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PRODUCTION PROCESS

State-of-the-art of plate forging in Japan

K. Mori[1] **· T. Nakano**[2]

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Abstract The state-of-the-art of plate forging processes for forming complicated parts without cutting and finishing in Japan was reviewed. For cups having comparative large thickness and plates having complicated cross-sectional shapes, plate forging is more useful than conventional billet forging due to due to comparatively small change in shape. In plate forging, forging processes such as upsetting, extrusion and ironing are included in the sequence of conventional stamping composed of shearing, bending and deep drawing in order to control metal flow in plates. Plate forging has the advantages of higher performance, larger productivity, lower cost, etc. Plate forging processes are classified into desired functions of products, local thickening, local thinning, formability improvement and forming of gears and plates.

Keywords Forging · Plate · Thickness control · Thickening · Thinning

1 Introduction

Net-shape and near-net-shape forming without additional cutting and finishing operations is increasingly required to reduce the production cost. In conventional stamping processes, sheets are mainly deformed by tensile force. Although requirements for shapes of formed products are satisfied, it is not easy to control the distributions of wall thickness as shown in Fig. 1a. The thickness becomes generally small around corners of formed products due to tension, whereas the edges of drawn cups are thickened by compression in the hoop direction. If the distributions of wall thickness are not optimal for requirement of local strength, the weight of the products becomes excessive. For automobile parts, the reduction in weight is significantly required to improve the fuel consumption. In particular, the excessive weight is serious for comparatively thick parts. In addition, the amount of used material for forming processes using material flow can be saved by optimising the distribution of wall thickness unlike cutting, and thus this leads to the reduction in cost. It is desirable to develop net-shape forming processes of products having an optimum distribution of wall thickness for required strength. In plate forging, thickness distributions and shapes of formed products are controlled by including compressive operations such as upsetting, extrusion, ironing, etc. (Fig. 1b) in stamping operations.

When a sheet is compressed in the length direction for thickening, the sheet is buckled due to a small thickness. On the other hand, the compression in the thickness direction for local thinning brings about a large increase in forming load (see Fig. 2). It is not easy to include compressive operations in forming processes of plates.

Although cold forging has the function of forming products into complicated shapes, Nakano [1] explained that conventional forging processes from bars are inappropriate to the production of cups having comparatively large thickness and plates having complicated cross-sectional shapes due to large change in shape as shown in Fig. 3. For these products, forging processes from comparatively thick sheets or plates are appropriate due to small change in shape. In addition, liquid lubricants are

✉ K. Mori
mori@plast.me.tut.ac.jp

1 Department of Mechanical Engineering, Toyohashi University of Technology, Toyohashi, Aichi 441-8580, Japan

2 Technooffice Lin, Nakano 240, Midori-ku, Sagamihara, Kanagawa 252-0157, Japan

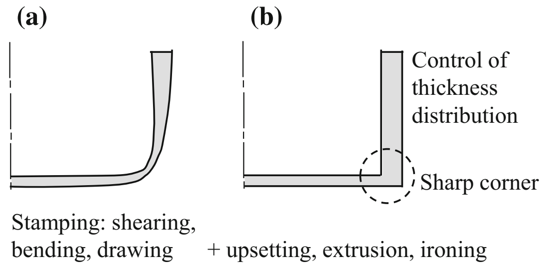

Fig. 1 Comparison between shapes of products formed by **a** conventional stamping and **b** plate forging

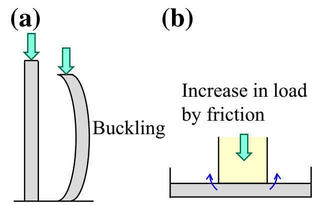

Fig. 2 Deformation behaviour in compression of sheet in **a** length and **b** thickness directions

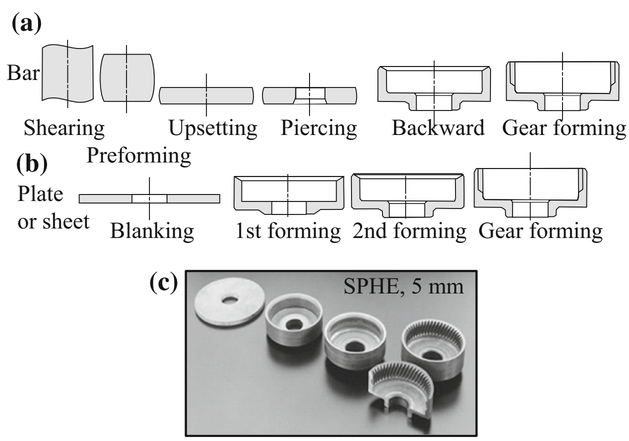

Fig. 3 Forging processes from **a** bar and **b** plate and **c** products formed by plate forging [1]

utilised for plate forging instead of zinc phosphate coatings generally used for forging from bars. Zinc phosphate coatings have environmental problems.

Merklein et al. [2] classified the bulk forming processes of sheet metals into translational and rotational motions of tools. The translational motion processes are forging of sheet metals including upsetting and extrusion, so-called plate forging, and the rotational processes are flow forming, shear spinning, orbital forming, etc. Although the rotational processes have high ability in controlling metal flow due to incremental forming, the productivity is not high. Since plate forging is operations using presses, the productivity is high, and industries have a wealth of

Fig. 4 Functional products formed by plate forging

knowledge for the press operations. Salfeld et al. [3] analysed an influence of presses on stability of plate forging operations.

The application of plate forging processes in Japan started from about 1990 for small-size precision parts used for watches and computers, e.g. net-shape forming having dimensional accuracy of micron order, forming of sharp steps using upsetting, severe ironing, blanking and shaving having small rollover and whole burnished surface. The application gradually expands in the automobile industry as an alternative to bar forging, powder metallurgy, casting and cutting to produce large-size functional parts used in transmissions, engines, etc. Deep drawing of thick plate and forming of different thicknesses using partial ironing are performed. The accuracy of stamped parts is heightened by introducing forging operations. Complicated parts shown in Fig. 4 can be produced by plate forging without cutting, and forming processes of these products are given in the following chapters.

2 Classification of plate forging

The features of stamping and forging processes are compared in Table 1. The stamping processes are mainly limited to the strength of sheets because of deformation by tensile force, and the forming pressure is kept comparatively small by increasing the number of stages. On the other hand, metal flow is actively controlled by high pressure in the forging processes, and thus the shape accuracy of products is heightened. In plate forging, forging processes such as upsetting, extrusion and ironing are included in the sequence of conventional stamping operations composed of shearing, bending and drawing in order to control metal flow in plates.

Table 1 Comparison between features of stamping and forging

Process	Stamping	Forging
Stress state	Tensile	Compressive
Forming limit	Tensile strength of sheet	Tool strength
Pressure	Low	High
Number of stages	Large	Small

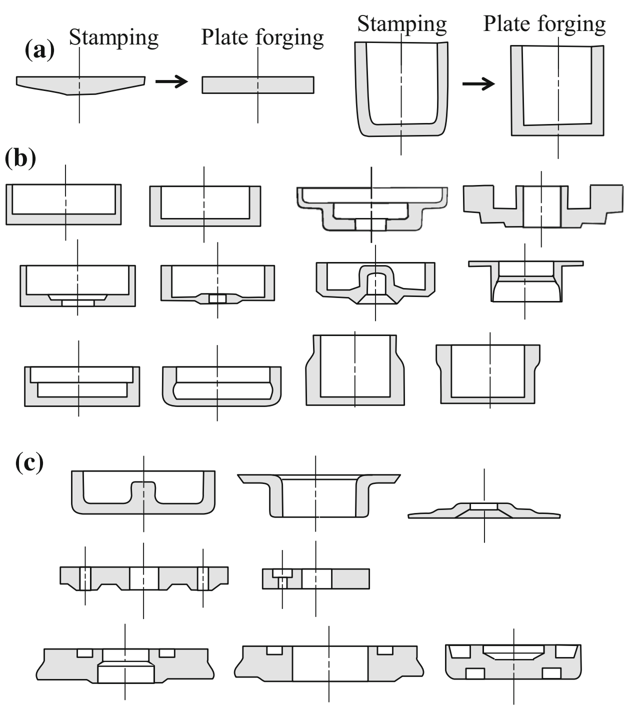

Fig. 5 Classification of cross-sections of products produced by plate forging processes. **a** Sharp corners, **b** different thicknesses and steps and **c** local shapes of products [4]

Nakano [4] classified the plate forging processes into some patterns of products as shown in Fig. 5. Although sharp corners, different thicknesses and local shapes are generally finished by cutting, these are finished by the compressive operations in plate forging.

The pressure range for plate forging is positioned between those for cold forging and stamping as shown in Fig. 6. The forming pressure of plate forging becomes higher than that of stamping due to the inclusion of forging operations. On the hand, the maximum pressure is limited, because presses and lubrication used for plate forging operations are similar to those for stamping operations. The design of sequence is a key to success in plate forging. The rise in forming load is prevented by increasing the number of stages. For the design of tools, stress concentration, elastic deflection, thermal expansion, seizure, etc. are taken into consideration, and tools are treated with shrink fitting and coating as well as cold forging. Tungsten carbide having high compressive strength and wear and seizure resistances is also utilised as tools for severe deformation. Kitamura et al. [5] measured plastic anisotropy used for simulation of plate forging processes from a small-cube compression test. Landkammer et al. [6] carried out a benchmarking of simulation of a plate forging process.

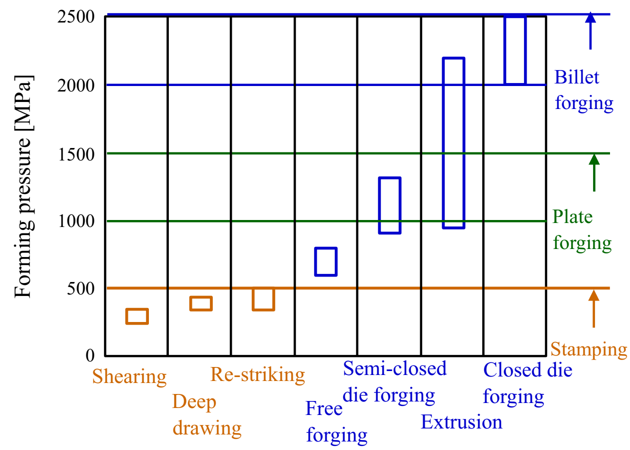

Fig. 6 Ranges of forming pressure for billet forging, plate forging and stamping [1]

The plate forging operations are included in stamping operations to control metal flow. Thinning and thickening of plates are performed to form complicated cross-sectional shapes. The plate forging processes have the following advantages:

1. Increase of flexibility in shapes of formed products
2. Increase in formability due to compressive stress
3. Smaller number of stages than conventional stamping
4. Forming of step and gear shapes
5. Improvement of dimensional accuracy due to small scatter of volume of sheared plates.

On the other hand, the disadvantages of plate forging are as follows:

1. Increases in tool wear and failure due to high contact pressure
2. Increase in material cost due to expensive sheets and large blanking scrap
3. Increase in press capacity due to large forming load and energy
4. Decrease in machinability and quenchability due to high formability of plates.

3 Local thickening

The most significant target for plate forging is local thickening of plates. Although surrounding material is piled up by indentation with a punch as shown in Fig. 2b,

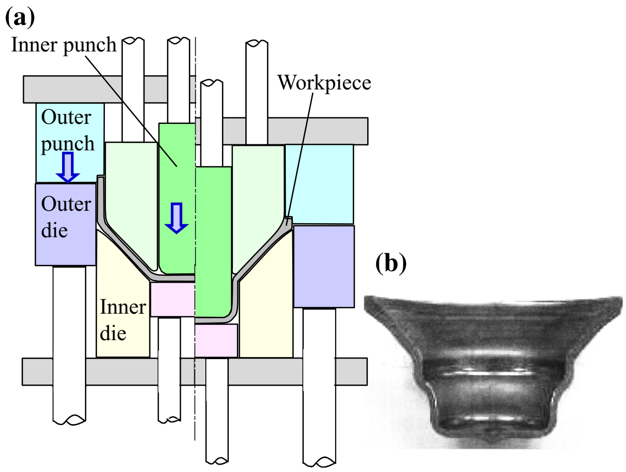

Fig. 7 Forming of step cup having thickened flange. **a** Drawing and compression and **b** formed product [8]

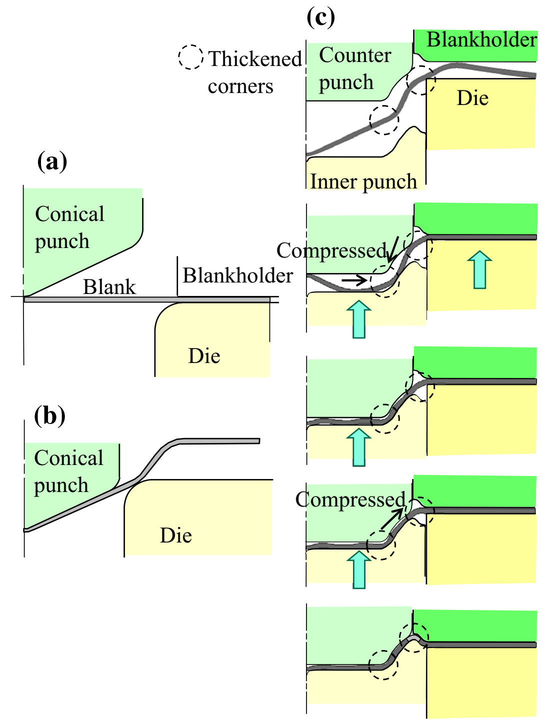

Fig. 8 Thickening around corner of wheel disk. **a** 1st, **b** 2nd and **c** 3rd stages [11]

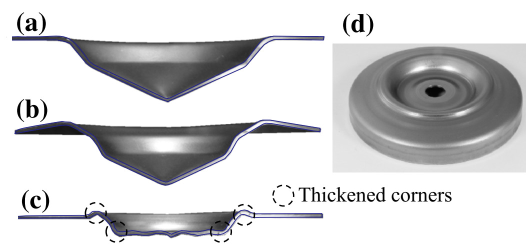

Fig. 9 Cross section of cup after **a** 1st, **b** 2nd and **c** 3rd stages and formed wheel disk [11]

the load for plate forging operations becomes excessively large as shown by Merklein et al. [7]. Local thickening of plates using compression in the thickness direction is inappropriate for plate forging. Plate forging processes for local thickening using control of metal flow have been developed.

Suzumura et al. [8] thickened the flange of the step cup by compression with the outer punch as shown in Fig. 7. In drawing of the bottom of the cup with the inner punch, the edge of the cup is pushed with the outer punch, and buckling of the flange is prevented with the outer die. The flange is thickened by the combination of drawing with the inner punch and compression with the outer punch, and the amount of thickening is adjusted by the strokes of the outer and inner punches. A multi-action press having three upper rams and two lower rams was designed to control these punches. Ishihara et al. [9] explained that the formed product approached an optimal shape, and the production cost was reduced by 30 %. This part is used as a sheave piston of a continuously variable transmission.

Tan et al. [10] developed a multi-stage forming process for increasing the wall thickness around a bottom corner in the cup with a flange. Abe et al. [11] increased the wall thickness around the bottom and flange corners in the cup with a flange by three stages as shown in Fig. 8. In the 1st and 2nd stages, the cup having a conical bottom is formed with the conical punches, and the volume of the drawn portion for the conical bottom is larger than that for the flat bottom. In the 3rd stage, the thicknesses around the bottom and flange corners are increased by compressing the conical bottom into a flat one. In the 3rd stage, the flange of the cup is first restricted by being sandwiched between the blankholder and die, and the side wall and conical bottom of the cup are compressed with the counter punch and inner punch. Local thickening of the two corners is attained by flattening the curved bottom under fixing the periphery.

The wall thicknesses around the bottom and flange corners of the cup with a flange are increased by about 10 % with the three-stage forming process as shown in Fig. 9. The cup with a flange is formed into a disk of an automobile steel wheel by subsequent four stages. The fatigue life of the automobile steel wheel is greatly improved by the increase in wall thickness around the two corners, and the weight of the wheel is reduced by the optimum distribution of wall thickness.

In the thickening of a side wall of a cup by compression, buckling tends to occur due to the gap between the container and side wall, and the laps are caused as shown in Fig. 10a. Katoh et al. [12] prevented the occurrence of

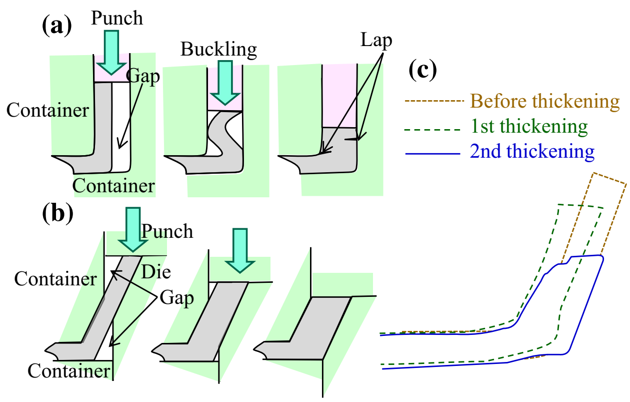

Fig. 10 Prevention of buckling in thickening of side wall cup. **a** Perpendicular side wall, **b** inclined side wall and **c** thickened side wall [13]

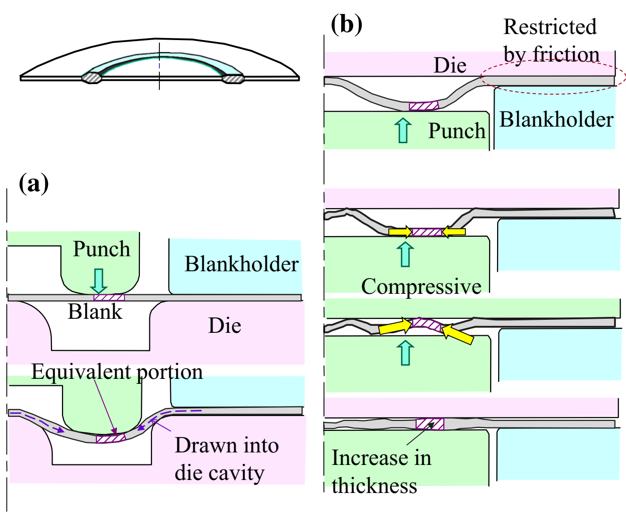

Fig. 11 Two-stage forming of circular tailor blank having local thickening. **a** Drawing and **b** compression [14]

bucking by compressing the inclined side wall under constraint with the tools as shown in Fig. 10b. Nishino et al. [13] exhibited the increase in wall thickness in the compression of the inclined side wall. Buckling is prevented by the restraint with the inclined dies during the compression.

The wall thickness around corners of parts is generally decreased by stamping, and this decrease often brings about reduction in strength of the parts. To compensate the decrease in wall thickness in stamping, Tan et al. [14] developed a two-stage forming process of circular tailored blanks having local thickening. In the 1st stage, the target ring portion of the sheet for local thickening is drawn into the die cavity, and then the bulging portion formed in the 1st stage is compressed with the flat die under clamping the flange of the sheet in the 2nd stage to thicken the target portion (see Fig. 11). The compressive load of the bulging portion is considerably lower than that for the direct compression of the sheet because of the cavity under the bulging portion. A 12 % increase of the thickness in the ring portion was successfully obtained. Tan et al. [15] stamped tailored high strength steel blanks having local thickening. In addition, Mori et al. [16] proposed a forming process of a tailored blank having local thickening for deep drawing of a square cup.

4 Local thinning

Since deeply drawn cups have a non-uniform distribution of wall thickness, the distribution is controlled by plate forging. The side wall of the product is largely ironed to a thickness of 1.5 mm from a plate having a thickness of 5 mm as shown in Fig. 12. By employing deep drawing, ironing and sizing in turn, the thickness of the side wall is accurately finished. This part is used in an electromagnetic clutch.

An extrusion process is applied to perform thinning of products in stamping. The ring is burred, drawn and ironed, and then is extruded into the thin tube as shown in Fig. 13. The tube is extruded by the friction of the punch simultaneously with pushing of the edge of the burred tube. Using ironing and extrusion, not only different thicknesses and steps but also sharp corners are formed.

Metal flow caused by local compression is useful for forming and shaping as shown in Fig. 14. When the blank is partially compressed, the edge of the blank is curved by the outer metal flow, and then the cup is formed by drawing the edge (see Fig. 14c). Using the compression, the

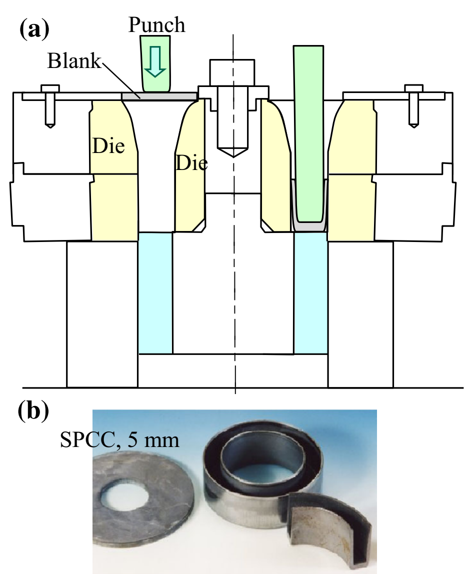

Fig. 12 Thinning of side wall by ironing. **a** Drawing and ironing and **b** product

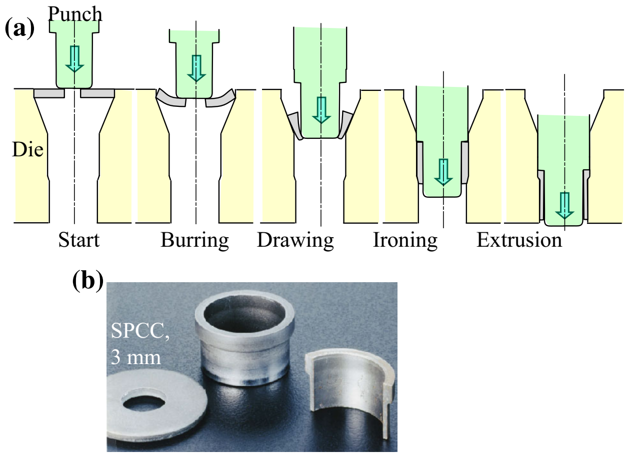

Fig. 13 **a** Forming process of thin tube from ring and **b** product

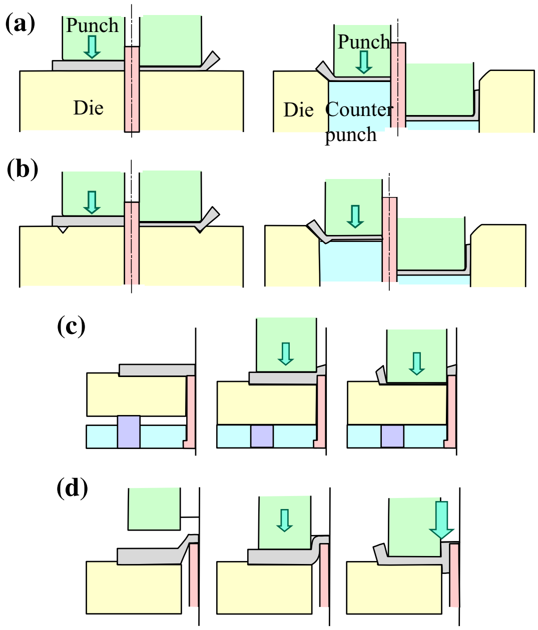

Fig. 14 Forming of functional cups using local compression. **a** Reduction of bottom, **b** sharp corner, **c** inner boss and **d** upper and lower bosses

thickness of not only the side wall but also the bottom can be controlled unlike conventional deep drawing. The sharp corner of the cup is formed by the circular dent of the die (see Fig. 14b). The central boss is formed with the central punch under compressing the blank (see Fig. 14c) and the lower boss is also formed by compressing the upper boss with the counter punch (see Fig. 14d).

The rotor having central upper and lower bosses formed by the process shown in Fig. 14d is shown in Fig. 15. Both outer and inner flows of material are caused by compressing the blank from 6 to 2.6 mm, and the central upper and lower bosses and the side are formed.

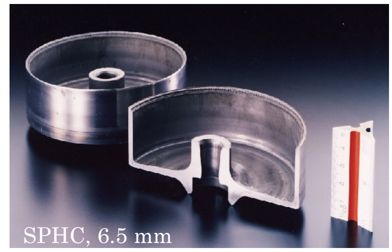

Fig. 15 Rotor having central upper and lower bosses formed by process shown in Fig. 14d

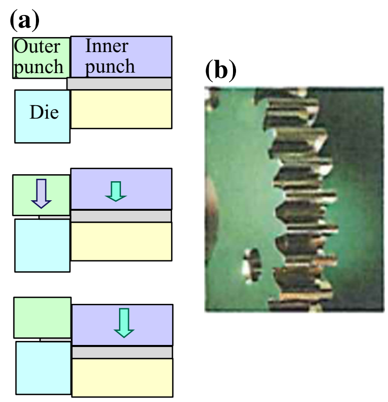

Fig. 16 **a** Double-action blanking operations for reducing rollover and **b** produced gear

5 Forming of sharp corner

To decrease the rollover of a blanked edge, a double-action forming process has been developed as shown in Fig. 16. The scraping portion is compressed with the outer punch and die, and then is blanked with the inner punch. The rollover is considerably reduced by compression with the outer punch and die, and the scrap is blanked under a compressive stress. The teeth of the blanked gear are sharply formed.

A tube with a flange is preformed by deep drawing of a cup having a flange and punching of the bottom of the cup. The preform is extruded under a comparatively low force by compressing the flange as shown in Fig. 17. The inside of the tube is stepped by the extrusion.

Warm stamping is generally employed for magnesium alloy sheets having low ductility at room temperature, the productivity is low. Mori et al. [17] developed a cold two-stage stamping process for forming magnesium alloy cups having a small corner radius from commercial magnesium alloy sheets (see Fig. 18). In the 1st stage, a cup having large corner radius is formed by deep drawing using a punch having large corner radius, and the corner radius of the cup is decreased by compressing the side wall with the outer punch in the 2nd stage. In deep drawing of the 1st

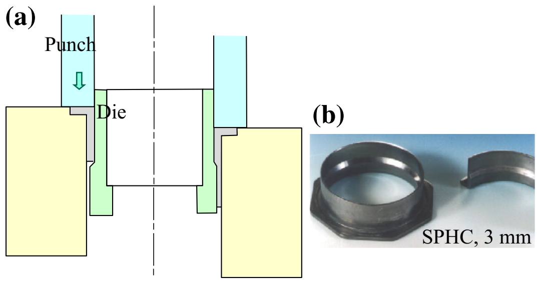

Fig. 17 **a** Double-action extrusion of stepped tube and **b** product

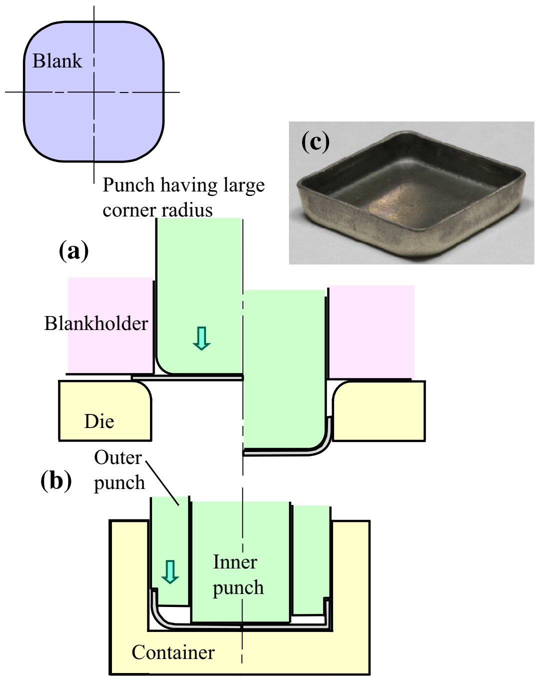

Fig. 18 Cold forming of magnesium alloy cups. **a** 1st and **b** 2nd stages and **c** formed square cup [17]

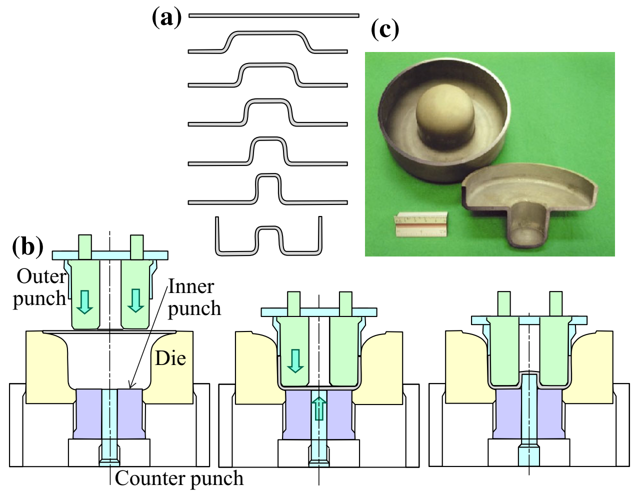

Fig. 19 One shot forming of double cup with multiple rams. **a** Conventional six stages, **b** one shot forming and **c** double cups

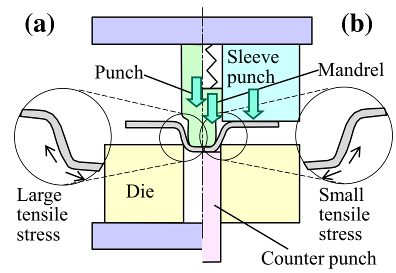

Fig. 20 **a** Conventional drawing and **b** compressive drawing for improving re-drawability of cup by applying compressive force to flange portion [21]

stage, fracture was prevented by relieving the concentration of deformation with the punch having large corner radius. Mori et al. [18] indicated that the magnesium alloy sheet was annealed at 500 °C to increase the cold formability. The square cup having a small corner radius was formed by two-stage cold stamping. Merklein et al. [19] formed a cup having bosses by compression of the side wall of a roughly drawn cup.

6 Improvement of formability

The forming process of double cups using multiple rams is shown in Fig. 19. Although the double cups are conventionally formed by six stages, the process is reduced to only one stage by drawing the internal boss of the cup under compressing the bottom. The compressive force of the bottom is controlled with the stroke of the boss to prevent the rupture. The accuracy of the product is improved by the one stage without transferring. Wang et al. [20] formed an internal boss of a double cup under deep drawing of an outer side wall.

Suzumura [21] increased the re-drawability of cups by applying the compressive force to the flange portion with the sleeve punch as shown in Fig. 20. The tensile stress acting around the corner of the cup is decreased by the compression. This leads to the reduction in the number of redrawing stages. The produced part is used in a planetary gear unit for increasing or decreasing torque of an engine.

7 Forming of gears

Gear drums used in automobile transmissions are produced by multiple forming operations using transfer dies. A plate is drawn into a cup, and the side wall of the cup is formed into a gear shape by ironing. Although the productivity is high for multiple forming using transfer dies, the capacity

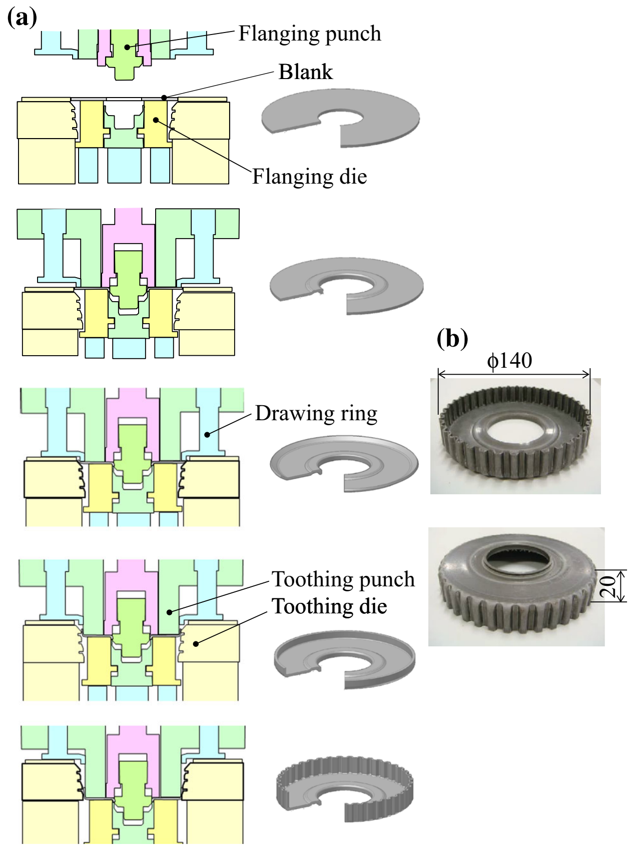

Fig. 21 **a** 1-shot multi-action forming process and **b** formed gear drum [23]

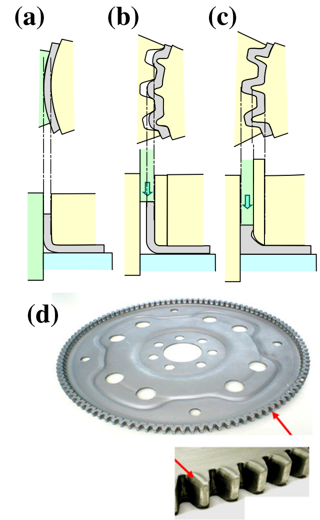

Fig. 22 Forming of disk gear having thick teeth. **a** 1st, **b** 2nd and **c** 3rd stages and **d** formed gear [24]

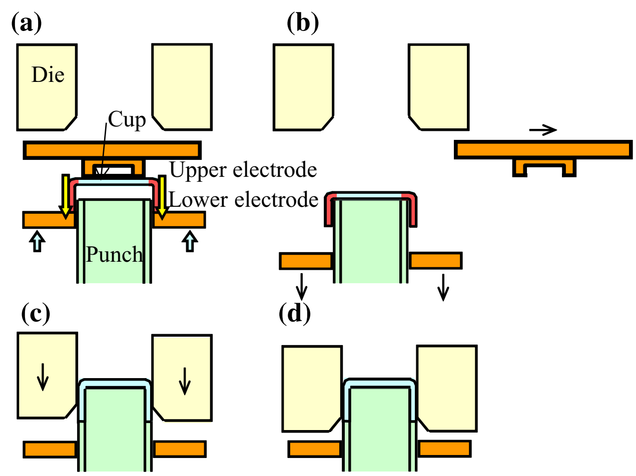

Fig. 23 Hot spline forming of steel gear drum using resistance heating of side wall of cup. **a** Resistance heating, **b** movement of electrodes, **c** spline forming and **d** die quenching [27]

of the press becomes large, and the number of dies increases. Wu et al. [22] designed forming processes of gear drums by finite element simulation.

To downsize presses for forming gear drums, Hayabuchi et al. [23] developed a 1-shot multi-action forming process as shown in Fig. 21. The central boss is flanged, the side of the drum is drawn, the sharp corner is formed and the side is splined. The formed gear drums have a high dimensional accuracy because of forming in a set of dies without transferring. The compact multi-action press is hydraulic and has three upper rams and two lower rams for controlling pressure and position individually.

The outer edge of the circular blank is formed into a gear as shown in Fig. 22. Maeda et al. [24] shaped the flanged edge into a gear by the compression with the punch. The teeth are thickened by flanging and compression. Sieczkarek et al. [25] incrementally formed a gear with indentation.

Although gear drums are conventionally made of mild steel sheets having high formability, it is desirable to produce the gear drums from the high strength steel sheets owing to the reduction in the weight of automobiles. However, cold spline forming of high strength steel cups having low formability is difficult due to severe deformation, in particular ultra-high strength steel cups. Mori et al. [26] developed a spline forming process of an ultra-high strength steel gear drum using resistance heating of a side wall of a cup formed by cold deep drawing and ironing (see Fig. 23). In Fig. 23a, the current is passed through the side wall of the cup between the upper and lower electrodes, and then the upper and lower electrodes are laterally and downward moved by the air cylinders, respectively as shown in Fig. 23b. The cup is formed into the gear drum with the punch and die (see Fig. 23c). The formed gear drum is die-quenched by holding at the bottom dead centre of a press as shown in Fig. 23d. When the thickness of the side wall of the cup is kept uniform by applying ironing in

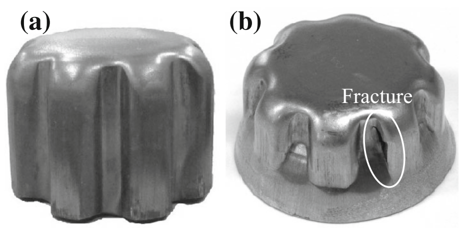

Fig. 24 **a** Gear drum produced by hot spline forming of quenchable steel sheet and **b** ruptured cup for cold forming [27]

the deep drawing operation, the side wall is uniformly heated by passing the current in the axial direction.

The gear drum was successfully formed by resistance heating of the side wall as shown in Fig. 24. The oxide scale hardy appeared on the surface of the drum because of rapid heating, only the colour change. The rupture of the cup is prevented by heating.

8 Forming of plates

When a plate is formed into a complicated shape by forging, the forming load largely increases. To decrease the load in plate forging, multiple stages are generally utilised, and not only transfer dies but also progressive dies are available in plate forging (see Fig. 25). Hayashi [28] explained a forming sequence in progressive dies for a double gear. Metal flow in the plate is controlled by repeating partial deformation in multi-stage forming, i.e. large increase in forming load is prevented by partial deformation.

In fine blanking, a plate is locked with V-shaped stingers to increase the compressive stress, and the clearance between a punch and die is very small, <1 %. The quality of the sheared edge is heightened by high compressive stress under locking. Since the fine-blanked parts generally have steps as shown in Fig. 26, fine blanking is combined with plate forging. Yoon et al. [30] carried out process design of plate forging of seat recliner parts.

High strength steel gear parts are conventionally produced by plate forging using progressive dies as shown in Fig. 25, and then are hardened by nitriding. The nitriding operation is long and costly. Hot stamping is applied to the latter stages of multiple operations using progressive dies to eliminate the post heat treatment as shown in Fig. 27. The former stages for punching and trimming were cold-stamping, and subsequently resistance heating, blanking, forging and die quenching were performed. The plate was partially resistance-heated with a pair of electrodes. Resistance heating is rapid enough to be included into progressive-die operations. The portion blanked into the teeth is held at the bottom dead centre of a press for die quenching. The times of resistance heating and die quenching are both about 10 s., and are balanced in each stage.

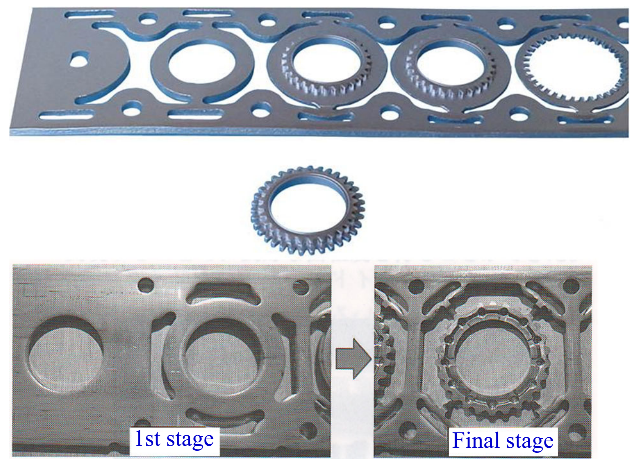

Fig. 25 Forming sequence in progressive dies [28, 29]

Fig. 26 Fine-blanked parts having steps

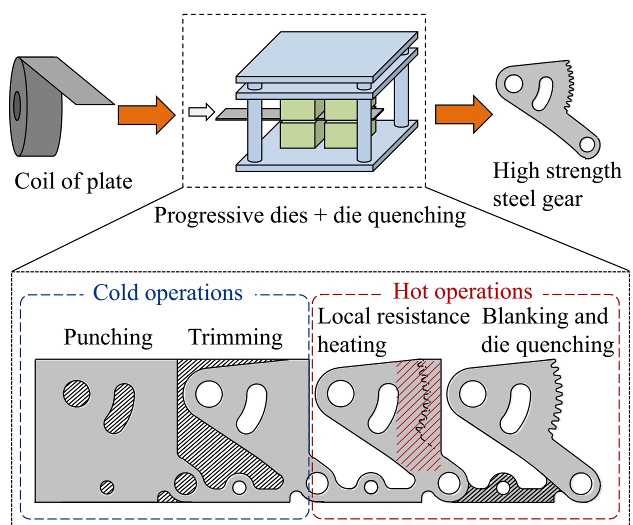

Fig. 27 Cold and hot operations in progressive-die hot stamping of gear part using partial resistance heating

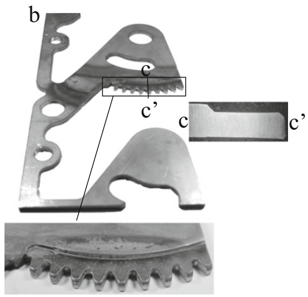

Fig. 28 Gear part produced by partial resistance heating, blanking of gear portion and die quenching

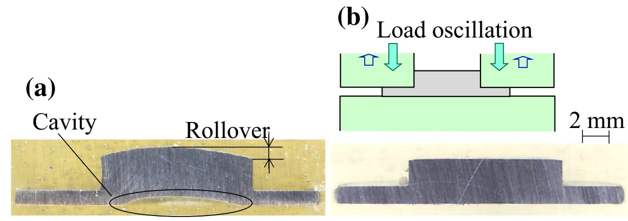

Fig. 30 Prevention of cavity in bottom of bottom and rollover of boss by load pulsation in forging of stainless steel plate. **a** No pulsation and **b** pulsation [34]

The produced gear part before removing from the plate is given in Fig. 28. The quenchable plate was used. The gear portion was flattened by the compression, and the rollover was improved. The local portion of the plate can be compressed because of local heating. The hardness in the gear portion was about 500 HV0.3 and that except for this portion was about 200 HV0.3. Mori et al. [31] developed plate forging processes including hot stamping for producing ultra-high strength steel parts.

Maeno et al. [32] proposed a plate forging process using load pulsation to decrease the forming load. In this process, the load is partially released at intervals of load to re-lubricate the surfaces of the plate. Gaps in the outer surfaces of the plate are caused in each release by the difference in elastic recovery between the die and plate, and the liquid lubricant is automatically fed into the gaps. The load-stroke curves with and without the load pulsation in compression of a circular plate using a servo press are given in Fig. 29. The sharp rise in compression load for a large stroke is prevented by the load pulsation. Since most of mechanical servo presses have the pulsation function as shown by Osakada et al. [33], the load pulsation is applicable to actual forming processes.

In the plate forging processes, mild steel and aluminium alloy plates are generally employed because of

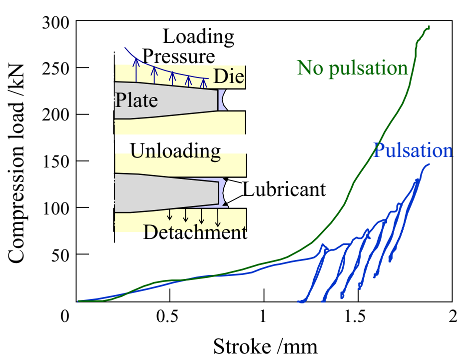

Fig. 29 Load-stroke curves in compression of plate with and without load pulsation [32]

comparatively low flow stress. Although forging of stainless steel plates is desirable in industry, it is not easy to form the stainless steel plates having large flow stress. Maeno et al. [34] applied the load pulsation to forging of a stainless steel sheet as shown in Fig. 30. The load pulsation is effective not only for the decrease in forming load but also for the improvement of forming shapes. The cavity in the middle of the bottom and the rollover of the boss are prevented by the decrease in friction for the load pulsation, and both upper and lower surfaces of the formed product become flat. This is due to the change in metal flow caused by the decrease in friction.

9 Conclusions

The plate forging processes are attractive for manufacturing products having a complicated shape. In these processes, forging operations are included in stamping operations. Since it is not easy to control distributions of wall thickness in sheets by the forming due to large increase in forming load, it is desirable in industry to develop forming approaches and sequences for attaining appropriate metal flow in the sheet. In addition, it is required to develop forming machines, tools, lubricants, etc. suitable for the plate forging processes. Servo presses and multi-action presses are useful for improvements of accuracy and flexibility. Tooling approaches that for bar forging because of high contact pressure. Tools are treated with shrink fitting and coating, and are made of tungsten carbide and cermet.

A mixture of tensile and compressive stresses is effective in accelerating metal flow in plate forging. On the basis of yield criterion in plasticity, the compressive stress in a plastically deforming body is decreased by action of tensile stress in the orthogonal direction, and thus the forming load can be decreased. On the other hand, the tensile stress is decreased by action of compressive stress in the orthogonal direction. This decrease is useful for preventing the occurrence of fracture. It is desirable that the forming process is designed to generate both tensile and compressive stresses. As described in this review paper, new processes are developed by combining tensile processes such as deep drawing and bulging, and compressive processes such as upsetting and extrusion.

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