ELSEVIER

Journal of Materials Processing Technology 170 (2005) 579–585

Journal of Materials Processing Technology

www.elsevier.com/locate/jmatprotec

Effect of blank holder force control in deep-drawing process of magnesium alloy sheet

Shoichiro Yoshihara [a,*], Ken-ichi Manabe [a], Hisashi Nishimura [b]

[a] *Department of Mechanical Engineering, Tokyo Metropolitan University, Japan*
[b] *Professor Emeritus, Tokyo Metropolitan University, Japan*

Received 18 February 2005; received in revised form 3 June 2005; accepted 3 June 2005

Abstract

A circular cup deep-drawing process was investigated using a magnesium alloy material, which is the lightest practical material for use in manufacturing structural components. An improvement in the limiting drawing ratio (LDR) at 300 °C was observed, by controlling a variable blank holder force (BHF) during the process, in comparison with the constant BHF conditions. The reason for the improvement of the LDR is that the magnesium alloy material has a low *F*-value, which was obtained from tensile tests when it was warmed to the elevated temperature. When the experimental conditions are not appropriate, such as when BHF is high, the experimentally drawn cup fractured at the wall part (β-rupture). The LDR of the magnesium alloy sheet was improved using the BHF control technique and verified using a finite element method (FEM) simulation. It is confirmed that the FEM simulations behaved in a similar manner to the experiments, with β-rupture being observed during the fracture at the wall part.

Keywords: Sheet metal forming; Deep-drawing; Blank holder force control; Magnesium alloy sheet; FEM simulation

1. Introduction

Magnesium alloy materials have been received much attention in automotive and electronic industries as the lightest weight structural and functional materials. The reason is that in particular, the specific density of magnesium alloy materials, which is approximately two-third that of aluminum alloy materials, has a lower environmental effect when used in casting and die-casting processes [1]. Forging is a typical bulk forming process to which mg alloys have been applied, however, sheet metal forming of these alloys has received little attention. Sheet forming is expected to be effective as an environmentally conscious processing technology for magnesium alloys. Deep-drawing is an important and popular sheet metal forming process and, to date, conventional deep-drawing processing of magnesium alloys has been studied by some researchers. Most researchers, however, have not realized the advantages in several specialized deep-drawing techniques.

The variable blank holding force (BHF) technique for controlling deep-drawing processes has been studied, and two types of variable BHF control systems were previously developed by the authors. The first is the fuzzy adaptive BHF control system for a circular cup deep-drawing system [2]. This BHF control system is considerably flexible, and is independent of not only blank materials, blank size and lubricants but also variation in lubrication conditions during the process. Furthermore, it is possible to improve the deep-drawing performance, with adaptive BHF control, from 2.09 to 2.14 in the case of aluminum alloy material and from 2.25 to 2.27 in the case of the steel sheet. Moreover, these results were confirmed using a plastic deformation model of the deep-drawing operation assuming a blank material with strain hardening characteristics. The low *F*-value is predicted to have a great effect on the improvement of the limiting drawing ratio (LDR) when using variable BHF control [2]. For the magnesium alloy sheet, this improvement of the LDR

* Corresponding author.
E-mail addresses: yoshihas@comp.metro-u.ac.jp (S. Yoshihara), manabe@comp.metro-u.ac.jp (K. Manabe), hinishi@herb.ocn.ne.jp (H. Nishimura).

0924-0136/$ – see front matter © 2005 Elsevier B.V. All rights reserved.
doi:10.1016/j.jmatprotec.2005.06.028

Nomenclature

BHF	blank holder force
DR	drawing ratio
F	strength coefficient
LDR	limiting drawing ratio
n	strain hardening exponent
R_0	initial radius of circular sheet blank
R_d	die hole radius
R_p	punch radius
r_0	current radius of circular sheet blank
r_d	die shoulder radius
r_p	die shoulder radius
S	punch stroke
T	blank holder displacement
t_0	initial thickness
α	die contact angle

is thought to be due to the fact that the F-value is low at the high forming temperature (300 °C) [3], however, the effect of variable BHF control on the LDR has not been verified for magnesium alloy sheets.

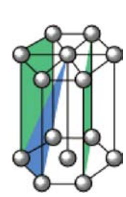
The objective of this study is to clarify the formability of deep-drawing of magnesium alloy sheet at elevated temperature, or, in other words, to estimate the LDR using variable BHF control and to understand the fracture mechanism of magnesium alloy sheet using FEM simulation.

2. Experimental and FE simulation works

2.1. Experimental conditions

Magnesium alloys sheets (AZ31-O) of 0.5 mm thickness were employed in the experiment. The chemical composition and the crystal structure of AZ31-O are given in Table 1. The crystal structure is the hexagonal close packed lattice (HCP). Fig. 1 shows the schematic of the deep-drawing apparatus. The dimensions of the die and punch are shown in Table 2. Graphite was applied to the blank as a lubricant.

Table 1
Chemical composition and crystal structure of magnesium alloy sheet (AZ31-O)

Chemical composition		HCP
Al	1.9	
Zn	1.1	
Zr	–	
Mn	0.5	
Fe	–	
Si	1.0	
Cu	0.1	
Ni	0.03	
Ca	–	

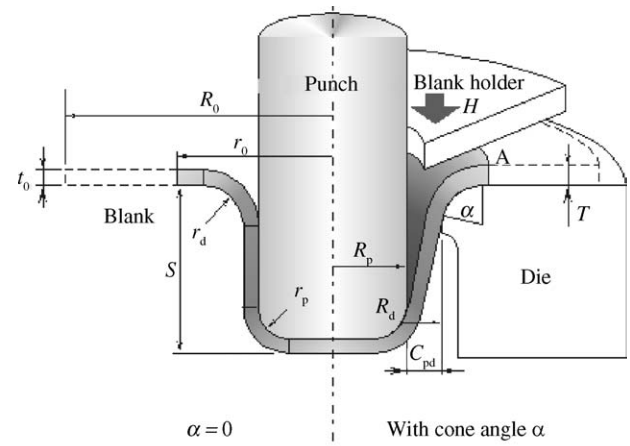


Fig. 1. Experimental apparatus of deep-drawing.

Table 2
Dimensions of punch and die used in experiment and FEM simulation

Punch shoulder radius, r_p (mm)	4
Punch diameter, D_p (mm)	33
Die shoulder radius, r_d (mm)	3
Die diameter, D_d (mm)	36.5

2.2. FEM model

The explicit finite element code LS-DYNA is used to simulate the deep-drawing process in this study. Fig. 2 indicates the FEM simulation model of the deep-drawing process. A Belytschko–Tsay thin shell element was used for the blank and the tool components were treated as rigid bodies. Only one-quarter of the blank and the tool components were simulated owing to symmetry. The blank of 69.3 mm in diameter (drawing ratio (DR) = 2.1) and 0.5 mm thickness was modeled with 2038 shell elements, and the tool components, and the tool components with a total of 2738 shell elements. The blank material was assumed to be an isotropic elasto-plastic material obeying n-power law $\sigma = F\varepsilon^n$, where n is

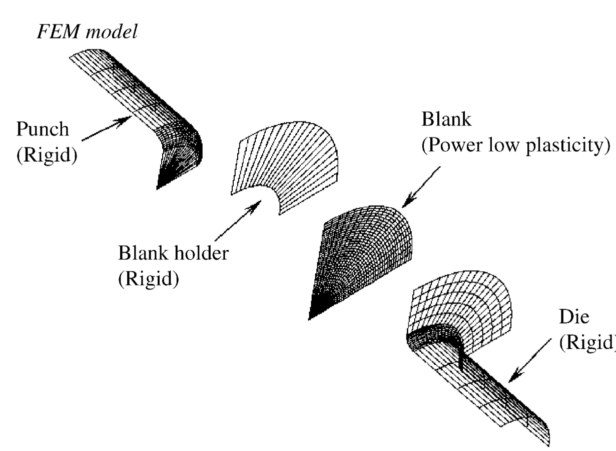


Fig. 2. FEM simulation model of deep-drawing.

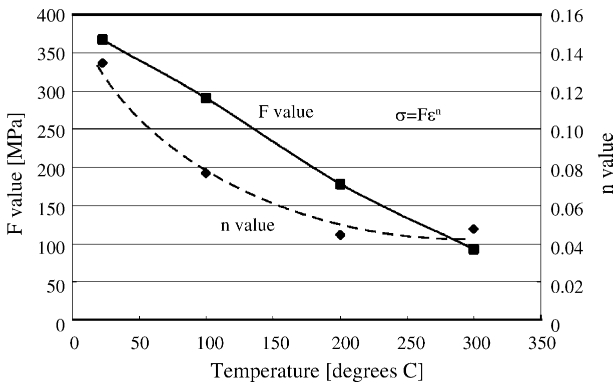


Fig. 3. Effect of temperature on material properties.

the strain hardening exponent and ε is the equivalent plastic strain. The material properties of the blank at 300 °C used in the simulation as follows: $\rho = 1.8 \times 10^3$ kg/m^3, $E = 45 \times 10^3$ MPa, $F = 90$ MPa, $n = 0.05$ and $r = 1.0$. Friction was modeled between the blank and the tool interfaces by using the Coulomb assumption ($\mu = 0.05$). Symmetrical boundary conditions were specified on the appropriate edges of the blank.

3. Results and discussion

3.1. Tensile test

The constitutive equation of the blank material is given by $\sigma = F\varepsilon^n$. Fig. 3 indicates the material properties of the blank obtained from the tensile test under various temperatures. F- and n-values decrease with increasing temperature. F-value decreases remarkably form 400 to 100 MPa and n-value approximately from 0.15 to 0.05.

3.2. Deep-drawing test

Fig. 4 shows the limit drawing ratio in the constant BHF tests at 300 °C. A cross-mark (×) means the fracture, a triangle indicates a wrinkle and circle indicates success. The LDR in the constant BHF (BHF$_{const}$) test is 2.09.

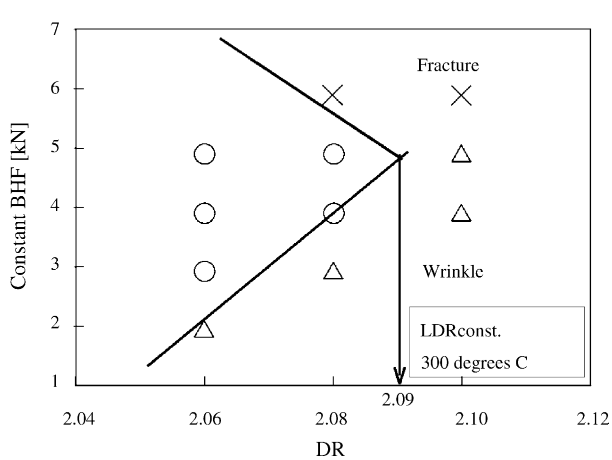


Fig. 4. LDR in constant BHF tests of magnesium alloy sheet.

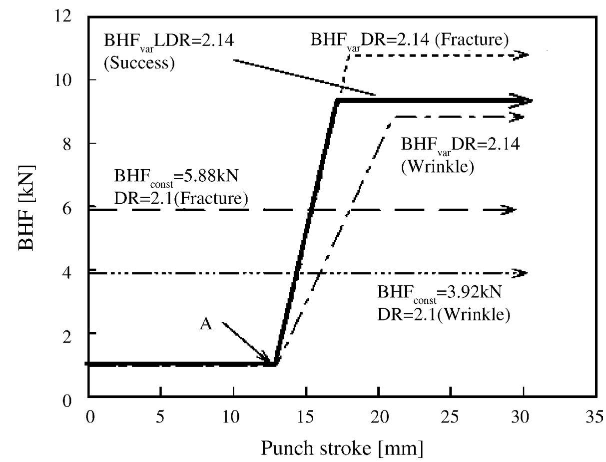


Fig. 5. Constant and variable BHF paths in experiments.

Fig. 5 shows the types of the variable BHF (BHF$_{var}$) patterns and the constant BHF patterns. The punch stroke where the BHF increased was decided experimentally to be a position of the maximum punch load in the constant BHF test. In the variable BHF test, the case of the high BHF resulted in fracture. On the contrary, low BHF resulted in wrinkle formation. When the BHF increases to 9 kN during the middle stage of the process it was found that a favorable product was produced. The LDR on the variable BHF test was 2.14.

The punch load curves of the constant BHF (BHF$_{const}$ = 5.88, 3.92 kN, DR = 2.1) and the variable BHF (DR = 2.14) tests are shown in Fig. 6. In the case of the constant BHF, the punch load is higher than the variable BHF test and the fracture at the straight wall part of the drawn cup occurred at 15 mm of the punch stroke. Whereas, in the variable BHF, the BHF remains low at the initial stage and increases from the middle stage to the last stage.

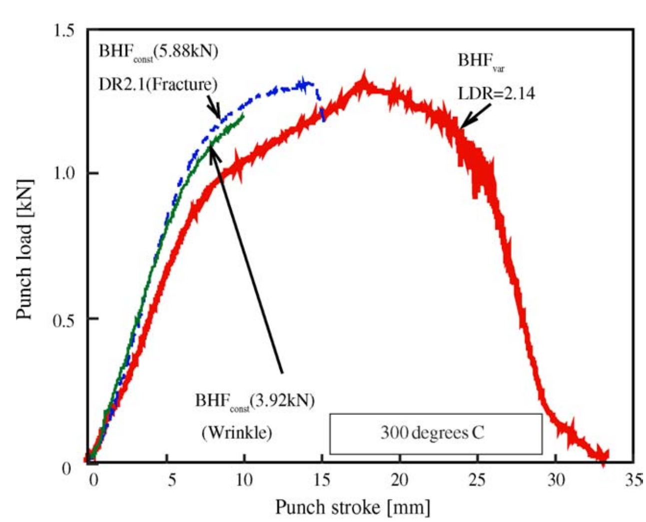


Fig. 6. Relationship between punch load and punch stroke.

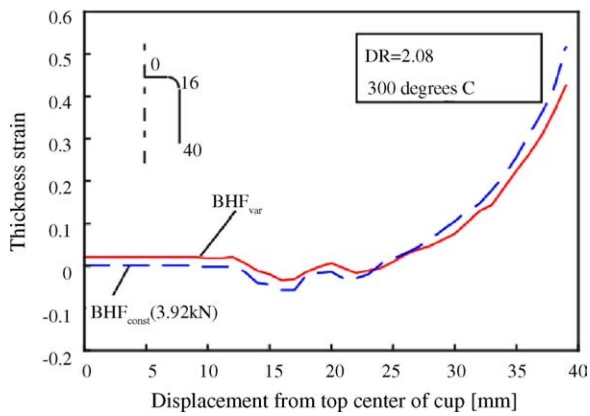


Fig. 7. Comparison of wall thickness distribution between constant and variable BHF.

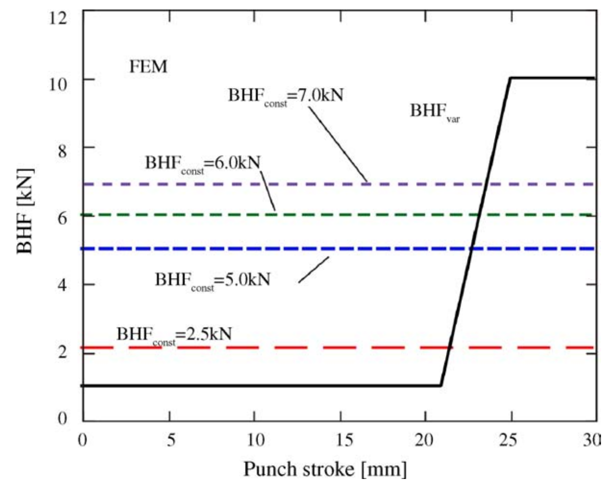


Fig. 9. BHF paths in FEM simulation.

A drawn cup without any fractures and wrinkles in the case of the variable BHF condition was obtained after the deep-drawing test. This result implies that the LDR in the variable BHF is greater than that in the constant BHF test. The LDR improved from 2.09 to 2.14 by the variable BHF condition since the low *F*-value of the magnesium alloy sheet at elevated temperature has a great effect on LDR when using the variable BHF method as with the aluminum alloy material at room temperature.

Fig. 7 shows a comparison of the wall thickness distribution of the drawn cups between the variable BHF test (DR = 2.08) and the constant BHF test (BHF_{const} = 3.92 kN, DR = 2.08). In the case of the constant BHF test, thinning takes place from the punch shoulder part to the wall part and thickening at the end site of the drawn cup. On the other hand, in the case of the variable BHF, thinning and thickening of the drawn cup is suppressed. The variable BHF has a significant effect to realize uniformity of the drawn cup. Contrarily, thinning occurred at the punch shoulder part and the wall part of the drawn cup.

Fig. 8 shows a photograph of the drawn cups from the constant BHF test (BHF_{const} = 3.92 kN, DR = 2.08) and the variable BHF test (DR = 2.14) and the drawn cup with fracture from the constant BHF test (BHF_{const} = 5.88 kN, DR = 2.1). In the case of the constant BHF test (DR = 2.1), fracture at the wall part of the drawn cup has occurred, which is not like a steel or aluminum alloy sheet and due to a sufficient strength (α-rupture) but is due to the low ductility (β-rupture) of the material. β-Rupture is defined during sheet metal forming as a fracture by a lack of own ductility under tensile stress state [4]. This phenomenon could be expected from the result of the wall thickness distribution as shown in Fig. 6. This confirms that the variable BHF technique affected not only α-rupture but also β-rupture in the deep-drawing process.

3.3. FEM simulation

In order to verify the experimental results from various angles, FEM simulation in the warm deep-drawing has been done using the general activity simulation code, DYNA-3D. Fig. 9 indicates the constant BHF and the variable BHF patterns. The punch load–punch stroke curves are shown in Fig. 10. The material properties, which are obtained from the tensile test experimentally at 300 °C, was used for looking into the warm deep-drawing simulation. In the case of

(a) Constant BHF = 3.92 kN (DR = 2.08) and variable BHF (DR = 2.14)

(b) Constant BHF = 5.88 kN (DR = 2.1)

Fig. 8. Photograph of drawn cups (300 °C).

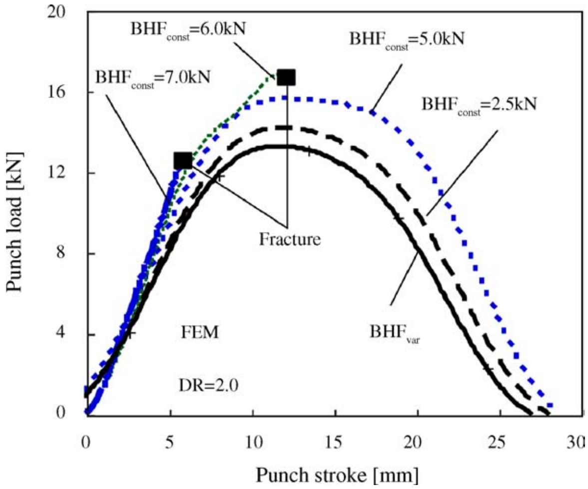


Fig. 10. Relationship between punch load and punch stroke in FEM simulation (material properties of blank at 300 °C in FEM).

the constant BHF, $BHF_{const} = 2.5$, 5.0 kN and the variable BHF test were successful. However, the punch load curves of the constant BHF, $BHF_{const} = 6.0$, 7.0 kN are higher than the lower BHF conditions, and fracture at the wall part has occurred.

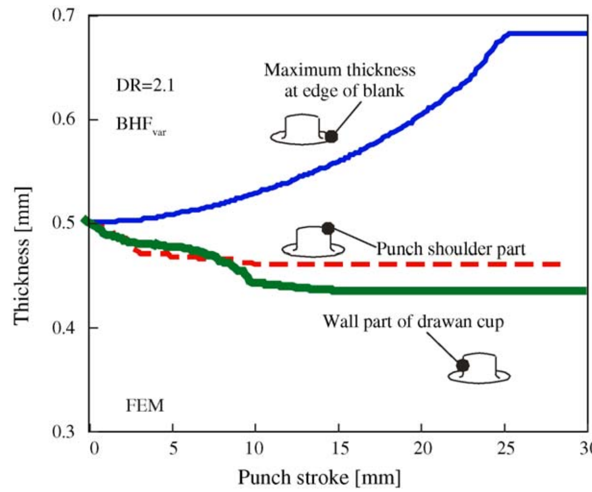


Fig. 13. Transformation of wall thickness in FEM simulation (material properties of blank at 300 °C in FEM).

Fig. 11 shows the results of a FE simulation. In the case of $BHF_{const} = 1.0$ kN, the minimum wall thickness has not increased in comparison with the $BHF_{const} = 5.0$ kN. Moreover, the wall thickness in the variable BHF is slightly increased at the end of the drawn cup. However, the wall

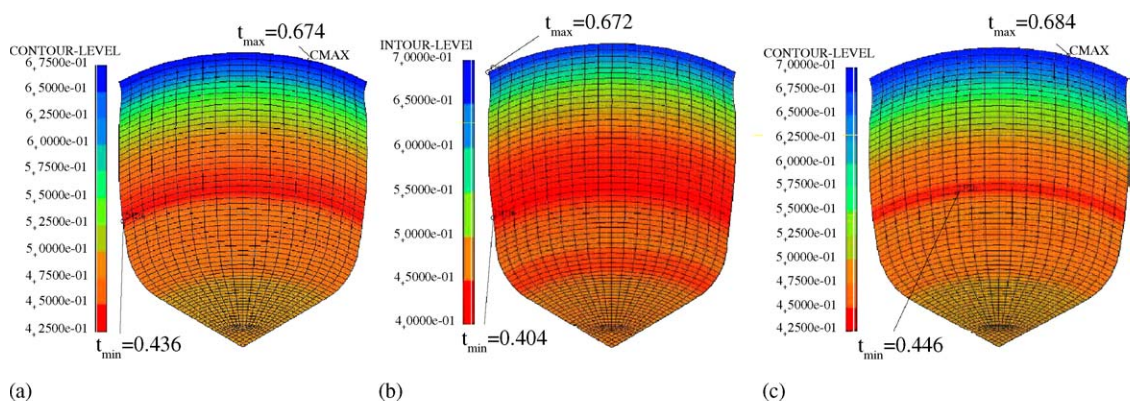


Fig. 11. Maximum and minimum thickness of drawn cup in FEM simulation (DR = 2.1, $\mu = 0.05$, material properties of blank at 300 °C in FEM): (a) $BHF_{const} = 1.0$ kN; (b) $BHF_{const} = 5.0$ kN; (c) $BHF_{variable}$.

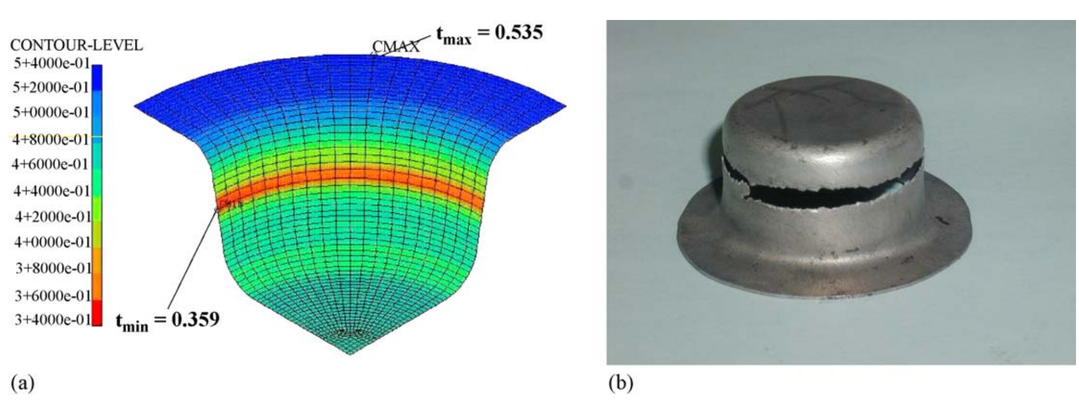


Fig. 12. Comparison between FEM simulation and experimental results (material properties of blank at 300 °C in FEM): (a) FEM simulation ($BHF_{const} = 6.0$ kN, DR = 2.1, $\mu = 0.05$); (b) experiment ($BHF_{const} = 5.88$ kN, DR = 2.1, 300 °C).

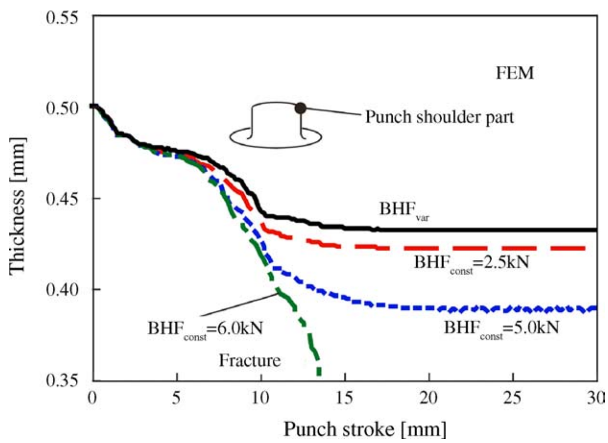


Fig. 14. Comparison of wall thickness distribution of drawn cup between constant BHF and variable BHF tests (material properties of blank at 300 °C in FEM).

thickness at the punch shoulder part is suppressed in comparison with the constant BHF conditions. On the other hand, the experimental results ($BHF_{const} = 5.88$ kN) and FE simulation results from Fig. 12 agree on fracture location, at the wall part of the drawn cup. As mentioned above, fracture of magnesium alloy material in deep-drawing is generally β-rupture and this result was confirmed by the FEM simulations.

Fig. 13 shows the transformation of the wall thickness at the punch shoulder part, the wall part and the end of the blank in the case of the variable BHF test. The thickness at the end of the blank was increased as the deep-drawing process progressed. On the contrary, the thickness at the punch shoulder part and wall part was decreasing. In particular, the thickness at the wall part is less than one at the punch shoulder part after punch stroke $S = 10$ mm. Furthermore, the transformation curves of the wall thickness at the punch shoulder part and the wall part were maintained after punch stroke $S = 10$ mm.

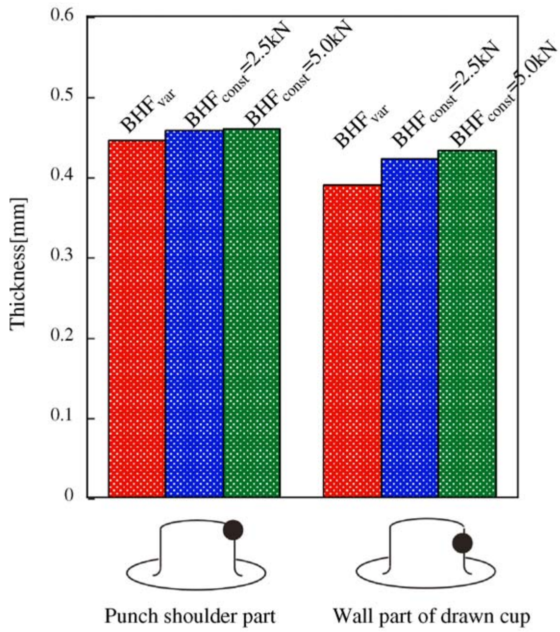


Fig. 15. Comparison of wall thickness on constant BHF and variable BHF at punch shoulder part and wall part (material properties of blank at 300 °C in FEM).

Fig. 14 shows the wall thickness at the wall part on the constant BHF and the variable BHF conditions. In the high BHF condition ($BHF_{const} = 6.0$ kN), the wall thickness is thinning at the initial stage. However, as the BHF is decreased, wall thickness is again increasing. Moreover, it was observed that wall thickness of the drawn cup depends upon the initial BHF value.

Fig. 15 shows the comparison of the wall thickness of the drawn cup on the constant BHF and variable BHF conditions. The wall thickness at the punch shoulder part was not influenced by the initial BHF conditions. However, the wall thickness at the wall part of the drawn cup was extremely dependant upon the initial BHF conditions.

4. Conclusions

(1) The LDR of the magnesium alloy sheet at 300 °C improved from 2.09 to 2.14 using the variable BHF technique since the low *F*-value of this material at the elevated temperature has a great effect on improvement of the LDR.
(2) In the warm deep-drawing of the magnesium alloy sheet, fracture occurs at the wall part of the drawn cup (β-rupture) because of the low ductility of the material.
(3) The β-rupture can be also simulated in the FEM results. Furthermore, it was confirmed that the thinning of the wall thickness at the punch shoulder part and the wall of the drawn cup depended on the initial BHF conditions.

Acknowledgements

The authors wish to thank Mr. H. Atarashi who carried out much of the experimental work. They also thank the Showa Shinku Corporation and Osaka Fuji Co., for supplying the experimental materials and Dr. B. Mac Donald of Dublin City University, Ireland, for his assistance in editing the manuscript. This work was partly supported by the Light Metal Education Foundation, Incorporated in Japan.

References

[1] T. Sano, S. Sado, T. Saiki, S. Fuchizawa, S. Horikoshi, Improvement of magnesium alloy processing for reduction of environmental impacts using life cycle assessment, in: Proceedings of the Interna-

tional Workshop on Environmental and Economic Issues in Metal Processing (ICEM-98), 1998, p. 57.

[2] S. Yoshihara, K. Manabe, M. Yang, H. Nishimura, Fuzzy Adaptive Control of Blank Holder Force in Circular Cup Deep Drawing (Forming Limit and Influencing Factors), Trans. JSME, Ser. C ,626-64 (1998), p. 39 4039 (in Japanese).

[3] S. Yoshihara, N. Kubota, K. Manabe, H. Nishimura, Effect of variable blank holder force control in circular cup deep drawing of magnesium alloy sheet, in: Proceedings of the 50th Japanese Joint Conference for the Technology of Plasticity, 1999, p. 189 (in Japanese).

[4] S. Yoshida, J. Jpn. Soc. Technol. Plast. 2–10 (1961) 657 (in Japanese).