Circular and square cups drawing and ironing of Ti alloy sheets by incremental press forming method

Yusuke Okude[1*], *Taku* Iwaoka[1], *Isao* Nakamura[1], *Tsuyoshi* Muraoka[1] and *Takashi* Katagiri[1]

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

Abstract. The low ductility of Ti–6Al–4V alloy at forming temperatures below 780°C is still a problem. Ti–6Al–4V alloy is usually hot press formed at 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. A new 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 was developed. In this study, the various forming conditions for developed press forming method were confirmed. In this method, the following two processes were separated: punch motion process without Blank Holding Force(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 circular and square cups drawing and ironing of Ti alloy sheets were achieved by applying developed method.

Keywords: Circular and square cups drawing and ironing; Warm and cold forming; Incremental press forming method; Titanium alloy sheets

1 Introduction

Ti-6Al-4V titanium alloy has been actively used in medical equipment and aerospace 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, because elongation improved dramatically in hot forming[5,6]. Hence, it is necessary to develop a new press forming for Ti–6Al–4V alloy sheets with low elongation and formability at forming temperatures below 780°C to improve productivity.

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 was developed[7,8]. In this study, the drawing an ironing by using developed press forming method was tried. 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, warm and cold tube forming of Ti–6Al–4V alloy was achieved without any undesirable deformation by applying the developed press forming method.

2 Experimental apparatus and warm circular cup deep drawing test of Ti-6Al-4V alloy sheets

In order to understand the basic formability of cylindrical deep drawing of Grade 5 titanium (Ti-6Al-4V alloy) sheet during warm forming, 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. A Ti-6Al-4V alloy sheet and a blank with a thickness of t_0 = 0.5mm were used as test materials. The test was performed with a blank diameter of ϕ 60mm(Drawing ratio, DR=1.85) to confirm the formability at the conditions with high drawing ratio. 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 blank holder. The punch was kept

* Corresponding author: okude.yusuke@iri-tokyo.jp

at room temperature under all conditions. The punch speed S_p was set to three conditions of 9, 90 and 900mm/min, and the BHF_{const} was applied at 4kN to prevent the wrinkling during drawing process. Fig.2 shows the punch load — punch stroke curve and photographs of cups drawn under each set of conditions. In each condition, fracture occurred at punch shoulder. Therefore, the low formability of Ti-6Al-4V alloy sheet was confirmed.

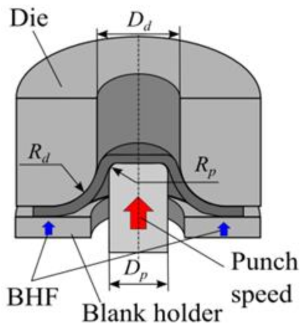
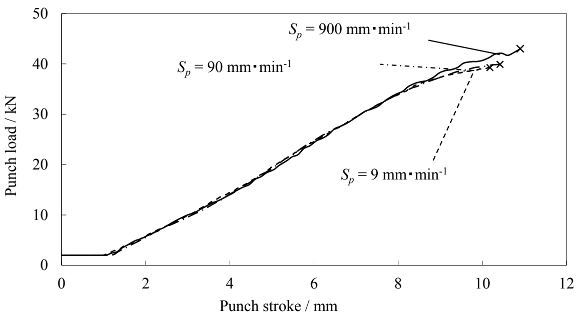


Fig. 1. Schematic of deep drawing process

Table 1. Dimension of dies of circular cup deep drawing process

Die	Diameter:D_d[mm]	35.0
	Shoulder radius:R_d[mm]	3.0
Punch	Diameter:D_p[mm]	32.5
	Shoulder radius:R_p[mm]	5.0



(a) Punch load－punch stroke curve

Conditions		Photo. of drawn cups
Punch speed S_p[mm/min]	9	
	90	
	900	

(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

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

In cylindrical deep drawing with BHF_{const}, fracture occurred at the punch shoulder at every punching speed S_p=9, 90 and 900mm/min at a forming temperature of 300°C. In this study, the wall thinning caused by BHF at punch shoulder was focused on. The wall thinning progressed by BHF from the start of the punch until the maximum punch load was reached. When the workpiece flows into the die with a punch under the condition of applying BHF, 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: I.punch motion without BHF and II.BHF without punch motion. Fig.3 shows the schematic of incremental press forming. In the I.punch motion without BHF, the workpiece flows into the die without the effect of BHF on thinning of workpiece. On the other hand, BHF was applied instantaneously in the II.BHF without punch motion.

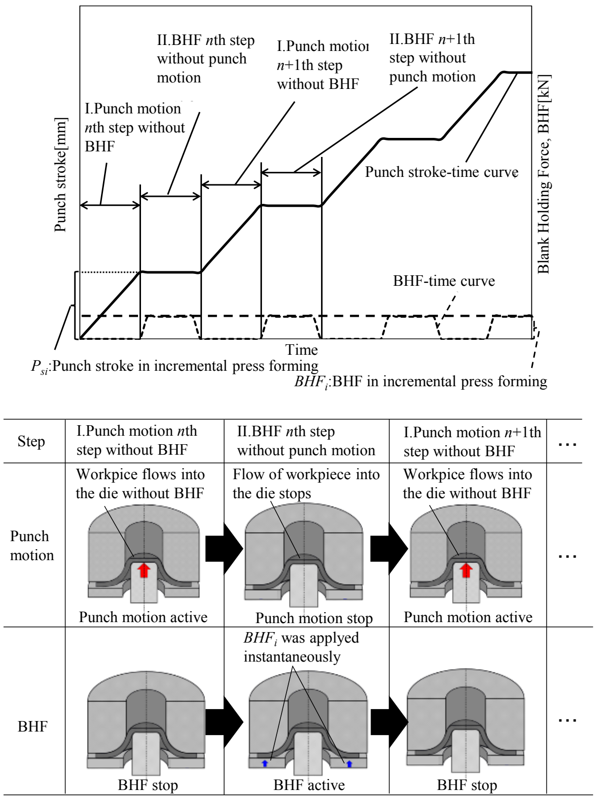
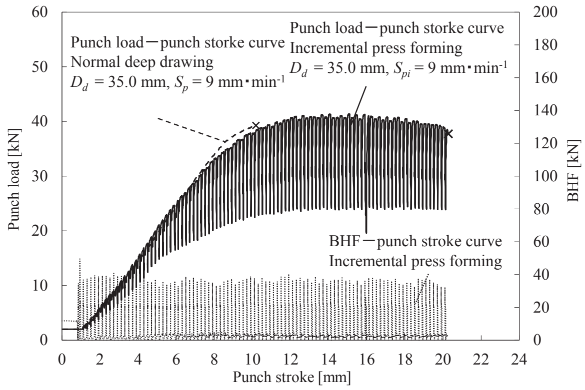


Fig. 3. Schematic of incremental press forming

And to confirm the effect of developed method on warm formability of Ti-6Al4V alloy sheet, the circular cup deep drawing experiment with incremental press forming were carried out. FORMKOTE T-50 was applied as a lubricant between the blank and the die. In the sequential forming, forming was performed under the conditions of S_{pi}=9mm/min, P_{si}=0.2mm, and BHF_i=20kN. For comparison, a cylindrical drawing was performed under the same lubricating conditions with a punch speed of 9mm/min and BHF of 4kN. Fig.4 shows the effect of sequential forming on formability.

However, the longitudinal fracture occurred at the flange as shown in figure caused by the compressive deformation of the flange. And the thickness of formed cup was investigated. Fig.5 shows the comparison of thickness strain of formed cup between high *DR* with incremental press forming and low DR with normal deep drawing. By applying of incremental press forming, the thinning at punch shoulder was prevented.

In addition, the effect of punch feed on the formability was investigated by forming under three conditions of P_{si}=0.2, 0.4, and 0.8mm, with the punch speed fixed at a fixed condition of S_{pi} = 9mm / min. As in the condition of over P_{si}=0.8mm, the wrinkling increased during the I.punch motion without BHF, it is difficult to prevent the wrinkling in the II.BHF without punch motion. Therefore, P_{si}=0.2 or 0.4mm are the suitable punch feed in these experimental conditions.



(a) Punch load－punch stroke curve

Method	Photo. of drawn cups
Incremental press forming	
Normal deep drawing with lubrication	

(b) Photographs of cups drawn under each set of conditions
Fig. 4. Schematic of deep drawing process

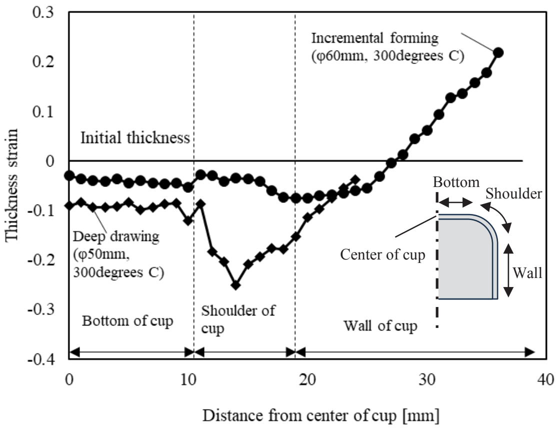


Fig. 5. Comparison of thickness strain of formed cup

4 Circular cup drawing and ironing by incremental press forming and formability of Ti–6Al–4V alloy sheets

It was difficult to prevent undesirable deformations in the deep drawing of Ti–6Al–4V alloy sheets, so metal flow control by the combining press motion control and clearance between a die and a blank was focused on. Fig.6 shows the schematic of the deformation behavior observed during drawing and ironing[8]. The deformation behavior, in metal flow was controlled by press motion and clearance. And to confirm the effect of metal flow controlling on deformation behaviour, drawing and ironing of Ti-6Al-4V alloy sheets(blank diameter ϕ 60 and ϕ 65mm) were carried out using two dies (D_d=33.8 and 31.3mm). For, the conditions of D_d=33.8mm, cold drawing and ironing processes of ϕ 60mm were carried out at the conditions of S_{pi}=90mm/min, P_{si}=0.4mm, and BHF_i=20kN. On the other hand, and cold drawing and ironing processes of ϕ65mm were carried out at the conditions of S_{pi}=90mm/min, P_{si}=0.5mm, and BHF_i=50kN for the tube forming with D_d=31.8mm condition. Fig.7 and 8 show the punch load – punch stroke curves for the cold drawing and ironing processes respectively. And, Fig.9 shows the photograph of the formed cups. By applying the developed method and an 80% clearance of the initial blank thickness, the cold tube forming by drawing and ironing of Ti–6Al–4V alloy sheets were achieved.

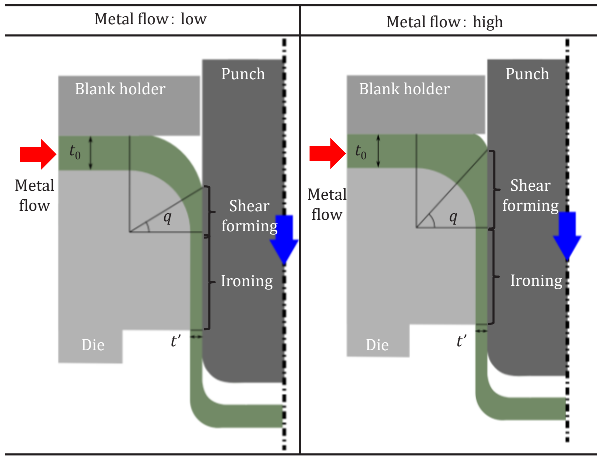


Fig. 6. Schematic of deformation behaviour during drawing and ironing process

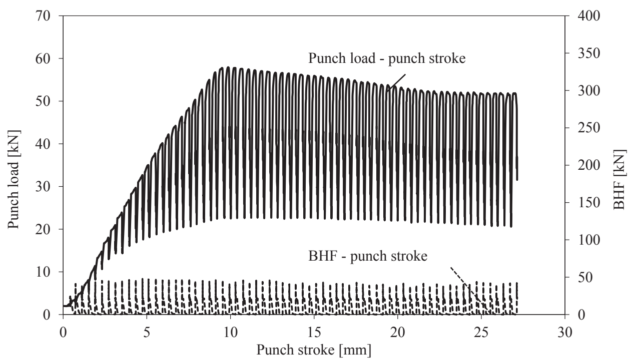


Fig. 7. Punch load – punch stroke curves for the cold drawing and ironing processes (ϕ 60mm, D_d=33.8mm)

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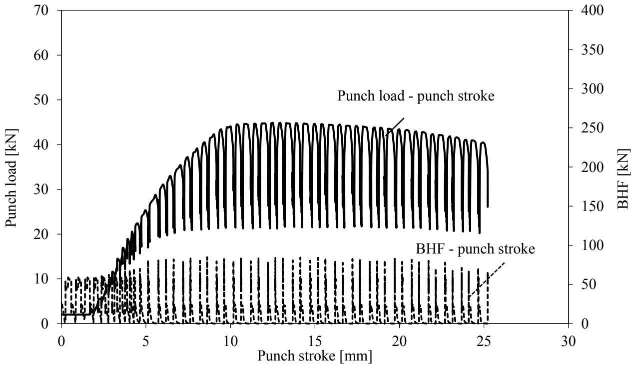


Fig. 8. Punch load – punch stroke curves for the cold drawing and ironing processes (ϕ65mm, D_d=31.3mm)

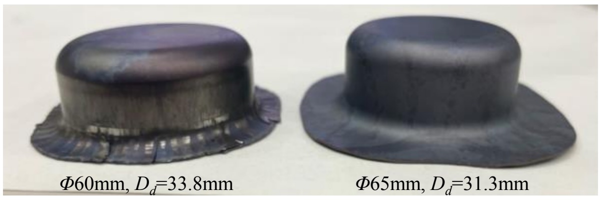


Fig. 9. Punch load – punch stroke curves for the cold drawing and ironing processes (ϕ65mm, D_d=31.3mm)

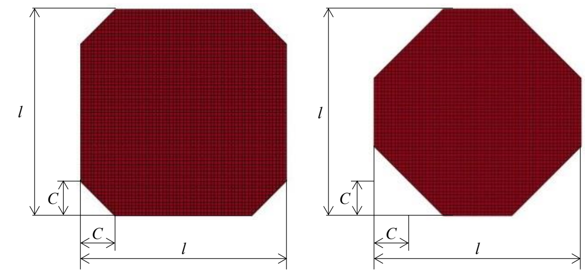
5 Square cup drawing and ironing by incremental press forming and formability of Ti–6Al–4V alloy sheets

To clarify the effect of the incremental press forming, FEA of square cup 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 two types of square workpieces were constructed as show in Fig.10. Table 2 indicates the properties of the sheet materials of Ti–6Al–4V alloy sheets (room temperature). An isotropic hardening elastoplastic material was assumed, satisfying an n power strain hardening law with the constitutive equation as follows,

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

where, C is plastic modulus, ε_n elastic strain, $\overline{\varepsilon_p}$ equivalent plastic strain, n work hardening exponential. Fig.11 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}=0.4mm, and BHF_i=20kN.

Fig.12 shows results of drawing and ironing process of grade 2 titanium (pure titanium) sheets (equivalent plastic strain distribution, P_{si}=0.4mm, BHF_i=20kN). As the results, during normal square cup drawing and ironing, equivalent plastic strain increased at the punch shoulder and the ironing part. By comparison of equivalent plastic strain between normal press forming and incremental press forming, the maximum reduction in strain of approximately 42% was observed because the tension at punch shoulder during drawing and ironing was reduced by applying incremental press forming.



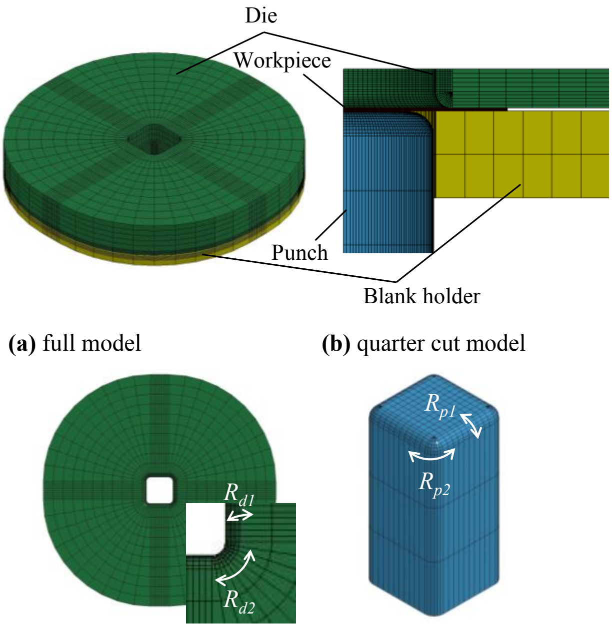
(a) C5 **(b)** C10

Fig. 10. Schematic of workpiece for square cup drawing and ironing process

Table 2. Material property of blank at room temperature

Material	Grade 2 titanium (Pure titanium)	Grade 5 titanium (Ti-6Al-4V alloy)
Density ρ[kg/m^3]	4.51×10^3	
Modulus of elasticity E[GPa]	106	
C value*[MPa]	1100	2800
n value*	0.35	0.22

$*\sigma = C(\varepsilon_e+\overline{\varepsilon_p})^n$



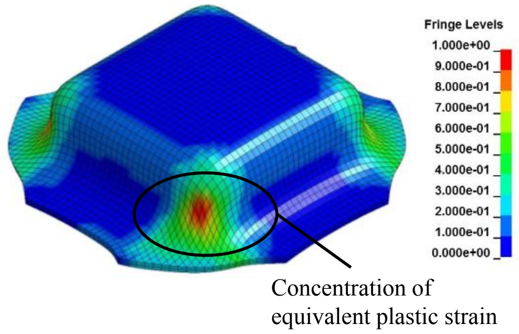
(a) full model **(b)** quarter cut model

(c) die **(d)** punch

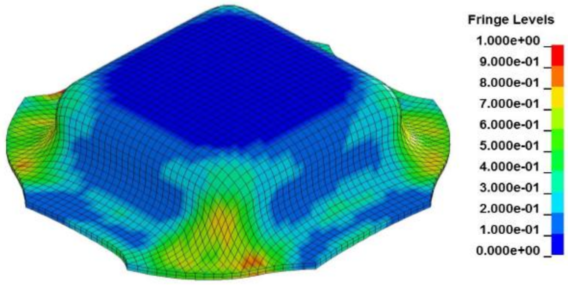
Fig. 11. FEA model of square cup drawing and ironing process

Table 3. Dimension of dies of quare cup drawing and ironing process

Die	Inner side length:D_i[mm]	16.0
	Shoulder radius 1:R_{d1}[mm]	2.0
	Shoulder radius 2:R_{d2}[mm]	2.0
Punch	Outer side length:D_o[mm]	15.0
	Shoulder radius 1:R_{p1}/mm	2.5
	Shoulder radius 2:R_{p2}/mm	2.5



(a) normal forming



(b) incremental press forming
Fig. 12. FEA results of square cup drawing and ironing process (grade 2 pure titanium sheets)

6 Square cup Drawing and ironing by incremental press forming and formability of Ti–6Al–4V alloy sheets

The possibility of achieving square-cup drawing and ironing was confirmed by the analysis, so square-cup drawing and ironing was performed. Fig.13 shows the punch load-punch stroke curve in square cup drawing and ironing of Ti-6Al-4V alloy sheet, Fig.14 shows the formed square cup of C10(30×30mm), and Fig.15 shows the square formed cup of C5(30×30mm). Square cup drawing and ironing was achieved regardless of the chamfering amount. In addition, in this experiment and analysis, the maximum punch load increased by about 20% due to the decrease in the chamfering amount, i.e., the increase in the deformation amount. As can be seen from Fig.13, the ears were significantly formed in C5, so it is considered that the increase in the deformation resistance due to bending and unbending at the flange part-die shoulder and the increase in the deformation resistance due to adhesion that occurred from the flange part to the ironing part contributed to the increase in the punch load. The analysis also showed the same form as the experiment, and the result showed that the concentration of strain at the punch shoulder was prevented.

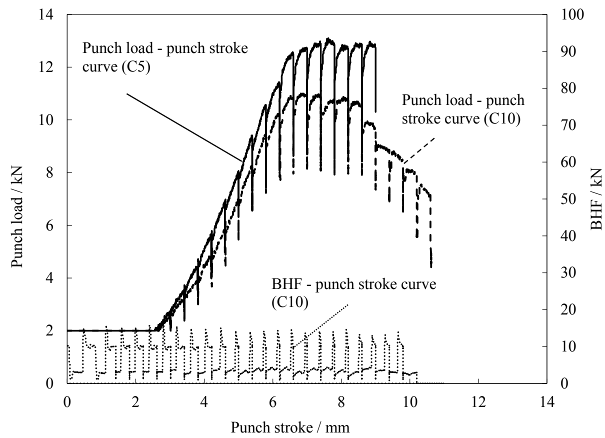
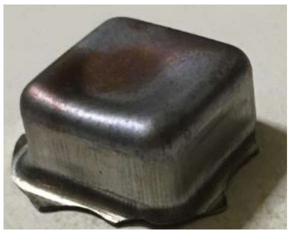
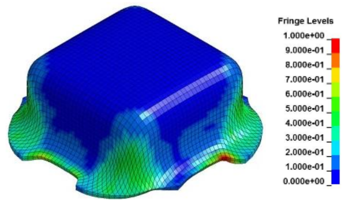


Fig. 13. Comparison of punch load – punch stroke curves and between C5 and C10 results (Ti-6Al-4V alloy sheets)

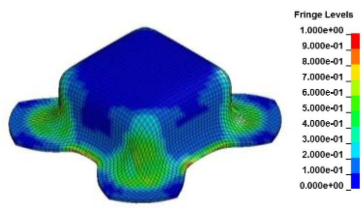


(a) experiment



(b) FEA
Fig. 14. Formed cup in square cup drawing and ironing process (C10)

(a) experiment



(b) FEA
Fig. 15. Formed cup in square cup drawing and ironing process (C5)

7 Conclusions

The developed incremental forming method was applied to circular and quare cup drawing and ironing of titanium alloy sheets, and the following results were obtained.

1.By applying incremental forming, the circular cup drawing and ironing of Ti-6Al-4V alloy sheets of the *DR*= 2.11 was achieved without any defects.
2.In FEA, by comparison of equivalent plastic strain between normal press forming and incremental press forming, the maximum reduction in strain of approximately 42% was observed because the tension at punch shoulder during drawing and ironing was reduced by applying incremental press forming.
3.In square cup drawing and ironing, the maximum punch load was affected by the chamfering amount of the test material and the increase in deformation resistance caused by adhesion that occurred from the flange to the ironing area.
4.The developed incremental forming improved formability of titanium alloy sheet with low elongation at circular and quare cup drawing and ironing.

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