Applicability of plastic tools additively manufactured by fused deposition modelling for sheet metal forming

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Abstract

The applicability of plastic tools additively manufactured by fused deposition modelling for sheet metal forming processes was evaluated. Aluminium and steel sheets were V-bent and deeply drawn with the plastic tools. The dimensional accuracy of bent sheets with the plastic tools was lower than that with steel tools due to low stiffness, and deteriorated with increasing flow stress of a sheet. The stiffness was increased by reinforcing the plastic tools with steel bars, and thus, the dimensional accuracy of the bent sheets was improved. Not only springback of the sheet but also elastic deformation of the plastic tools was successfully corrected by modifying the shapes of the tools. In addition, the deep drawability of a cylindrical cup with a plastic die was examined.

1 Introduction

The development of the 3D printing technology is considerably remarkable, and additive manufacturing processes such as stereolithography of photopolymers, selective laser melting using metallic and ceramic powders, and fused deposition modelling using plastics are included in this technology, as reviewed in the book by Kalpakjian et al. [1]. Using these processes, mechanical parts are manufactured directly without the use of traditional dies and tools. The qualities of manufactured parts such as the dimensional accuracy, strength, surface roughness, etc. are considerably improving with capability enhancement of additive manufacturing machines. However, costs of raw materials are generally high, and the lead time required to produce each part is too long to be viable for large production runs. These processes are limited to small production of parts.

One of the useful applications of additive manufacturing processes is rapid tooling. This is to manufacture not mechanical parts directly but tools for producing parts. Since the tools are generally expensive and the lead time is relatively long,

drawbacks in cost and time are not problematic in comparison with direct manufacturing of parts. In addition, tools are automatically manufactured from CAD data without skilled labour. Additive manufacturing of tools for casting, injection moulding, metal forming, etc. has started in industry. Gebhardt [2] explained the use of additive manufacturing for rapid tooling.

Hölker-Jäger et al. [3] reviewed metal forming dies made from metallic powders by laser additive manufacturing. Abe et al. [4] manufactured prototype dies by a selective laser melting process of nickel-based alloy powder. In this process, a thin layer of powder is locally melted with a laser beam, and a three-dimensional die is successively formed layer by layer. The strength and reliability of the die are improved by replacing selective laser melting with selective laser sintering, i.e. the increase in relative density by a higher heating temperature. Moreover, the strength of the die is increased by using high alloy powders in selective laser melting. Shipley et al. [5] reviewed selective laser melting processes of hard titanium alloys. Wu et al. [6] and Cortina et al. [7] additively manufactured cooling channels in dies used for injection moulding and hot stamping, respectively. Although channels made by conventional drilling are limited to straight ones, curved channels along tool surfaces can be made by additive manufacturing, and thus, the cooling efficiency becomes high. Laser additive manufacturing processes using metal powders are employed for dies used for metal forming processes, while laser additive manufacturing

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Fig. 1 Nominal stress-strain
curves measured from simple
compression test of plastic
cylinders manufactured by fused
deposition modelling
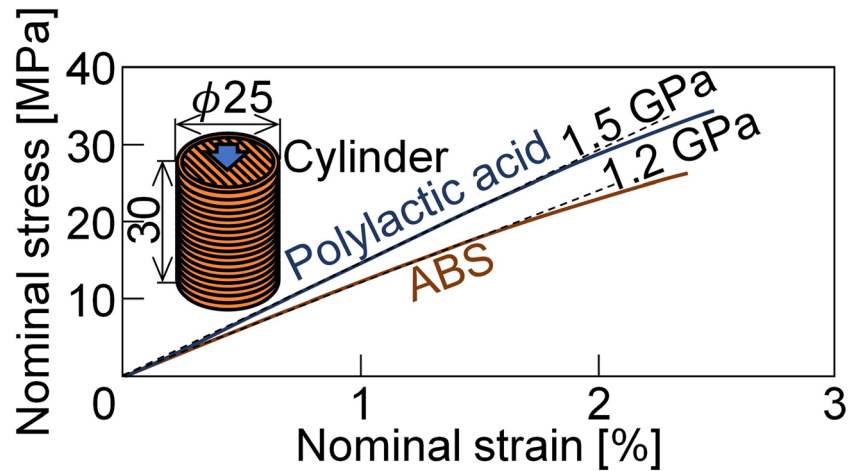
machines and powders are considerably expensive, and thus, industrial application is still limited.

The price of fused deposition modelling machines for plastic parts drastically decreases, and the application of this modelling process is expanding remarkably. In the fused deposition modelling process, mechanical parts are manufactured by laying down successive layers of molten plastic without dies [8], and the machines become cheap because of extrusion of molten plastic. In addition, the plastic filament, the raw material for fused deposition modelling, is low-cost. However, the strength of plastic parts manufactured by fused deposition modelling is lower than that by conventional injection moulding, because the parts are somewhat porous. Sood et al. [9] examined effects of modelling conditions such as the layer thickness, orientation, raster angle, raster width and air gap on the tensile, flexural and impact strengths. It is desirable to increase the strength of parts manufactured by fused deposition modelling. Mori et al.

[10] developed a dieless forming process of carbon fibre-reinforced plastic parts using fused deposition modelling. Nakagawa et al. [11] improved the strength of carbon fibre-reinforced plastic parts manufactured by fused deposition modelling by using a microwave oven to thermally bond carbon fibre to plastic layers.

The use of plastic tools manufactured by fused deposition modelling for sheet metal forming processes leads to large reductions in the lead time and die cost. Since the yield stress for the plastic tools is considerably lower than that for steel tools, the risk of tool failure becomes high. In addition, low Young's modulus for the plastic tools deteriorates the dimensional accuracy of formed parts. Durgun [12] employed plastic tools manufactured by fused deposition modelling for small production runs of sheet metal forming. Leacock et al. [13] simulated a stretch forming process of double curvature components with plastic tools manufactured by fused deposition modelling. Nakamura et al. [14] measured the elastic
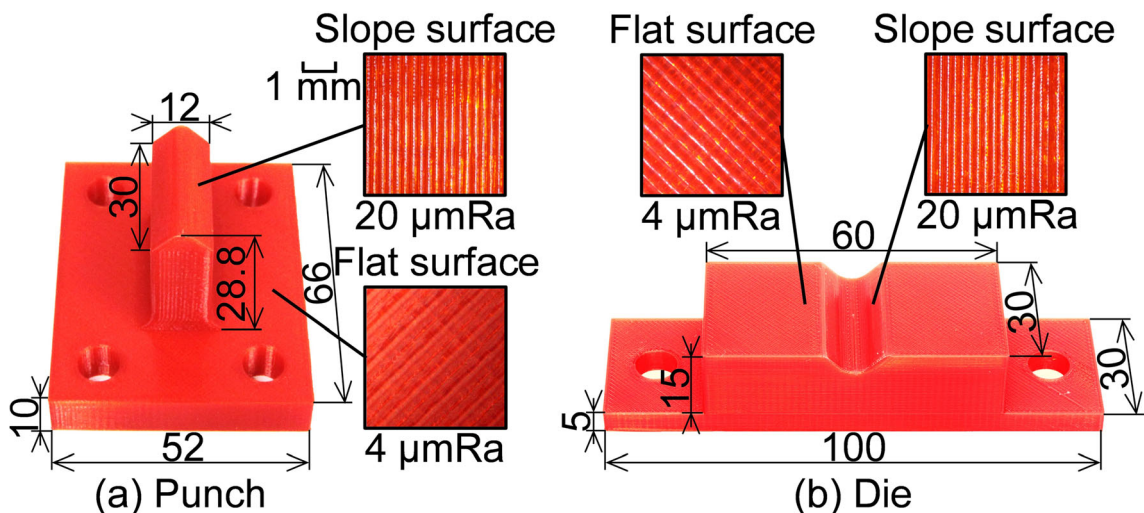

Fig. 2 Plastic punch and die manufactured by fused deposition modelling employed for V-bending experiment
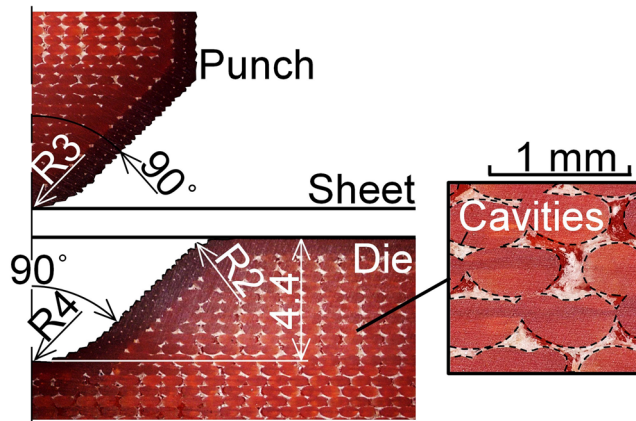
Fig. 3 Cross-sections of plastic punch and die employed for V-bending experiment

fused deposition modelling are shown in Fig. 1. The yield stress and Young's modulus of a polylactic acid cylinder are about 30 MPa and 1.5 GPa, respectively, whereas an ABS cylinder has 22 MPa in yield stress and 1.2 GPa in Young's modulus. These values for the polylactic acid are lower than those measured from the compression test by Mercado-Colmenero et al. [16], and the values for the ABS are higher than those measured from the tensile test by Samykano et al. [17]. The polylactic acid was selected as a material for plastic tools because of higher strength. Since the yield stress and Young's modulus are about 1/10 and 1/100 of steel, respectively, the applicability of the plastic tools for sheet metal forming was evaluated.

deformation of plastic tools manufactured by fused deposition modelling during V-bending of sheet metals. On the other hand, Harada et al. [15] exhibited that dies cut from a bulk plastic have high seizure resistance in deep drawing of aluminium and titanium cups.

In this paper, the applicability of plastic tools manufactured by fused deposition modelling for sheet metal forming processes was evaluated. The dimensional accuracy of formed parts was improved by reinforcing the plastic tools using steel bars and modification of tool shapes.

2 V-bending using plastic tools manufactured by fused deposition modelling

2.1 Plastics used for fused deposition modelling

When plastic tools manufactured by fused deposition modelling are applied to sheet metal forming, tool failure, low tool life and low product accuracy are problematic due to the low strength and stiffness. For the application, the mechanical properties of polylactic acid and ABS were measured. Two materials are typical ones used for fused deposition modelling.

The nominal stress-strain curves measured from a simple compression test of the plastic cylinders manufactured by

2.2 V-bending tools manufactured by fused deposition modelling

The plastic punch and die manufactured by fused deposition modelling employed for a V-bending experiment are shown in Fig. 2. The punch and die were manufactured from CAD data by piling plastic layers for about 3 h. The plastic layers were piled from the bottoms of the punch and die, and the slope surfaces were finely stair-like. In each layer, the outline was first formed, and then the inside was crosshatched. The strength orientation of the punch and die becomes comparatively small. The slope surfaces piled from the sides of the punch and die become smooth in the slope direction, and not smooth in the orthogonal direction due to piling of layers.

In additive manufacturing, a one-piece punch and die having an attaching plate can be made, and even holes for attachments are made without post-drilling. The price of the filament used for one tool is only 2 US dollars. This is much cheaper than the price of powder in selective laser melting. Furthermore, no excess material is required because of deposition of molten plastic. Although tool surfaces are not smooth as well as other additive manufacturing processes, the friction between the tool and sheet is not high due to the elastic deformation of the tool surface during forming. This is different from metal tools having small elastic deformation manufactured by selective laser melting for which surface finishing is generally necessary. Angelo et al. [18] evaluated the surface quality of parts manufactured by fused deposition modelling.

The cross-sections of the plastic punch and die employed for the V-bending experiment are given in Fig. 3. The punch and die are porous due to the cavities between extruded plastics, and relative densities of the punch and die were about 85%. It is not easy to further raise the relative density. The aluminium sheets A1100-H, A5052-H and 440 MPa steel sheet given in Table 1 were bent with the plastic punch and die having an angle of 90°. The width and length of the sheets were 30 and 60 mm, respectively.
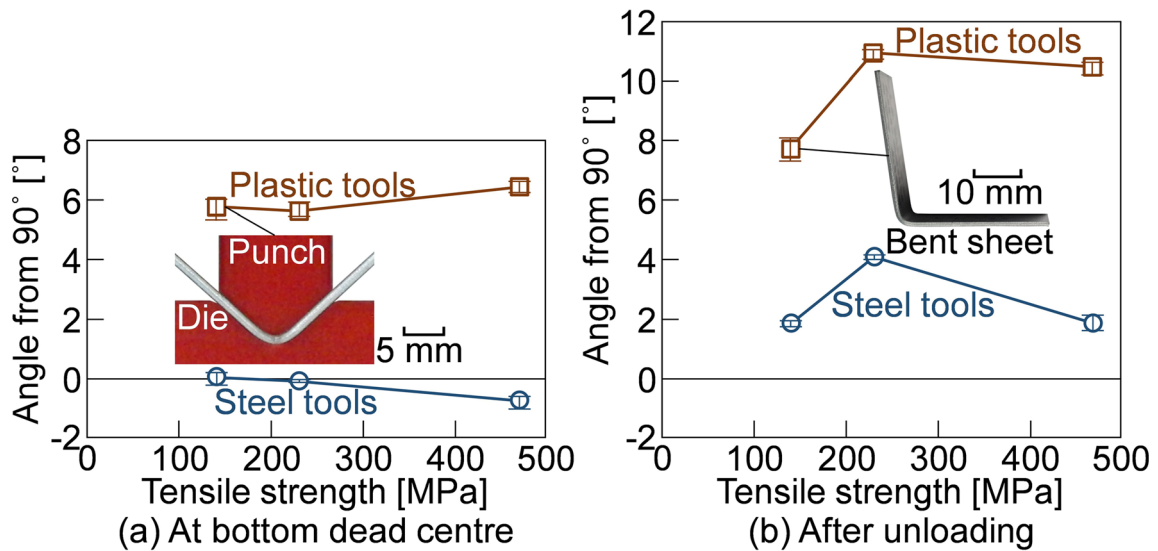
Table 1 Mechanical properties of sheet metals used for V-bending experiment

Sheet	Thickness [mm]	Tensile strength [MPa]	Elongation [%]
A1100-H	0.96	140	5
A5052-H	0.96	230	9
440 MPa steel	1.01	470	30

Fig. 4 Relationships between angle from 90° of bent sheet and tensile strength of sheet

2.3 Results of V-bending using plastic tools

The relationships between the angle from 90° of a bent sheet and the tensile strength of the sheet are shown in Fig. 4, where the location of the bottom dead centre is equivalent to a punch stroke of 4.4 mm. The angle of the bent sheet at the bottom dead centre was measured with a CCD camera. With the plastic tools having low strength, the sheet was bent without tool failure even for the 440-MPa steel sheet. Since the compressive stress applied to the tools is comparatively low for bending, the plastic tools can be employed. The angle from 90° of the bent sheet at the bottom dead centre for the plastic tools is larger than that for the steel tools because of low stiffness, and increases with increasing tensile strength of the sheet. The slightly thick 440-MPa

steel sheet is overbent with the steel tools having high stiffness, and has the minus angle at the bottom dead centre. The low stiffness of the plastic tools deteriorates the dimensional accuracy of the bent sheet; thus, it is desirable to increase the stiffness of the tools.

3 Improvement of dimensional accuracy of V-bent products with plastic tools

3.1 Increase in stiffness of plastic tools by reinforcements

To improve the dimensional accuracy, the stiffness of the plastic tools is increased by reinforcements. The plastic tools are
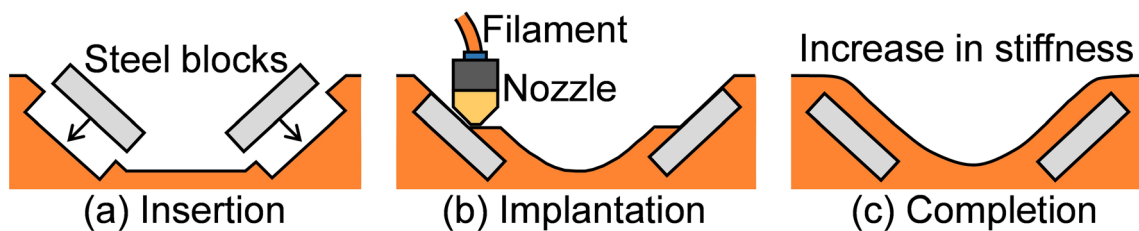

Fig. 5 Increase in stiffness of plastic tools by reinforcing in fused deposition modelling
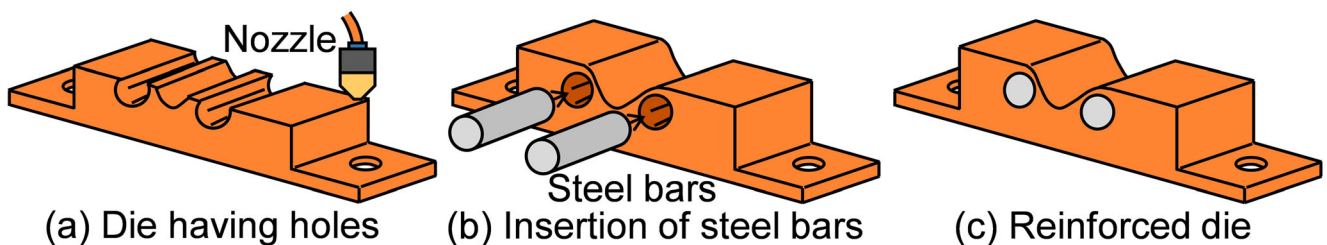

Fig. 6 Reinforcing method using steel bars of plastic tools used for V-bending experiment
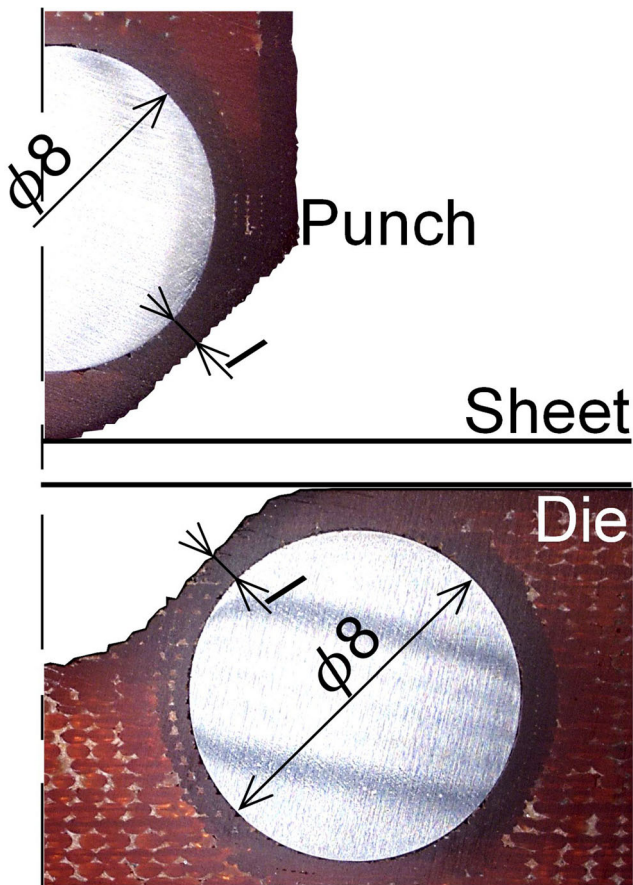
Fig. 7 Cross-sections of reinforced plastic punch and die for l = 0.8 mm

low unlike selective laser melting, and thus, no distortion of the reinforcements occurs.

The plastic punch and die used for the V-bending experiment are reinforced with 0.45% carbon steel bars, as shown in Fig. 6. To increase the stiffness of the plastic tools, the plastic punch and die having holes were manufactured by fused deposition modelling, and then the steel bars were inserted into the holes. The dimensional accuracy of the bent sheets with the reinforced plastic punch and die was examined.

The cross-sections of the reinforced plastic punch and die for l = 0.8 mm are given in Fig. 7, where l is the minimum distance between the surface of the tool and the steel bar. The steel bars were inserted into the tools to increase the stiffness. The reinforced plastic punch and die were employed for the V-bending experiment.

3.2 Results of V-bending using reinforced plastic tools

The relationships between the angle from 90° of the bent sheet and the tensile strength of the sheet for the plastic tools reinforced with the steel bars are shown in Fig. 8. The dimensional accuracy of the bent sheet is improved by reinforcing the plastic punch and die. As the steel bars approach the tool surfaces, the angle from 90° decreases due to the increase in stiffness, whereas the fracture occurs for l = 0.6 mm.

The variations in the angle from 90° of the bent sheet in repeated bending using the plastic tools with and without the reinforcements are illustrated in Fig. 9. The angle of the bent sheet by the plastic tools with and without the reinforcements is almost constant up to
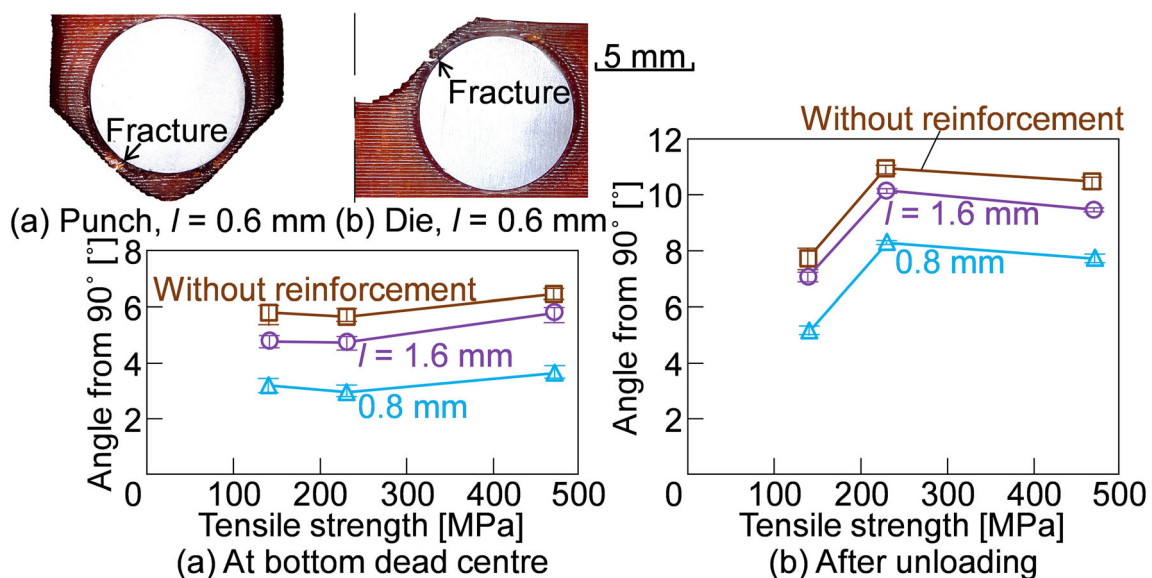
reinforced with the steel blocks, as shown in Fig. 5. Since the tools are formed by piling up plastic layers in fused deposition modelling, it is easy to include the reinforcements in the tool. Moreover, the temperature of molten plastic is comparatively

Fig. 8 Relationships between angle from 90° of bent sheet and tensile strength of sheet for plastic tools reinforced with steel bars
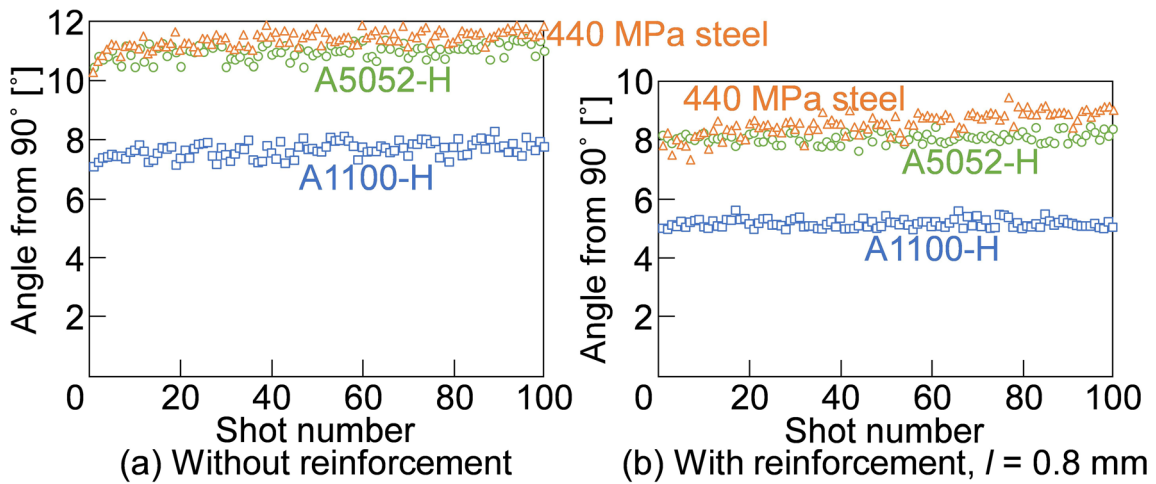
Fig. 9 Variations in angle from 90° of bent sheet in repeated bending using plastic tools with and without reinforcements

(a) Without reinforcement   (b) With reinforcement,   (c) Steel tools
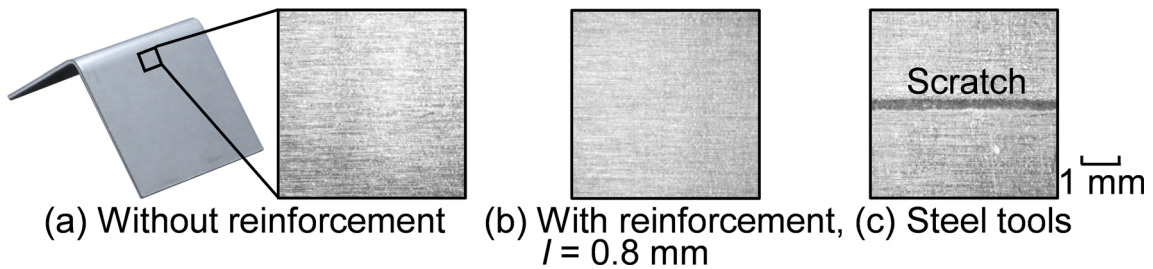   l = 0.8 mm

Fig. 10 Surfaces of bent A1100-H sheet with plastic tools with and without reinforcements

100 shots. It was found that the plastic tools are sufficiently applicable for small production runs.

The surfaces of the bent A1100-H sheet with the plastic tools with and without the reinforcements are shown in Fig. 10. In the bending of a sheet having

low strength, the steel tools cause the scratches around the corner of the bent sheet, whereas the plastic tools having low Young's modulus prevent the scratches. The plastic tools are suitable for forming sheets having low flow stress.

Fig. 11 Modification of tool angles for approaching desired shape of bent sheet
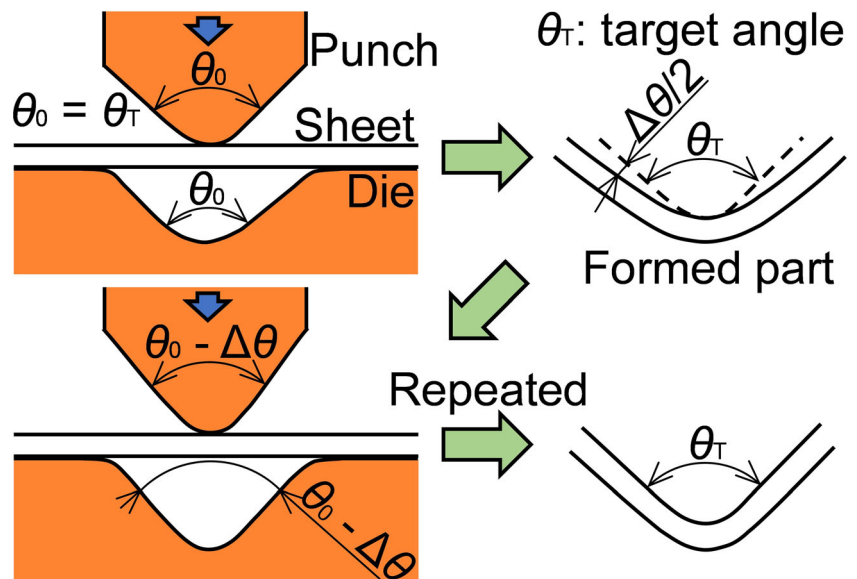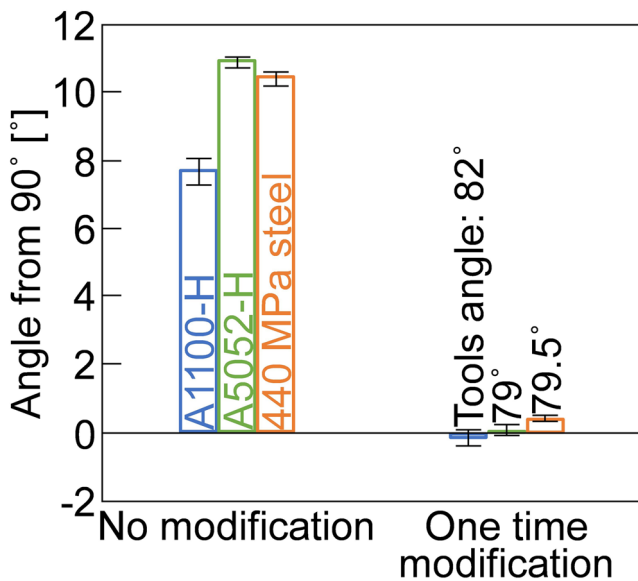
Fig. 12 Angles from 90° of bent sheet by modification of shapes of plastic punch and die

Table 2 Mechanical properties of sheet metals used for deep drawing experiment

Sheet	Thickness [mm]	Tensile strength [MPa]	Elongation [%]
A1050-H	0.47	130	4
A5052-H	0.47	260	8
SPCC	0.50	290	46

3.3 Modification of plastic tool shapes for improvement of dimensional accuracy of formed part

In finite element simulation of bending processes, tool shapes are generally modified to correct the springback. The shape of real plastic tools manufactured by fused deposition modelling was repeatedly modified in a similar manner to improve the dimensional accuracy of formed parts because of fast manufacturing and cheap filament cost, as shown in Fig. 11. The sheet is bent with the punch and die having an initial angle of θ_0; the difference $\Delta\theta$ between the obtained and target angles of the bent sheet is calculated. The sheet is bent with the punch and die having an angle changed by $\Delta\theta$, and this procedure is repeated until the angle of the bent sheet is close to the target angle. The angles of the punch and die are modified to the same ones. The angles of the real punch and die are modified to correct both elastic deformation and springback, and the shape of the formed part approaches the desired one with increasing modification.

The angles from 90° of the bent sheet by the modification of the shapes of the plastic punch and die are given in Fig. 12. For one-time modification, the shape of the formed part is almost similar to the desired one because of simple bending. Both elastic deformation of the tools and springback of the sheet are successfully corrected by the modification of the tool shapes.

4 Deep drawing of cylindrical cup with plastic die

4.1 Conditions of deep drawing

For deep drawing having severer deformation than bending, the applicability of the plastic tools was evaluated. The aluminium sheets A1050-H, A5052-H and SPCC steel sheet given in Table 2 were deeply drawn with a plastic die, as shown in Fig. 13. Only the die was made of plastic by fused deposition modelling, and the punch and blankholder having comparatively simple shapes were made of steel. The blankholder force for the A1050-H sheet was 2 kN, and that for the

Fig. 13 Deep drawing of cylindrical cup with plastic die manufactured by fused deposition modelling
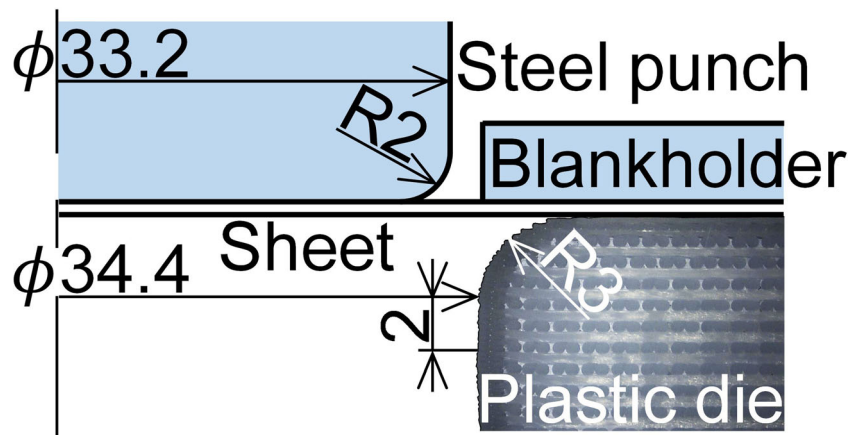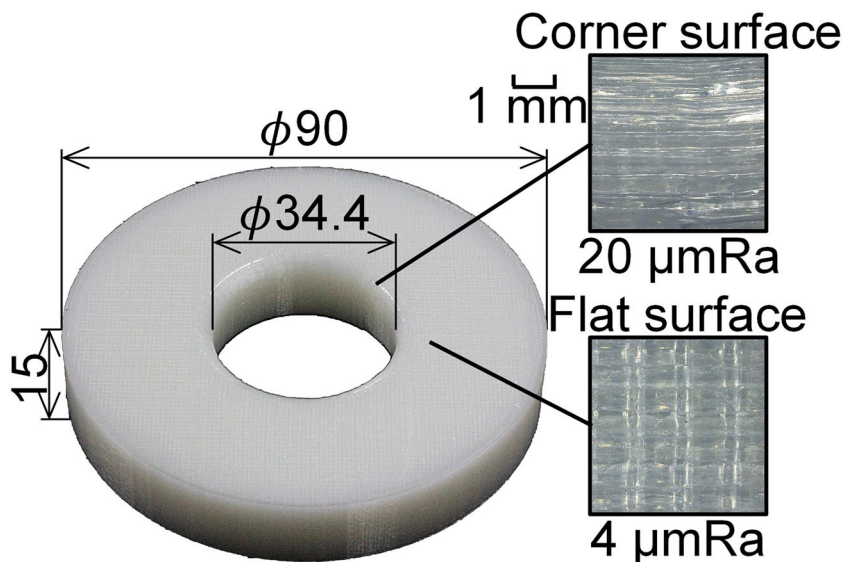
Fig. 14 Plastic die manufactured by fused deposition modelling employed for deep drawing experiment

A5052-H and SPCC sheets was 4 kN. The lubricant was a press oil, and the die and blankholder were lubricated.

The plastic die manufactured by fused deposition modelling employed for the deep drawing experiment is given in Fig. 14. The relative density of the die was about 90%, and the production time of the die was about 5 h. The corner surface is finely stair-like.

4.2 Results of deep drawing lubricated with press oil

The drawn cups with the plastic and steel dies for the press oil are shown in Fig. 15, where β is the drawing ratio. The drawn cups with the plastic and steel dies are almost similar.

For a large drawing ratio, the A1050-H sheet fractured, whereas the A5052-H and SPCC sheets wrinkled, as shown

Plastic die Steel die Plastic die Steel die Plastic die Steel die
(a) A1050-H, β = 1.93 (b) A5052-H, β = 1.57 (c) SPCC, β = 1.45

Fig. 15 Drawn cups with plastic and steel dies for press oil

Drawn cup Plastic die Drawn cup Plastic die
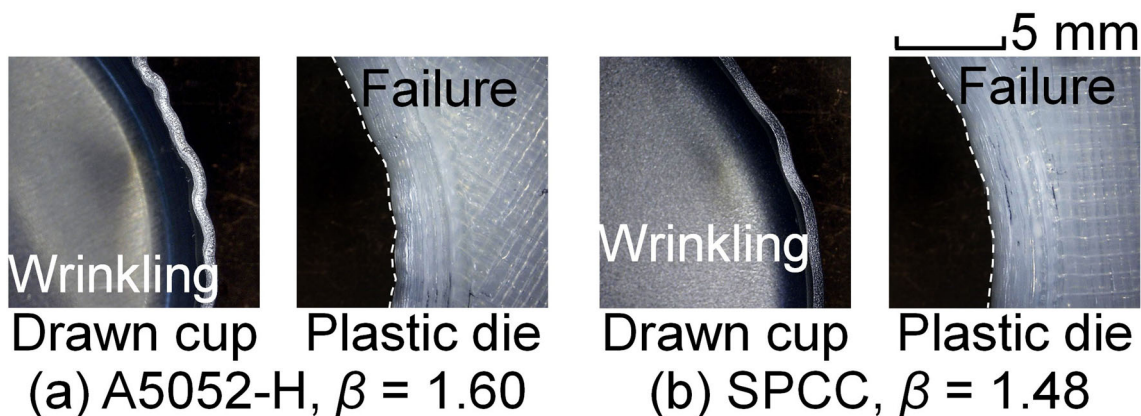(a) A5052-H, β = 1.60 (b) SPCC, β = 1.48

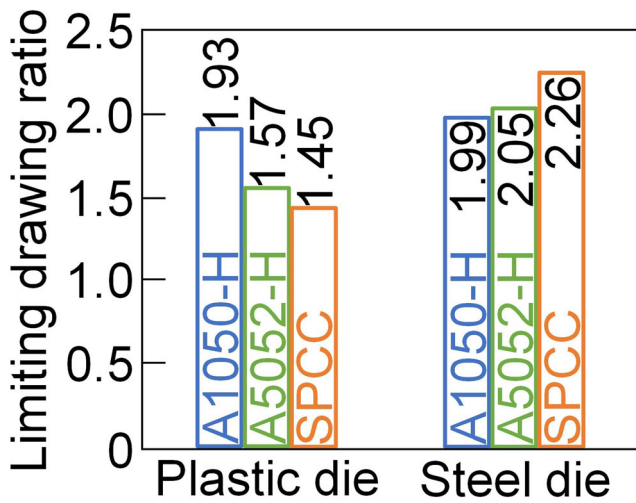**Fig. 16** Plastic die failure by wrinkling of drawn cup

Fig. 17 Limiting drawing ratios with plastic and steel dies for press oil

in Fig. 16. In wrinkling, the plastic die undergoes plastic deformation caused by high pressure and cannot be employed anymore.

The limiting drawing ratios with the plastic and steel dies for the press oil are illustrated in Fig. 17. The limiting drawing ratios of the A1050-H sheet for the two dies are almost similar, whereas the ratios of the A5052-H and SPCC sheets for the

plastic die are lower than those for the steel die. The low limiting drawing ratios of the A5052-H and SPCC sheets for the plastic die are caused by wrinkling shown in Fig. 16 before attaining the limit of the sheet. It was found that sheets having low flow stress are suitable for deep drawing.

4.3 Results of repeated deep drawing without lubrication

The post-treatment of lubricants used for metal forming processes is environmentally problematic, and it is desirable to develop forming processes without lubrication. Properties of the plastic die in repeated deep drawing without lubricant were evaluated.

The surfaces of the drawn A1050-H cup with the plastic and steel dies without lubrication for $\beta = 1.84$ and 1st shot are shown in Fig. 18. For the steel die, the seizure appears in the side wall of the drawn cup, whereas no seizure occurs for the plastic die.

The die corners and drawn A1050-H cups with the plastic and steel dies without lubrication for $\beta = 1.84$ are shown in Fig. 19. For the steel die, the seizure appeared from the 1st shot and the cup fractured after 3 or 4 shots. On the other hand, no seizure occurred after 10 shots for the plastic die.
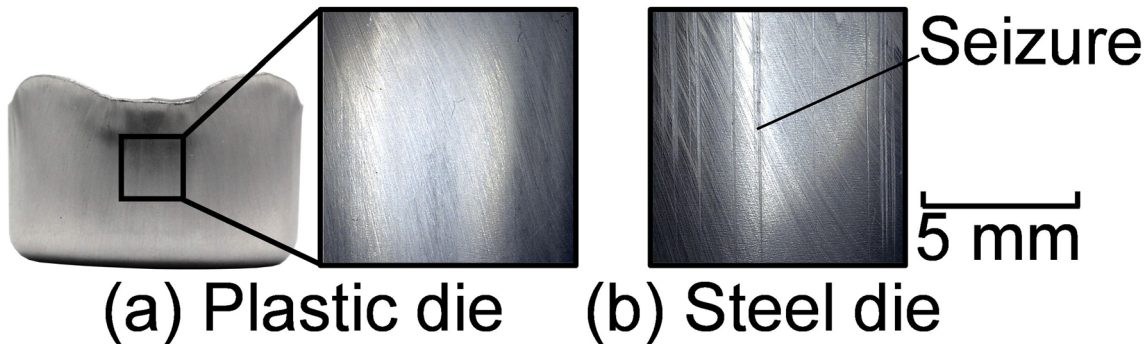

Fig. 18 Surfaces of drawn A1050-H cup with plastic and steel dies without lubrication for $\beta = 1.84$ and 1st shot
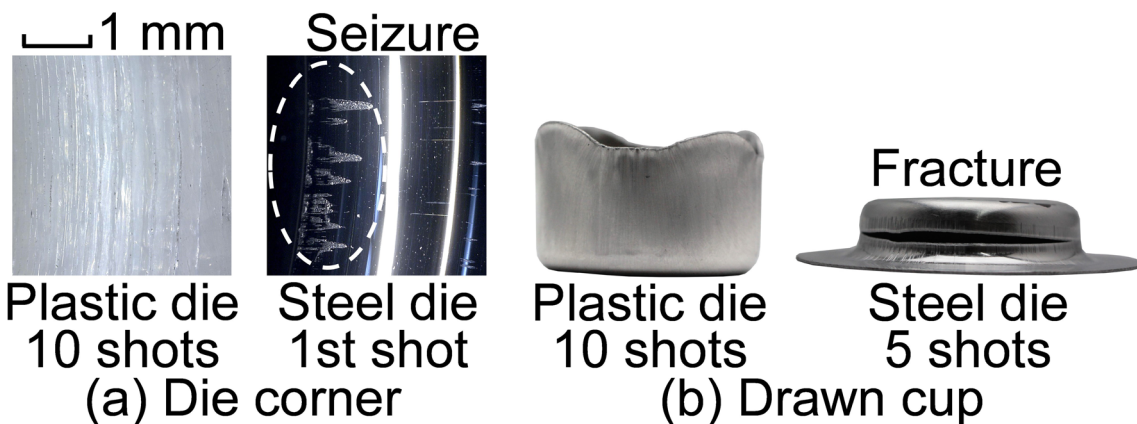

Fig. 19 Die corners and drawn A1050-H cups with plastic and steel dies without lubrication for $\beta = 1.84$
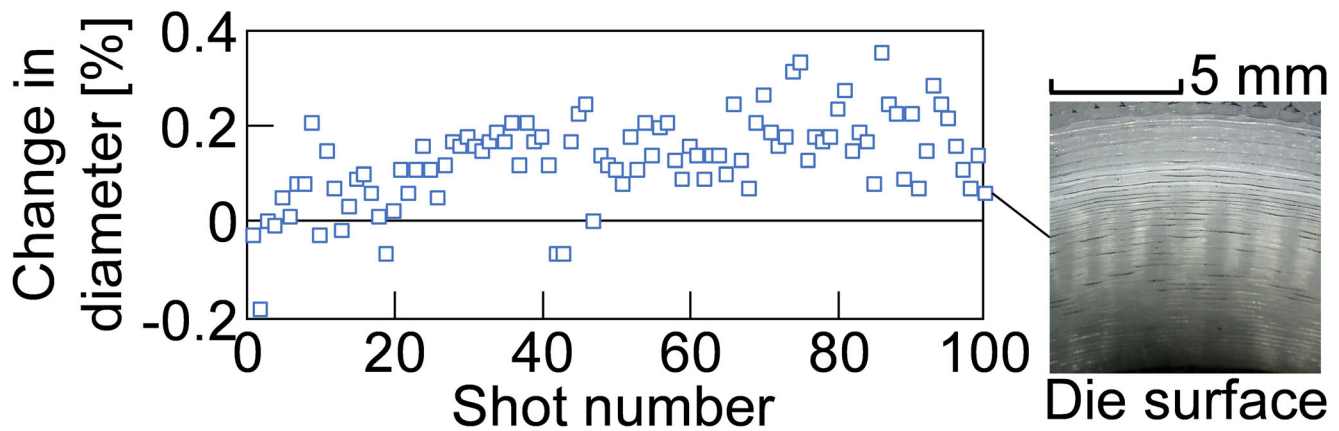
Fig. 20 Variation in diameter change of drawn A1050-H cup in repeated deep drawing with plastic die without lubrication for $\beta = 1.84$

The variation in the diameter change of the drawn A1050-H cup in repeated deep drawing with the plastic die without lubrication for $\beta = 1.84$ is given in Fig. 20. The diameter of the drawn cup slightly increases with increasing shot number, where no failure of the cup and die occurred even after 100 shots.

5 Conclusions

The application of fused deposition modelling as a manufacturing process has been expanding rapidly due to cheap machines. The fused deposition modelling process has advantages of automatic manufacturing from CAD data, cheaper raw materials, almost no material loss, etc. Although this manufacturing process is attractive for rapid tooling, manufactured plastic tools have been hardly applied to metal forming processes yet because of low strength and stiffness.

In this paper, the applicability of the manufactured plastic tools was evaluated for bending and deep drawing. In bending, the shape accuracy of the bent sheets was improved by the reinforcement using hard materials and the modification of the tool shapes. The optimisation of the size, shape and number of the reinforcements is required for applied bending processes. The modification of tool shapes is speedy in comparison with conventional machining processes. On the other hand, sheet metals having comparatively low flow stress are suitable for deep drawing. The plastic tools are useful to prevent scratches in sheet metal forming. Without lubrication, although the seizure appears for conventional deep drawing with the steel die, the seizure is prevented for deep drawing with the plastic die. By manufacturing plastic tools using fused deposition modelling, small production runs of sheet metal forming become low-cost and speedy.

References

1. Kalpakjian S, Schmid SR (2014) Manufacturing engineering and technology, 7th edn. Pearson, pp 535–562
2. Gebhardt A (2011) Understanding additive manufacturing: rapid prototyping, rapid tooling, rapid manufacturing. Hanser
3. Hölker-Jäger R, Tekkaya AE (2017) Additive manufacture of tools and dies for metal forming. In: Brandt M (ed) Laser additive manufacturing: materials, design, technologies, and applications. Woodhead, pp 439–464
4. Abe F, Osakada K, Shiomi M, Uematsu K, Matsumoto M (2001) The manufacturing of hard tools from metallic powders by selective laser melting. J Mater Process Technol 111:210–213
5. Shipley H, McDonnell D, Culleton M, Coull R, Lupoi R, O'Donnell G, Trimble D (2018) Optimisation of process parameters to address fundamental challenges during selective laser melting of Ti-6Al-4V: a review. Int J Mach Tools Manuf 128:1–20
6. Wu T, Jahan SA, Zhang Y, Zhang J, Elmounayri H, Tovar A (2017) Design optimization of plastic injection tooling for additive manufacturing. Procedia Manuf 10:923–934
7. Cortina M, Arrizubieta JI, Calleja A, Ukar E, Alberdi A (2018) Case study to illustrate the potential of conformal cooling channels for hot stamping dies manufactured using hybrid process of laser metal deposition (LMD) and milling. Metals 8(2):102
8. Kumar S, Kruth JP (2010) Composites by rapid prototyping technology. Mater Des 31:850–856
9. Sood AK, Ohdar RK, Mahapatra SS (2010) Parametric appraisal of mechanical property of fused deposition modelling processed parts. Mater Des 31:287–295
10. Mori K, Maeno T, Nakagawa Y (2014) Dieless forming of carbon fibre reinforced plastic parts using 3D printer. Procedia Eng 81:1595–1600
11. Nakagawa Y, Mori K, Maeno T (2017) 3D printing of carbon fibre-reinforced plastic parts. Int J Adv Manuf Technol 91:2811–2817
12. Durgun I (2015) Sheet metal forming using FDM rapid prototype tool. Rapid Prototyp J 21(4):412–422
13. Leacock A, Volk G, McCracken D, Brown D (2017) The use of fused deposition modelled tooling in low volume production of stretch formed double curvature components. Procedia Eng 183:343–350
14. Nakamura N, Mori K, Abe F, Abe Y (2018) Bending of sheet metals using plastic tools made with 3D printer. Procedia Manuf 15:737–742

15. Harada Y, Murao T, Mori K, Tsuchida N, Fukaura K (2006) Prevention of seizure in deep drawing using plastic die. Mater Sci Forum 505–507:763–768

16. Mercado-Colmenero JM, Rubio-Paramio MA, Dolores la Rubia-Garcia M, Lozano-Arjona D, Martin-Doñate C (2019) A numerical and experimental study of the compression uniaxial properties of PLA manufactured with FDM technology based on product specifications. Int J Adv Manuf Technol, 103(5–8):1893–1909

17. Samykano M, Selvamani SK, Kadirgama K, Ngui WK, Kanagaraj G, Sudhakar K (2019) Mechanical property of FDM printed ABS: influence of printing parameters. Int J Adv Manuf Technol 102(9–12):2779–2796

18. Di Angelo L, Di Stefano P, Marzola A (2017) Surface quality prediction in FDM additive manufacturing. Int J Adv Manuf Technol 93:3655–3662