Effects of forming conditions on limit of drawing ratio during cold drawing and ironing process of Ti-6Al-4V alloy sheets

OKUDE Yusuke[1,a *], IWAOKA Taku[1,b], NAKAMURA Isao[1,c], MURAOKA Tsuyoshi[1,d] and KATAGIRI Takashi[1,e]

[1]Tokyo Metropolitan Industrial Technology Research Institute, 2-4-10, Aomi, Koto-ku, Tokyo, Japan

[a]okude.yusuke@iri-tokyo.jp, [b]iwaoka.taku@iri-tokyo.jp, [c]nakamura.isao@iri-tokyo.jp, [d]muraoka.tsuyoshi@iri-tokyo.jp, [e]katagiri.takashi@iri-tokyo.jp

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Abstract. The low ductility of Ti–6Al–4V alloy at forming temperatures below 780°C is still a problem. Ti–6Al–4V is usually hot press formed at 780 to 900°C. A hot press formed Ti–6Al–4V alloy has been utilized in various devices such as medical and aerospace equipment. However, hot press forming increases cost, especially because it uses a furnace. To reduce cost, hot stamping by electric heating has been applied to titanium sheets or continuous resistance heating has been applied to the bar forming of Ti–6Al–4V alloy. Both electric heating and continuous resistance heating reduce the heating time in the forming temperature range from 780 to 900°C. Hence, it is necessary to develop a new press forming for Ti–6Al–4V alloy sheets at forming temperatures below 780°C to improve productivity. We have developed a method to achieve of cold press forming of Ti–6Al–4V alloy sheets by combining press motion control and clearance between a die and a blank. In this study, we tried to form various forming conditions for developed press forming method. In this method, the following two processes were separated: punch motion process without BHF and BHF motion process without punch motion. These two processes were carried out alternately during deep drawing or drawing and ironing. Three forming parameters, namely, the punch speed S_{pi}, punch stroke P_{si}, and blank holding force BHF_i, were controlled separately and the effect of forming conditions on deformation behavior was investigated by using experiment and finite element analysis(FEA). As a result, the effects of forming conditions on limit of drawing ratio of Ti–6Al–4V alloy sheets were investigated.

Introduction

Ti-6Al-4V titanium alloy has been actively used in medical equipment and aero-space due to its characteristics of light weight, corrosion resistance, and high specific strength [1–3]. A hot press formed Ti–6Al–4V alloy has been utilized in various devices such as medical and aerospace equipment [4]. However, hot press forming increases cost, especially because it uses a furnace. To reduce cost, hot stamping by electric heating has been applied to Ti sheets or continuous resistance heating has been applied to the bar forming of Ti–6Al–4V alloy. Both electric heating and continuous resistance heating reduce the heating time in the forming temperature range from 780 to 900°C [5,6]. Hence, it is necessary to develop a new press forming for Ti–6Al–4V alloy sheets at forming temperatures below 780°C to improve productivity.

We developed a method to achieve of warm and cold press forming of Ti–6Al–4V alloy sheets by combining press motion control and clearance between a die and a blank [7,8]. In this study, we tried tube forming by developed press forming method. In this method, the following two processes were separated: punch motion process without BHF and BHF motion process without punch motion. These two processes were carried out alternately during deep drawing or drawing and ironing. Three forming parameters, namely, the punch speed S_{pi}, punch stroke P_{si}, and blank holding force BHF_i, were controlled separately and the effect of forming conditions on deformation behavior was investigated by using experiment and finite element analysis(FEA). As a result, the LDR of Ti–6Al–4V alloy sheets in drawing and ironing was investigated by applying the developed incremental press forming method.

Experimental apparatus and formability of Ti-6Al-4V alloy sheet at warm temperature of deep drawing test

In order to understand the basic formability of cylindrical deep drawing of Ti-6Al-4V alloy sheet, cylindrical deep drawing with a general blank holding force (BHF) was first performed. Fig. 1 shows a schematic of deep drawing process, and Table 1 the dimensions of the dies of deep drawing process. The die material used was SKH51. Ti-6Al-4V alloy sheet and a blank with thickness of t_0 = 0.5mm were used as test materials. The test was performed with a blank diameter of ϕ 60 mm (Drawing ratio, DR = 1.85). Cylindrical deep drawing was carried out at the condition of 300°C forming temperature. Test was performed at the same temperature as the blank for the drawing die and the wrinkle control plate. The punch was kept at room temperature under all conditions. The punch speed S_p was set to three conditions of 9, 90 and 900 mm/min, and the constant wrinkle suppressing force BHF_{const} was applied at 4 kN. Fig. 2 shows the punch load－punch stroke curve and photographs of cups drawn under each set of conditions. In the each condition, fracture occurred at punch shoulder. Therefore, the low formability of Ti-6Al-4V alloy sheet was confirmed.

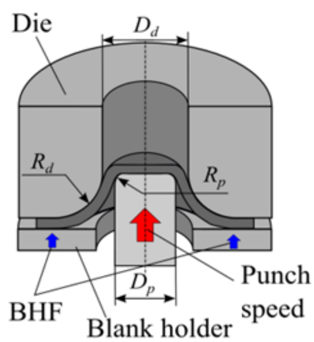
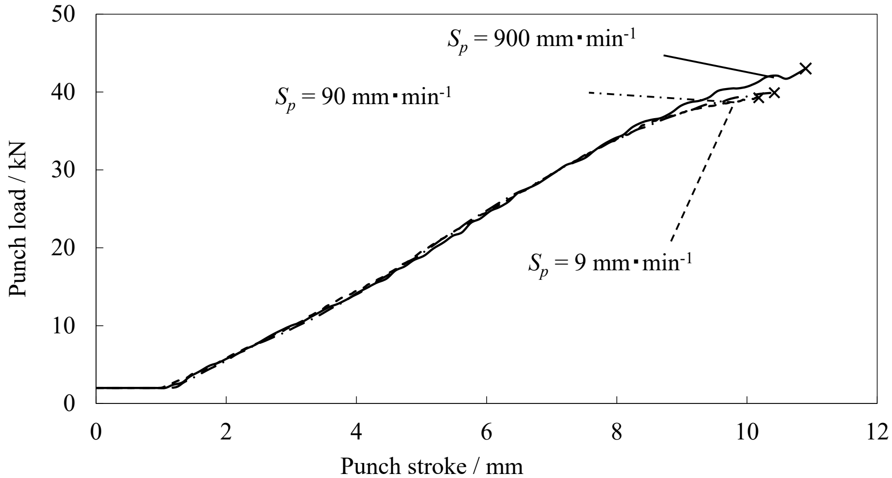


Fig. 1. Schematic of deep drawing process .

Table 1. Dimension of dies of deep drawing process.

Die	Diameter : D_d [mm]	35.0, 33.8, 31.6
	Shoulder radius : R_d [mm]	3.0
Punch	Diameter : D_p [mm]	32.5, 33.0, 30.8
	Shoulder radius : R_p [mm]	5.0



(a) Punch load－punch stroke curve

Conditions	Punch speed S_p [mm/min]		
	9	90	900
Photo. of drawn cups	 Occurrence of fracture at punch shoulder	 Occurrence of fracture at punch shoulder	 Occurrence of fracture at punch shoulder

(b) Photographs of cups drawn under each set of conditions

Fig. 2. Effects of punch speed on deformation behaviour of Ti-6Al-4V alloy sheet at 300°C.

Incremental press forming process method and formability of Ti-6Al-4V alloy sheet

In cylindrical deep drawing with a constant blank holding force, cracks occurred at the punch shoulder at any punching speed at a forming temperature of 300°C. In this study, we focused on the fact that wall thinning progressed due to tension due to wrinkle suppressing force from the start of the punch until the maximum punch load was reached during press forming. When the material is pressed into the mold with a punch under the condition of applying wrinkle suppressing force, the thickness of the punch shoulder is significantly reduced. Therefore, in order to perform press forming in the sequential forming developed in this study, two processes were separated: a punch motion process and BHF without punch motion wrinkle force loading process. Fig.3 shows the schematic of incremental press forming.

To confirm the effect of developed incremental press forming on deformation behavior, the warm and cold drawing and ironing of Ti-6Al-4V alloy sheet were carried out. In the incremental press forming, warm and cold drawing and ironing experiment was performed under the conditions of S_{pi} =90 mm/min, P_{si} =0.4 mm, and BHF_i =20 kN. The forming temperature 300°C and room temperature was utilized. Die dimensions D_d = 33.8 mm and D_p = 33.0 mm were selected for drawing and ironing. For lubrication, the surface oxide film of Ti-6Al-4V alloy was focused on. Ti-6Al-4V alloy sheet was treated with atmospheric oxide film at the conditions of 500°C for 2 hours before experiment. And for comparison, a cylindrical drawing was performed under the same lubricating conditions with a punch speed of 90 mm/min and blank holding force of 4 kN. Fig. 4 shows the effect of incremental press forming on formability of Ti-6Al-4V alloy sheet in warm drawing and ironing, and Fig. 5 the effect of incremental press forming on formability of Ti-6Al-4V alloy sheet in cold drawing and ironing. By the application incremental press forming method, the warm and cold drawing and ironing of Ti-6Al-4V alloy sheets was achieved.

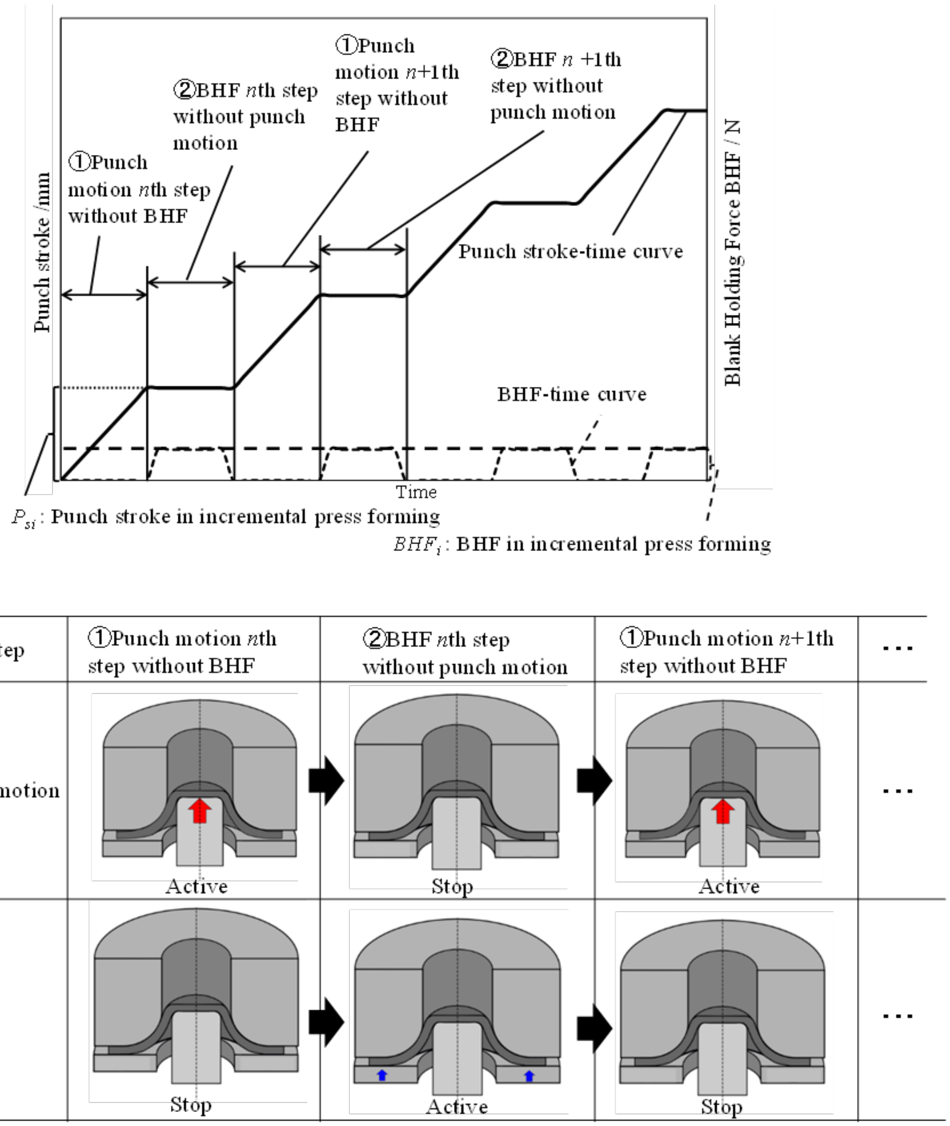
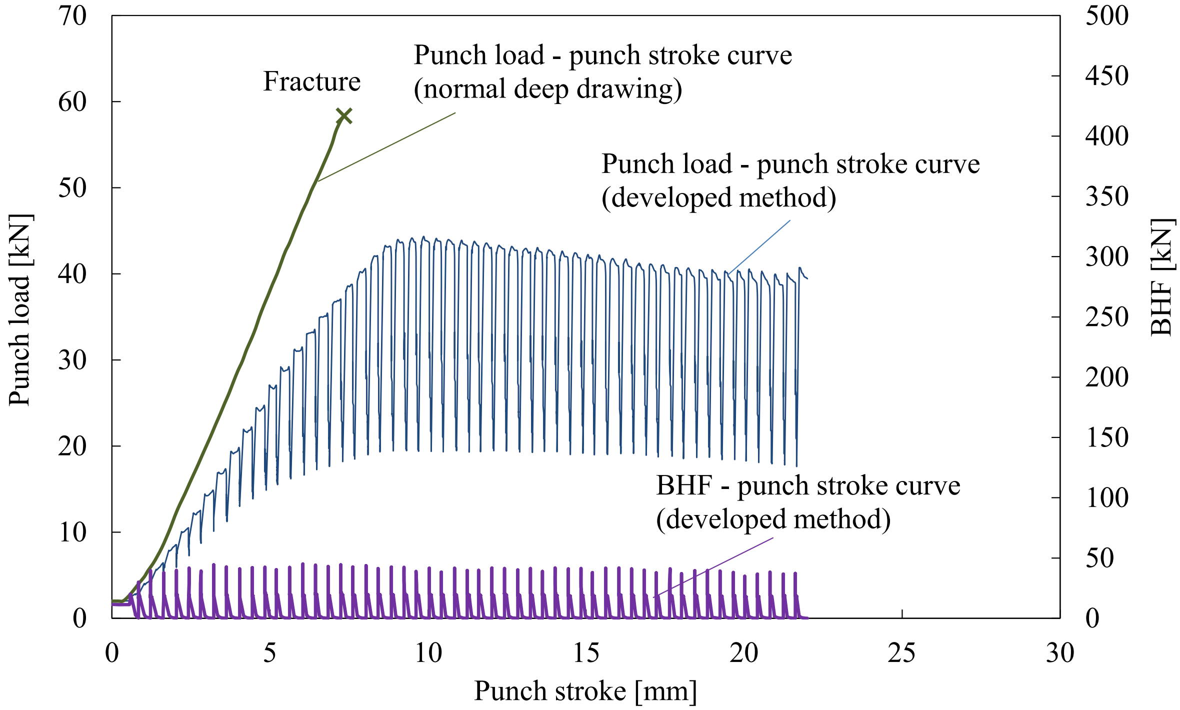


Fig. 3. Schematic of incremental press forming.

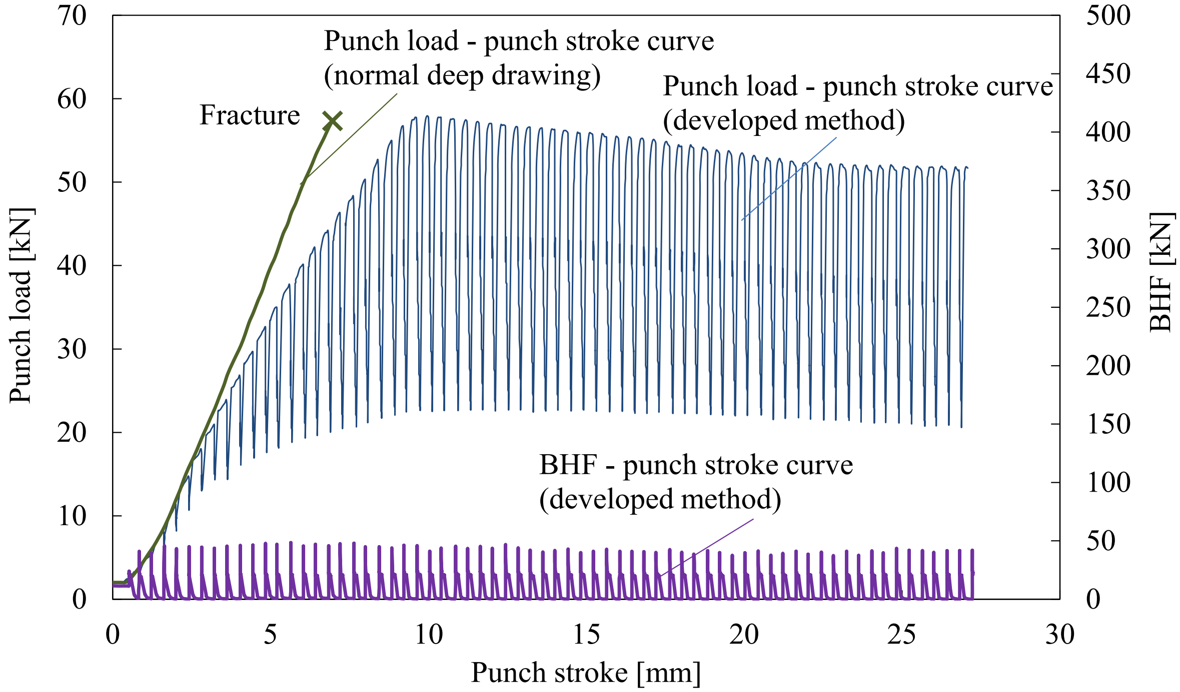


(a) Punch load－punch stroke curve

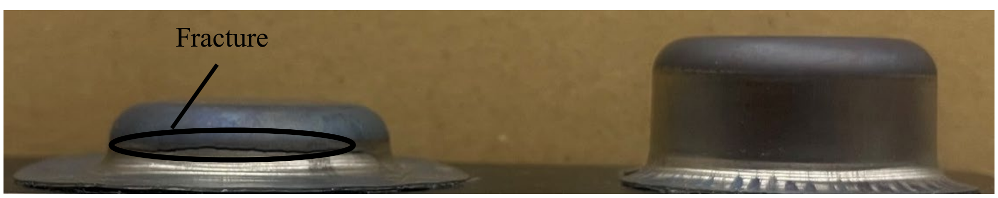
Normal deep drawing Incremental press forming

(b) Photographs of cups drawn under each set of conditions

Fig. 4. Effect of incremental press forming on deformation behavior at 300°C.



(a) Punch load－punch stroke curve



Normal deep drawing Incremental press forming

(b) Photographs of cups drawn under each set of conditions

Fig. 5. Effect of incremental press forming on deformation behavior at room temperature.

Drawing and ironing by incremental press forming and formability of Ti–6Al–4V alloy sheets to clarify the effect of the incremental press forming, FEA of drawing and ironing of Ti–6Al–4V alloy sheets was calculated. The finite element analysis code LS-DYNA3D was used for drawing and ironing simulation. Representative finite element models of workpieces (Ti–6Al–4V,t_0 = 0.5 mm, blank diameter = ϕ 60 mm) were constructed. Table 2 indicates the properties of the sheet materials of Ti–6Al–4V alloy sheets (room temperature). An elastoplastic material was assumed, satisfying an n power strain hardening law with the constitutive equation as follows,

$$\sigma = C(\varepsilon_n + \overline{\varepsilon_p})^n . \tag{1}$$

where, C is plastic modulus, ε_n elastic strain, $\overline{\varepsilon_p}$ equivalent plastic strain, n work hardening exponential.

Fig. 6 shows the schematic and FEA model of deep drawing process and Table 3 the dimensions of dies. In FEA, the friction coefficients between dies and blank are set to 0.1 without lublication(punch and blank, blank holder and blank), and 0.05 with lubrication (die and blank). In the incremental forming, press forming was performed under the conditions of P_{si} = 0.4 mm, and BHF_i = 20 kN.

Fig.7 shows results of drawing and ironing process of Ti–6Al–4V alloy sheets (shear strain distribution, P_{si} = 0.4 mm, BHF_i = 20kN). At the point I, the workpiece was formed for the bottom of drawn cup by drawing process only. Hence, the punch load gradually increased until starting the drawing and ironing (point II). When the starting point of drawing and ironing is reached, the punch load increased sharply. And shear strain caused by ironing process occurred at the thickness of workpiece near the die radius end. Then, shear strain increased with the progress of ironing process as shown in Fig. 7 (point III). As the results, the drawing and ironing process was calculated by FEA, and ironing due to shear strain could be estimated by simulation as shown in Fig. 8 [8].

Table 2. Material property of blank at room temperature.

Material	Ti–6Al–4V
Density, ρ [kg/mm^3]	4.61×10^3
Modulus of elasticity E [GPa]	106.3
Poisson's ratio	0.3
C value [MPa] *	1724
n value*	0.19

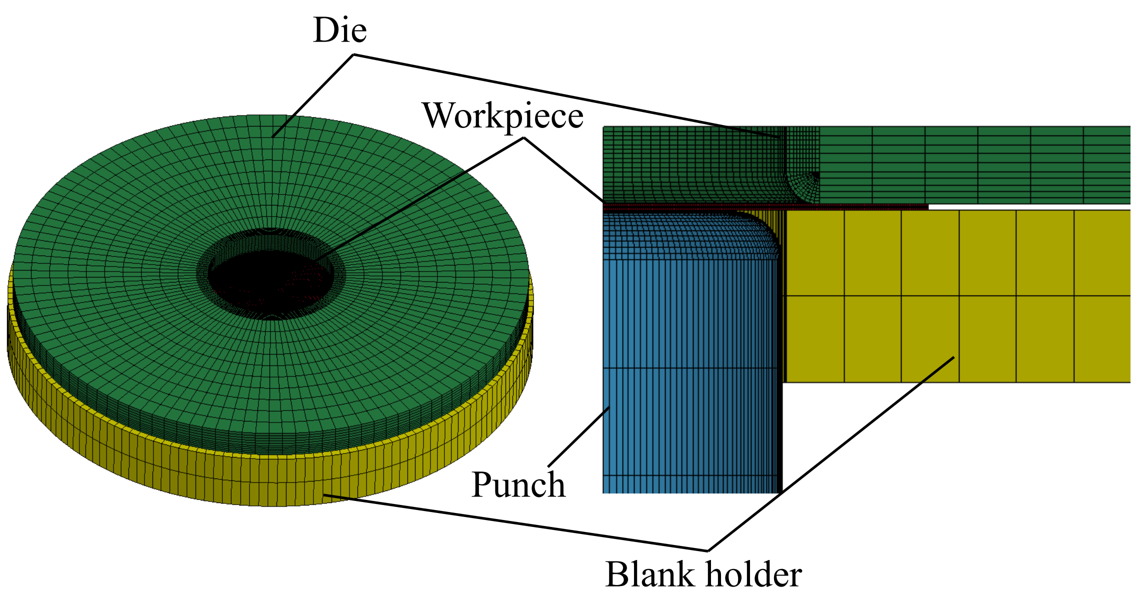


Fig. 6. Effect of incremental press forming on deformation behavior at room temperature.

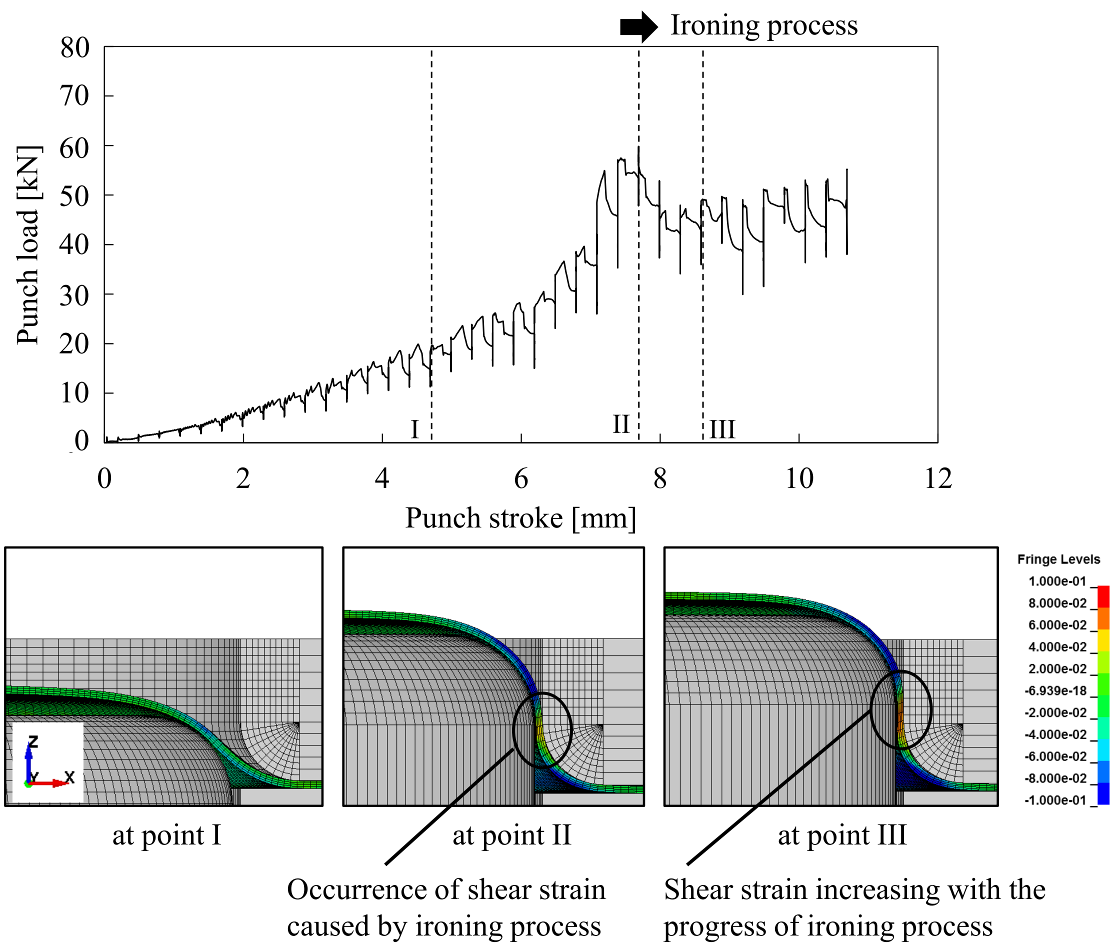


Fig. 7. FEA results of drawing and ironing process of Ti-6Al-4V alloy sheets (Shear strain distribution, $t_0 = 0.5$ mm, $P_{si} = 0.4$ mm, $BHF_i = 20$ kN).

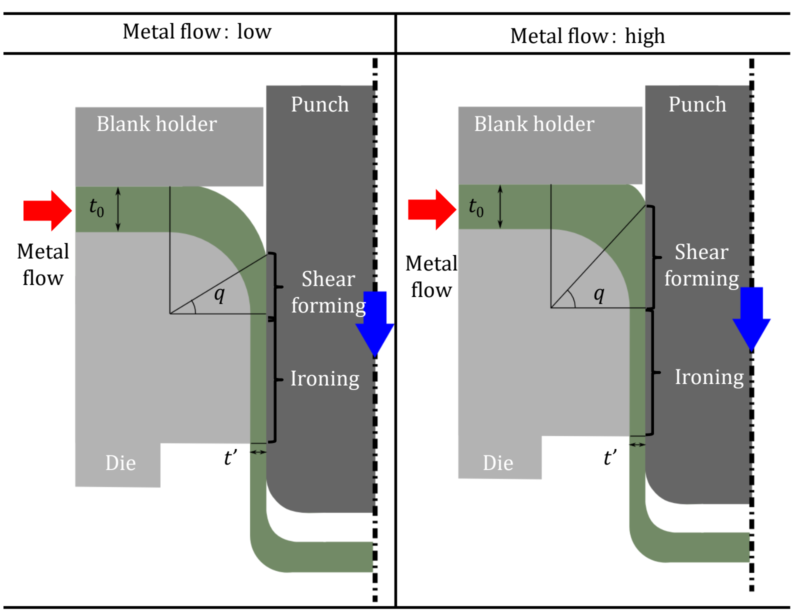


Fig. 8. Schematic of deformation behaviour during drawing and ironing [9].

Limit of Drawing Ratio During Cold Drawing and Ironing Process of Ti-6Al-4V Alloy Sheets
Finally, the Limit of Drawing Ratio (LDR) during cold drawing and ironing process were investigated. Ti-6Al-4V alloy sheet with thickness of t_0 = 0.5 mm were used. The eperiment was performed with a blank diameter of ϕ43, 50, 55 and 60 mm (*DR* = 1.4, 1.67, 1.79,). Die dimensions D_d = 31.6 mm and D_p = 30.8 mm were selected. The conditions of incremental press forming S_{pi} =90 mm/min, P_{si} =0.4 mm, and BHF_i =10, 20, 30, 40 kN were utilized. Fig. 9 shows the punch load – punch stroke curves and photographs of formed cups during drawing and ironing at the conditions ϕ43 (*DR* = 1.4) and BHF_i =30 kN. And Fig. 10 LDR of Ti-6Al-4V alloy sheets in cold drawing and ironing(D_d = 31.6 mm, D_p = 30.8 mm).

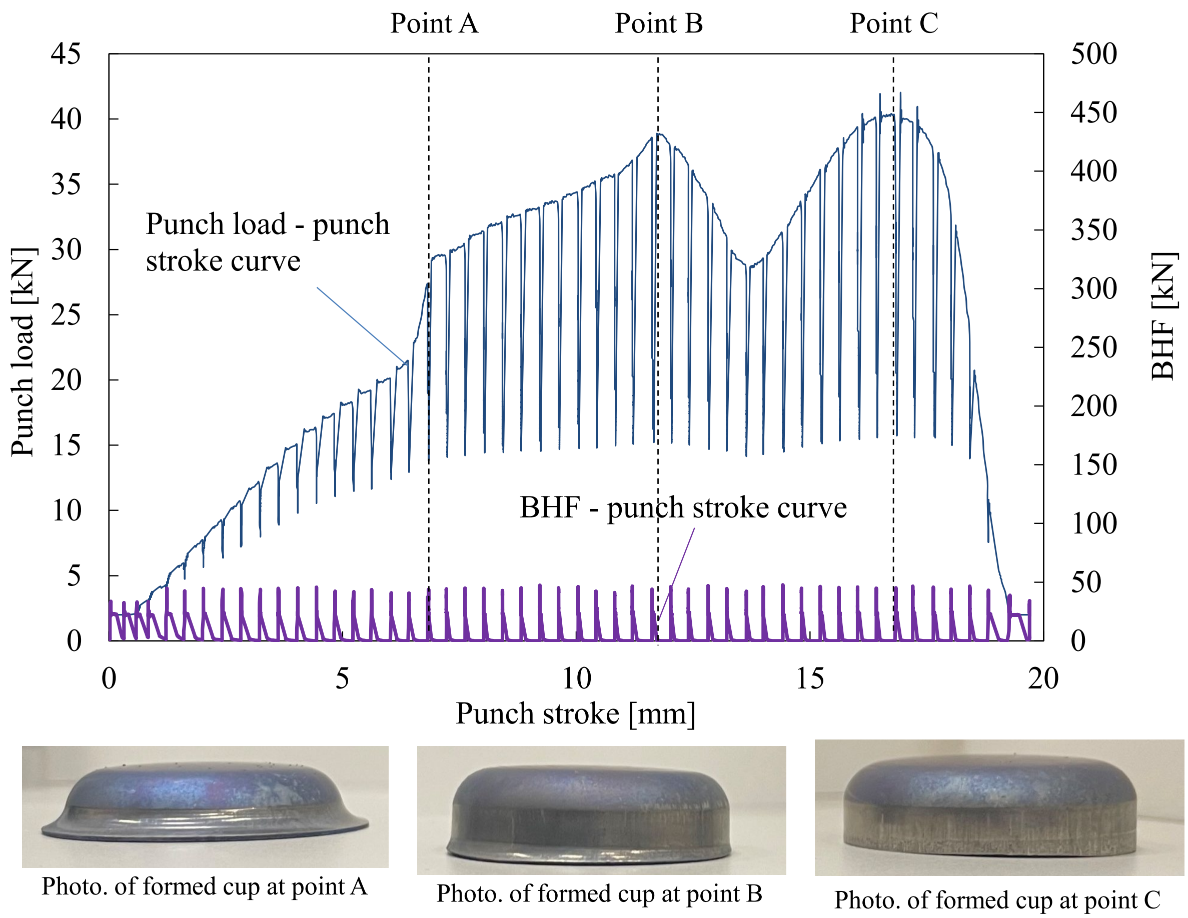


Fig. 9. punch load – punch stroke curves and photographs of formed cups during drawing and ironing at the conditions at room temperature (Blank diameter ϕ43, DR = 1.4 and BHF_i =30 kN).

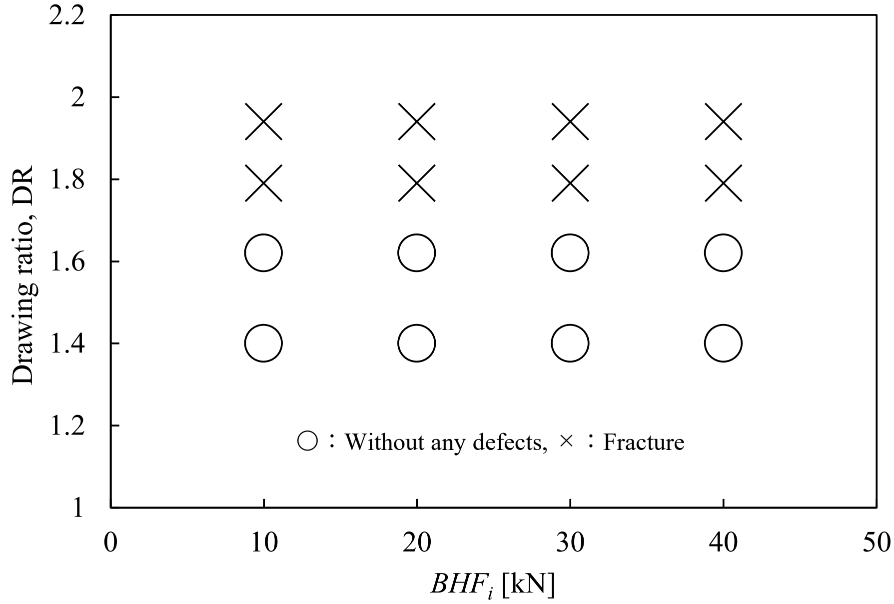


Fig. 10. LDR of Ti-6Al-4V alloy sheet in drawing and ironing at room temperature (D_d = 31.6 mm, D_p = 30.8 mm).

Summary

1) By the application incremental press forming method, the warm and cold drawing and ironing of Ti-6Al-4V alloy sheets was achieved.
2) The drawing and ironing process was calculated by FEA, and ironing due to shear strain could be estimated by simulation.
3) This study indicates the LDR during of Ti-6Al-4V alloy sheets in cold drawing and ironing (*Dd* = 31.6mm, D_p = 30.8mm).

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