnesium alloy rod) for tensile test in mass%

	Al	Zn	Mn	Si	Fe	Cu	Ni	Mg
ZM21	0.004	1.81	0.68	0.01	0.028	0.001	0.001	Bal.

Table2 Test conditions of tensil test (ZM21 magunesium alloy rod)

Material	ZM21
Test pease size [mm]	$\Phi 6 \times L30$
Tensile speed [mm/min]	0.6
Temperature [˚C]	RT, 50, 100, 150, 200, 250, 300

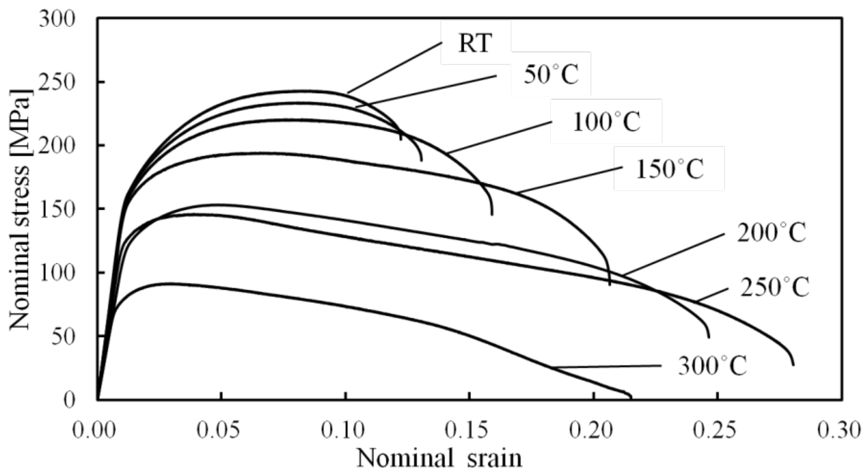


Fig.1 Noninal stress-Nominal strain curve of ZM21rod

Table3 Composition of specimens (ZM21 magnesium alloy tube) for tensile test in mass%

	Al	Zn	Mn	Si	Fe	Cu	Ni	Mg
ZM21	0.0035	1.83	0.7	0.015	0.0026	0.001	0.001	Bal.

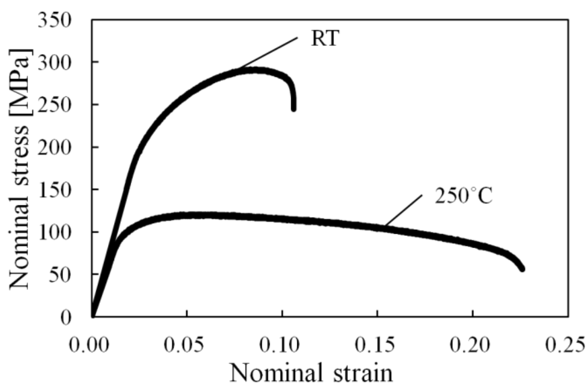


Fig.2 Noninal stress-Nominal strain curve of ZM21tube

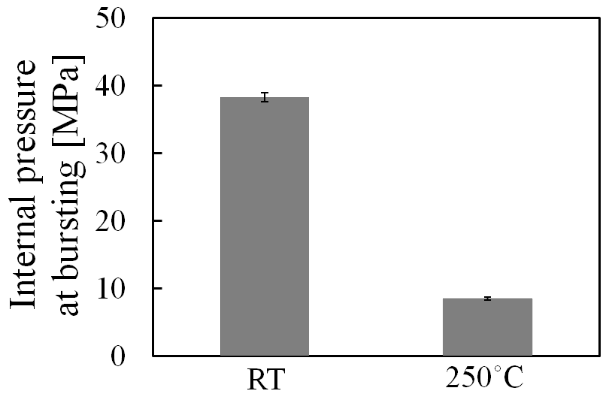


Fig.3 Bursting peressure of ZM21 tube

2.2 FE model

Fig.4 shows FE model for THF which is constructed by dies and tubular blank model. The length of tube is 20mm with an outer diameter of 2.0mm and a wall thickness of 0.2mm. The maximum expansion diameter in the die cavity is 4.0mm. A 1/2 model was selected owing to symmetrical shape. FE analyzes were conducted using the dynamic explicit FEM code LS-DYNA 3D. Material properties are shown in **Table4**. The blank tube is modeled in a solid element with the elastic-plastic material, and the dies are rigid-body models. The model of tube has six elements in the thickness direction. The total number of element is192000 for tube blank, and for the dies, the total number of element is 1350. The dies are defined as a rigid body using surface contact with the tube. The coefficient of friction between the dies and the tube is 0.1. The analysis time is set to 0.01s.

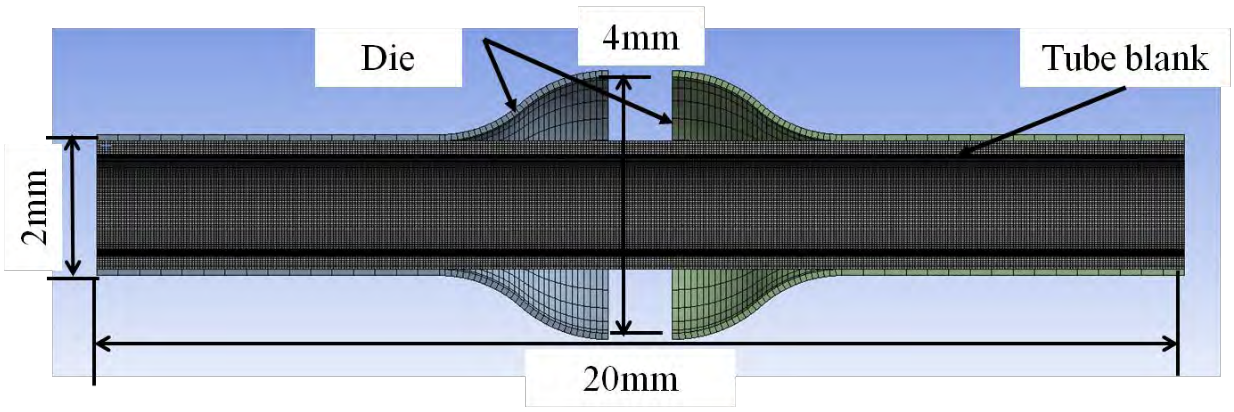


Fig.4 FE model for THF

Table4 Material properties for FE analysis

Body	Blank	Die
Material	ZM21	SKD61
Material model	Multiliner plasticity	Isotropic elastic
Yield stress σ_y [MPa]	90.76	---
Young's modulus E [GPa]	8.2017	200
Density [kg/mm^3]	1800	7850
Poisson coeffcient	0.35	0.3

2.3 FE analysis and experimental conditions

The loading path of the internal pressure and the axial feeding amount is shown at **Fig.5**. Pass (1) in the figure, the pressure was loaded up to the internal pressure p without the applying axial feeding. The internal pressure p was set 80% on against the bursting pressure p_B. In the FE analysis, the pressure was determined by following equation (1). Here, p_B is bursting pressure, σ_B is tensile strength, t is the wall thickness, D_0 is the initial outer diameter of the tube.

$$p_B = 2(t/D_0)\sigma_B \tag{1}$$

The axial feeding was loaded during maintaining the internal pressure constantly. The axial displacement ΔL is 0.5mm. Here, **Fig.6** shows the loading mechanism of the axial feeding and pressure in THF machine. **Fig.7** shows the die cavity. The axial feeding is performed by moving the distance between left and right dies to resolve the problem such as preparation of the high precision punch for the small diameter tube. The die cavity could be corresponding to a spherical expansion which has a cavity of 200% larger than the initial outer diameter of tube.

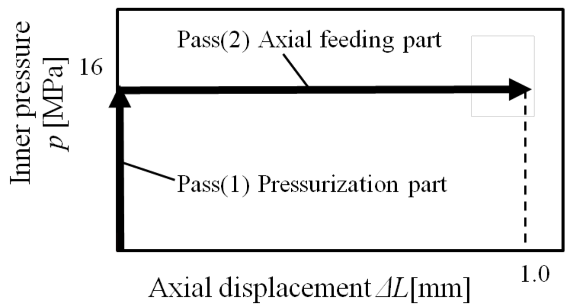


Fig.5 Loading path for THF

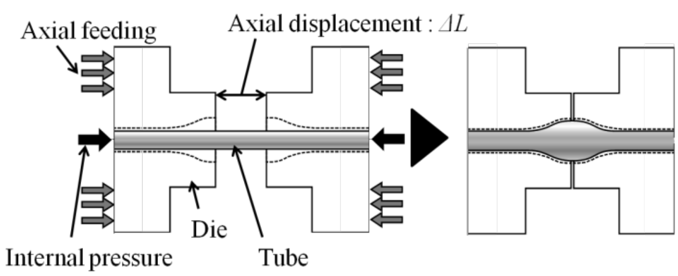


Fig.6 Axial feeding and pressure load system

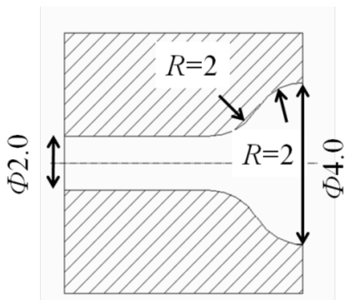


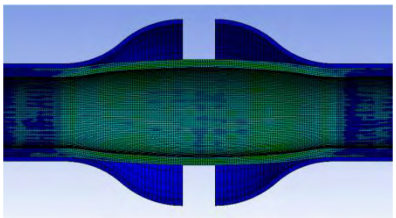
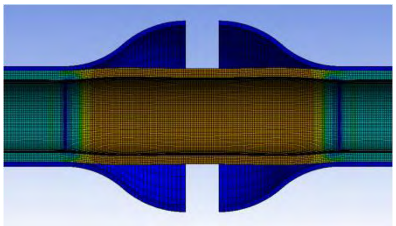
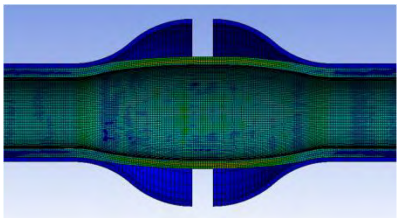
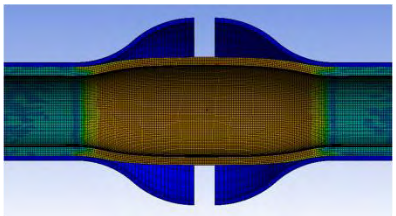
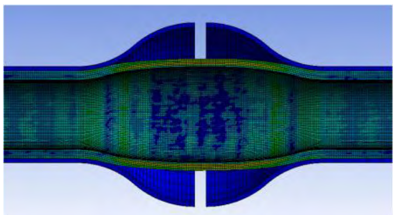
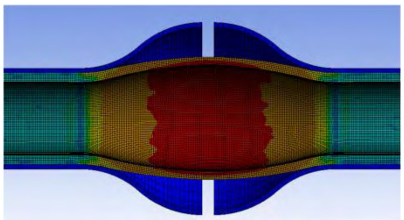
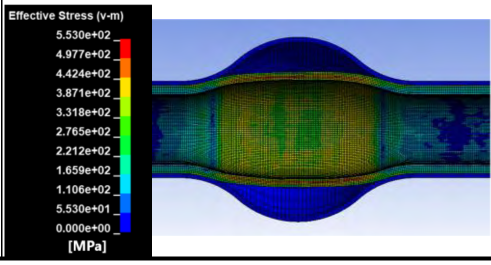
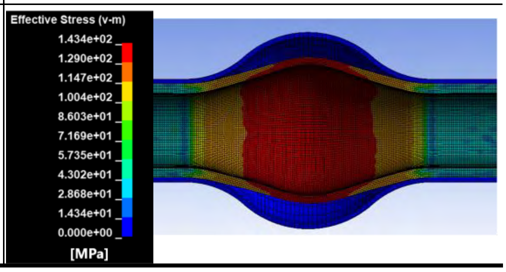
Fig.7 Die cabity

3 RESULTS AND DISCCUSIONS

3.1 Effect of temperature on the formbility

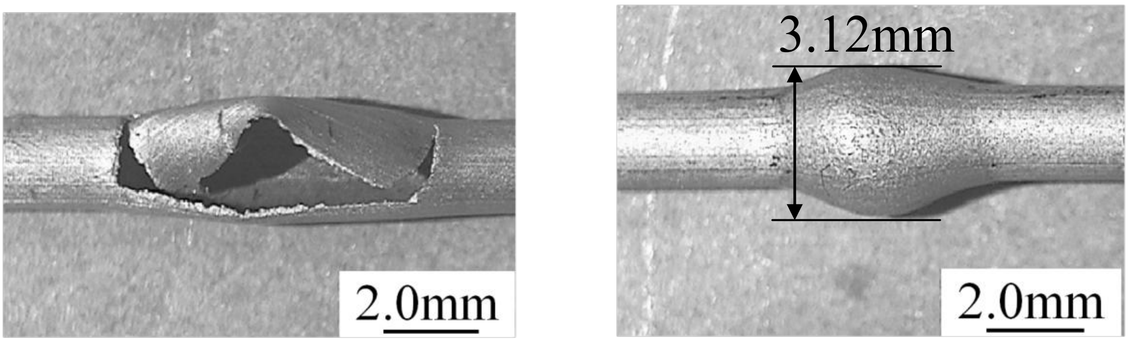
Table5 shows the effect of the temperature on the formability of ZM21 tube. The model was analyzed using material characteristics at RT and 250℃ as shown in Table4. The conditions of processing temperature were named CASE A and CASE B. The internal pressure p was set 80% against the bursting pressure p_B. In FE analysis, the internal pressure is set on p = 35MPa for CASE A and p = 16MPa for CASE B. In Table5, the von Mises stress was shown in FE models. CASE B has large expansion than CASE A because of high ductility in the warm area. The expansions were proceeded by an increase of axial displacement ΔL. The result of effective stress in CASE A means the fracture stress of the tube could be exceeded immediately after the start of axial feeding. A decrease of wall thickness was observed at the center of the expanded section at CASE B.

Table5 Effect of temperature on formability at FEM

	CASE A (RT)	CASE B (250℃)
0.0025s		
0.005s		
0.0075s		
0.01s		

The decrease of the wall thickness during the process is predicted that the thinning leads to failure of tube. It is necessary to avoid the thinning part by examining the internal pressure *p* in the loading path.

The experiments of warm THF were conducted for comparison with FE analysis results. ZM21 magnesium alloy tubes with an outer diameter of 2.0mm, a wall thickness of 0.2mm and length of 73mm were used for THF. The silicone oil was applied for loading the internal pressure. The surface between the dies and the tube was lubricated by MoS_2 paste. **Fig.8** shows the experiment results of ZM21tube deformed by THF at RT and 250℃. **Fig.8(a)** shows the material bursts immediately after start of the axial feeding at RT. In the experiment, shear mode fracture was observed in spite of no fracture in the FE analysis in Table5. The initiation of this shear type of fracture could not be predicted since the fracture criterion is not considered in the FE simulation [5]. **Fig.8(b)** the experiment result of deformation and expansion of the tube at 250℃. It was possible to deform objective shape with expansion on the loading path in Fig.5 as with FE simulation. The workpiece has not excellent surface quality which is caused by low work hardening in the warm area. In the experiment, the internal pressure *p* for available deformation of the tube is lower than the FE analysis. The cause of difference could be considered that the anisotropy of the material and the mesh size of FE model influence the internal pressure *p* for available deformation [3].



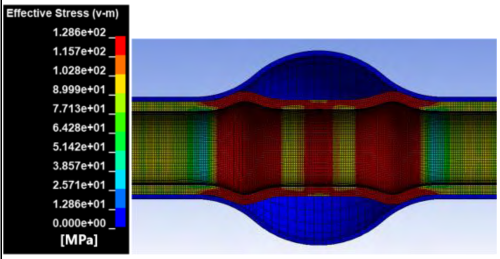
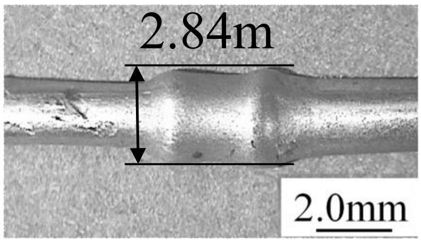
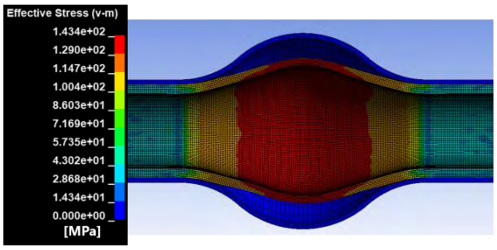
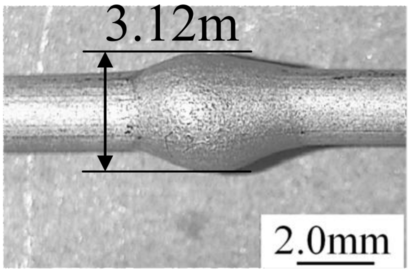
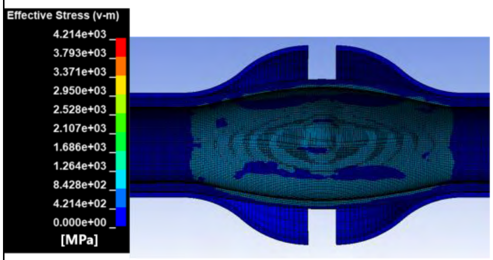
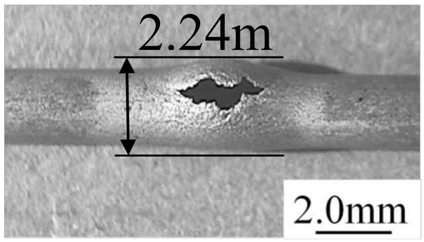
(a) Bursting of tube at RT (b) Expansion of tube at 250℃

Fig.8 Experimental results of ZM21 tube on warm THF (250˚C)

3.2 Influence of internal pressure on formability

The influence of different internal pressure *p* on formability was analyzed at 250℃ with the three internal pressure conditions of *p* = 70%, 80% and 90% against the bursting pressure p_B. Each condition was named CASE 1, CASE 2 and CASE 3. In FE analysis, the internal pressure is set on *p* = 14MPa for CASE 1, *p* = 16MPa for CASE 2 and *p* = 18MPa for CASE 3. **Table6** shows the analysis results and the experimental results of THF. The von Mises stress was shown in FE models. In CASE 1, wrinkles were appeared on the tube owing to not enough internal pressure for expansion of the tube and accumulating of material by axial feeding. The FE analysis was interrupted in CASE 3 because of the negative volume of elements in tube blank. High internal pressure leads to fracture at the thinning section of the wall thickness. As the experimental result of CASE 3, it was tended that tubes burst easily after the start of axial feeding. In experiments, high internal pressure in THF is affected by tube tolerances [8]. It could be difficult to deform stably. If the experiments of THF are conducted by using the loading path in Fig.5, it is considerate that the internal pressure p setting on 80% against the bursting pressure p_B is suitable for deforming stably.

Table6 Influence of internal pressure on formability at FE analysis and experiment

Condition	FE analysis	Experimental
CASE 1		
CASE 2		
CASE 3		

3.3 Examination for suppress of thinning

It was impossible that the tubes deform larger than ΔL = 1.0mm of axial displacement in the experiment of THF at 250℃. Fracture of material could be affected by the thickness reduction. **Fig.9** shows the measurement results of thickness strain of the tube at the result of FE analysis and experiment of CASE 2. As the result, the decrease of wall thickness was 30% against the original tube was observed at the experiment of THF. In the FE analysis result, the highest thickness strain of thinning was 25%. It is necessary to considerate the suppression of the thinning to expand the tube with high bulge height. Studies have been conducted to expand the tube in THF using a preform with the wrinkles and calibration of the prefom [9], [10]. In this study, the suppression of thinning was investigated with the loading path shown at **Fig.10**. In the loading pass (1) and (2) in Fig.10, the internal pressure p set on 50% against the bursting pressure p_B in order to accumulate the material such as the wrinkles on the tube. The tube is expanded by the straightening in pass (3).

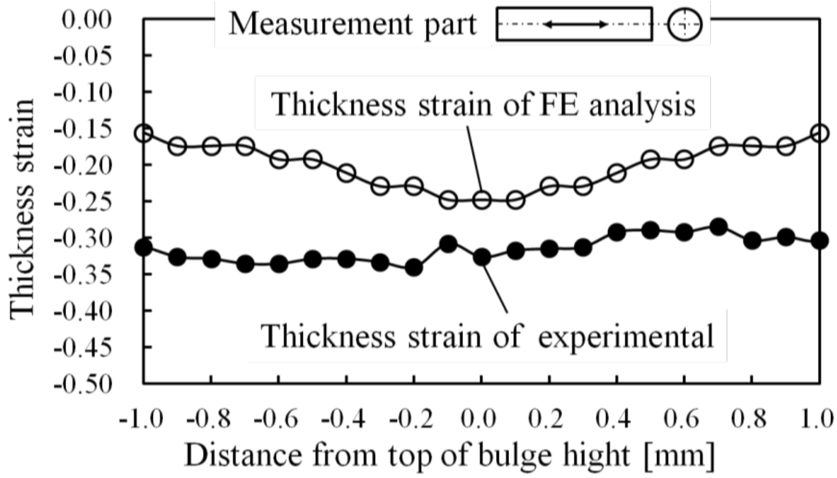


Fig.9 Thickness strain of FE analysis and experimental results with axial feeding amount 1.0mm

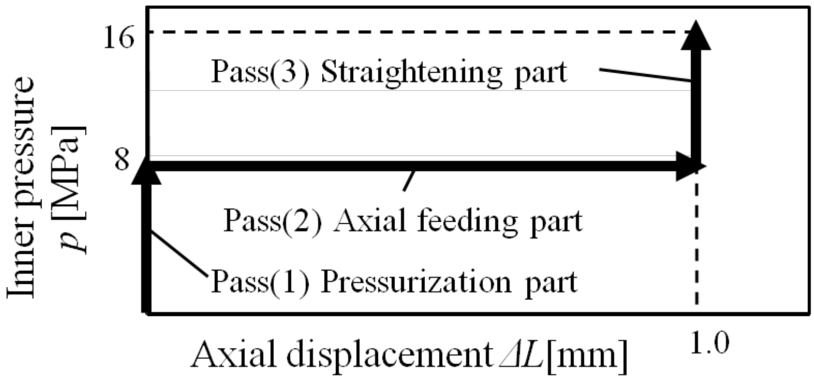
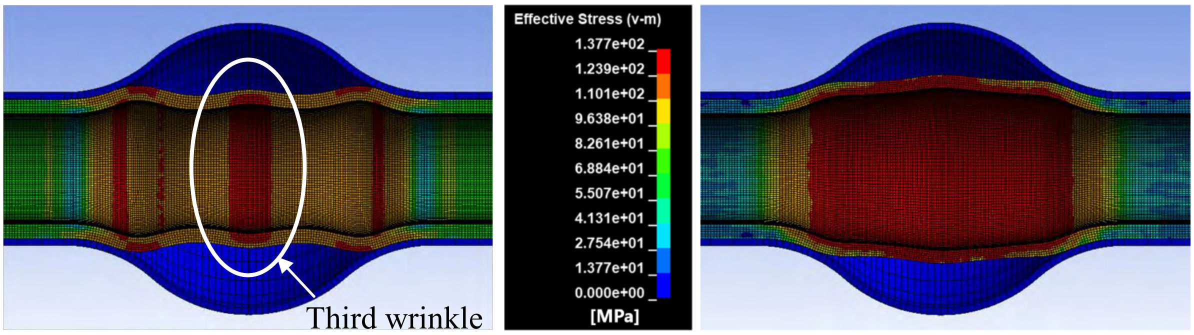


Fig.10 Loading path with straightening part



(a) Before the straightening (b) After the straightening

Fig.11 Wrinkle and straightening in FE analysis

Fig.11 shows the FE analysis result of THF using the straightening in the loading path. FE model of the tube was analyzed at 250℃. The effective stress was shown in FE models. **Fig.11(a)** shows the FE analysis result of the tube after completion of pass(2) at loading path in Fig.10. A third wrinkle on the tube shown in Fig.11(a) was occurred in the center of the tube blank by lower internal pressure *p* than CASE 1. **Fig.11(b)** shows the FE analysis result the deformation of the tube with the straightening part in loading path. Compared with the FE analysis results of CASE 2 in Table6, the tube at Fig.11(b) has a lower decrease for the wall thickness of the tube. The outer diameter after deformation was 2.80mm, and the highest thickness strain of thinning was 13% against the original tube. As the results, it could be considered that the tube is processed for the die cavity having a maximum expansion ratio of approximately 1.5 times against the original tube with suppressing the thinning of the wall thickness. Also, it was clarified that third wrinkle at center of the tube blank in the FE model was effectiveness preform for suppressing the thinning of wall thickness in THF of small diameter magnesium alloy tube.

4 CONCLUSION

FE analysis and experiment of THF were carried out for small diameter ZM21 magnesium alloy tube to clarify the influence of processing conditions on formability and investigate the deformation behavior of tube. Furthermore, the processing conditions available improve the formability of the tube were investigated. Results obtained in this study are summarized as follows.

(1) The behavior of thinning during the processing is revealed by FE analysis. It is necessary for the suppression of thinning of the wall thickness to avoid the fracture of the tube.
(2) In THF of small diameter magnesium alloy tube, the difference of the formability and the behavior of thinning are clarified by revise the loading path.
(3) The elucidations of influence of anisotropy of material and mesh size on the formability of FE model are required.

REFERENCES

[1] S. Yoshihara and T. Furushima. *J. Jpn. Soc. Technol. Plast*. (2016) **57**-670: 8-13.
[2] R. Yamamoto. *J. Jpn. Inst. Light Met*. (2008) **58**-11: 570-576.
[3] S. Mori, H. Satoh, K. Itai and K. Manabe. *J. Jpn. Soc. Technol. Plast*. (2017) **58**-672: 72-77.
[4] C. L. Cahn. *J. Minerals, Met. Mat. Society*. (2015) **67**-2: 450-458.
[5] K. Manabe, K. Fujita and K. Tada. *J. Chin. Soc. Mech. Eng*. (2010) **31**-4: 284-287.
[6] K. Manabe, T. Morishima, Y. Ogawa, K. Tada, T. Miura and H. Nakagawa. *Mater. Sci. Forum.* (2010) **654**-656: 739-742.
[7] B. J. Macdonald. *J. Jpn. Soc. Technol. Plast*. (2012) **53**-614: 176-179.
[8] A. Shirayori, T. Ando, M. Narazaki and M. Usui. *J. Jpn. Soc. Technol. Plast.* (2013) **54**-634: 42-46.
[9] G. Liu, Z. J. Tang, Z. B. He and S. J. Yuan. *Trans. Nonferrous Met. Soc. China.* (2010) **20**: 2071-2075.
[10] S. Yuan, X. Wang, G. Liu and Z. R. Wang. *J. Mater. Process. Technol.* (2007) **182**: 6-11.