# Incremental Forging of Long Plates having Inclined Cross-Section and Local Thickening

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***Abstract--*** **Incremental forging processes of long plates having an inclined cross-section and local thickening were developed. A long plate was compressed with an inclined punch to produce long parts having an inclined cross-section. Since local deformation was repeated in incremental forging, the forging load is comparatively small and hence small mechanical presses conventionally used in the forming industry can be used. Although waving and depression of the plate were decreased by a tapper bottom inclined punch, the plate curvature was large. A grooved die was employed to eliminate the curvature of the forged plate having an inclined cross-section. Plates having local thickening were also produced by beading and compression. The plate was freely compressed by a punch to form a beaded portion at the center of the sheet. The beaded portion was then compressed to form a local thickening without changing the width of the plate. The thick part possesses higher strength as compared to the thin part due to work-hardening during compression.**

***Index Term--*** **Incremental forging, Local thickening, Inclined cross-section, Tailored blank.**

## 1. INTRODUCTION

The weight of automobiles has grown steadily over the years to meet the rising demands for cars with power increase, safer structures, improved comfortableness, etc. The increase in car weight leads to a rise in fuel consumption. For the reduction in weight and the improvement in the crash safety of automobiles, plates are formed into various shapes and thicknesses. Kleiner et al. (2006) reviewed metal forming processes of lightweight components. Net-shape and near-net-shape forming without additional cutting and finishing operations is essential to optimize the performance and weight of parts. Although long plates having a uniform cross-section are generally produced by cutting, material loss is problematic and the cost of production increases. On the other hand, tailored blanks having different thicknesses are stamped to produce parts having large thickness in portions requiring high strength. Merklein et al. (2014) reviewed the application of tailored blanks in automobile parts. Chan et al. (2003) analyzed the formability of tailor-welded blanks having different thicknesses. Stress concentration by the change of thickness between the welded sheets brings about a reduction in formability. On the other hand, Mori et al. (2016) reviewed plate forging processes for forming complicated parts without cutting and finishing.

Extrusion processes have been employed to produce long products having a complex cross-section. For direct extrusion, sliding between the metal and the container wall causes increases in friction, temperature and extrusion force. Zhou et al. (2003) investigated the extrusion of aluminum alloy billet for parts having symmetrical cross-sections. Fang et al. (2009) produced parts having complex cross-section by extruding aluminum alloy at high temperature through double-pocket dies. Generally, aluminum alloy bar is extruded into various cross-sections. Stainless steel bars on the other hand are not extruded because of high heating temperatures.

Rolling processes have been applied to produce long plates having a uniform cross-section. The long plate is gradually formed into a complex profile through a series of rotating rolls. For thin walled structures, the long plates are subjected to buckling and wrinkling due to heterogeneous elongation along the strip. Tehrani et al. (2006) examined the effect of the folding angle on the formation of edge buckling during cold rolling of a channel. The large change in longitudinal strain occurring during rolling contributed to edge buckling defects. Using a numerical method, Zeng et al. (2009) optimized the forming angle and roll radius to reduce the number of stands, springback and waving of rolled parts. Carruth and Allwood (2012) produced beams having a non-uniform cross-section by multi-stage hot rolling. Parts with large curvature and wrinkles are produced by rolling of long plates.

Not only long plates but tailored blanks are also produced by rolling processes. Tailored blanks having a thickness distribution are produced by adjusting the roller gap (Kopp et. al (2005)). The produced tailor-rolled blanks having a thickness distribution offer substantial weight reduction and improvement in strength. The stress concentration from welding is reduced by the gradual change in thickness. Urban et al. (2006) prevented thinning of formed parts by controlling the thickness distribution of tailor-rolled blanks. Meyer et al. (2008) analyzed deep drawing of a square cup having a thickness distribution from tailor-rolled blanks. Tailor-rolled blanks improved the cup depth and reduced weight in deep drawing of square cups. Although rolling produces tailored blanks without joining, the distribution of strength is contrary for cold stamping. The thin portions of the tailor-rolled blank have a high strength through work-hardening.

Parts having thickness distribution are also produced by bulk forming processes of sheet metals. Allwood and Utsunomiya (2006) reviewed flexible forming processes including the forging process. Merklein et al. (2012) reviewed bulk forming processes of sheet metals including plate forging. Tan et al. (2008) produced tailored blanks having a local thickening for wheel disks by drawing and compression. In a similar approach, Mori et al. (2011) produced a tailored blank having thickness distribution by plate forging to prevent thinning at bottom corners of a deeply drawn square cup. Salfeld et al. (2012) formed gearing components by deep drawing and extrusion. Yoon et al. (2013) developed a plate forging process for seat recliner parts. Although complex functional parts are produced by plate forging, the large friction between the tools and sheet increases the forging load. As for long plate, forging entire parts in a single time requires a much higher load.

Plates of final desired shape and geometry are produced by incremental forging. Groche et al. (2007) reviewed incremental bulk metal forming processes including forging. Instead of forging of whole body of the plate, portions of the plate undergo multiple deformations and hence forging load is reduced. Hirt et al. (2007) developed multi-mesh method for incremental forging by finite element method. Jin and Murata (2004) developed an incremental forging process of curved plates with an inclined punch and adjusted the curvature of the forged plate by changing the forging interval of the plate. In a similar approach, Kuboki et al. (2014) developed a tiltable punch to bend the plates incrementally and control the radius of curvature.

In this study, incremental forging processes for producing plates having inclined cross-section and local thickening was proposed. In the first part, an incremental plate forging process was developed to produce long parts having an inclined cross-section. Since the plate was forged incrementally, only a small portion of the sheet is forged at one time, hence the forming load is reduced. In the second part, a forging process was carried out to produce plate having local thickening by beading and compression. The relationship between the degree of thickening and beading height was investigated.

## 2. INCREMENTAL FORGING OF LONG PLATE HAVING INCLINED CROSS-SECTION

The incremental forging process was developed to produce a long plate having an inclined cross-section as shown in **Fig. 1**. In step (a), the long plate is fed into the compression region using a feeder machine. The plate is then compressed with an inclined punch in step (b). The plate is moved again for the next compression using the same forging interval (see step (c)). These steps are repeated until the desired compression length is achieved.

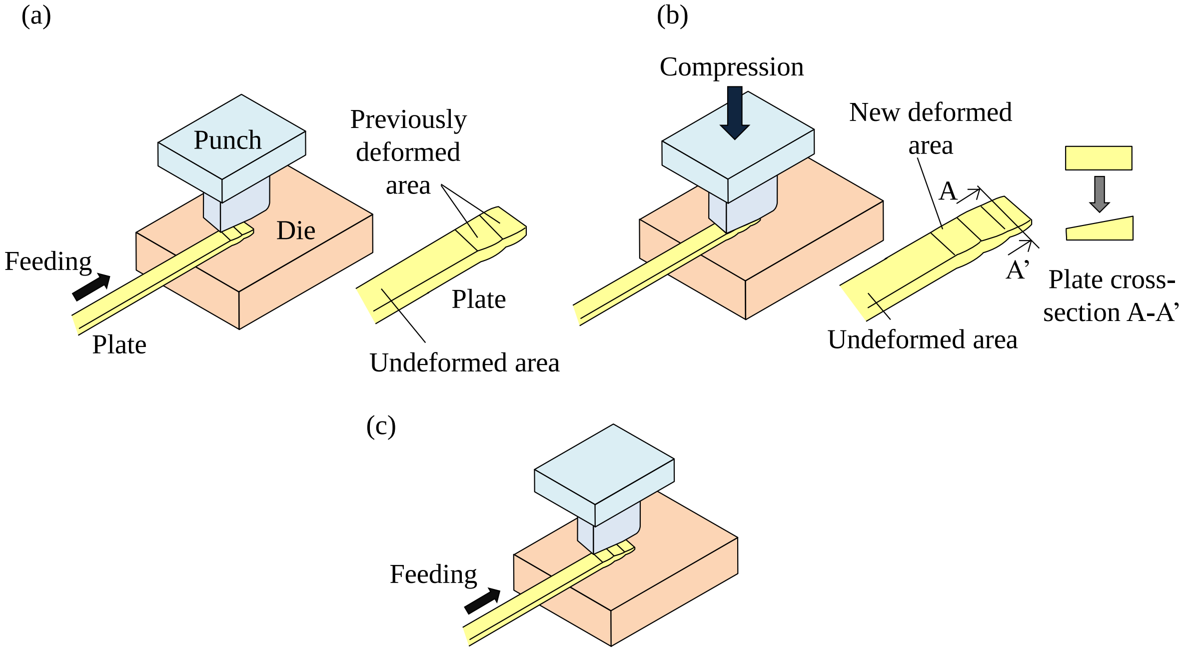


Fig. 1. Steps in incremental forging of long plate having inclined cross-section, (a) feeding, (b) compression and (c) feeding.

The experimental setup for incremental forging of long plates having an inclined cross-section is shown in **Fig. 2**. A 1500 kN mechanical servo press was employed. The plate is fed by the feeder at a specific interval. The curvature of the forged plate is prevented by the upper and side guides.

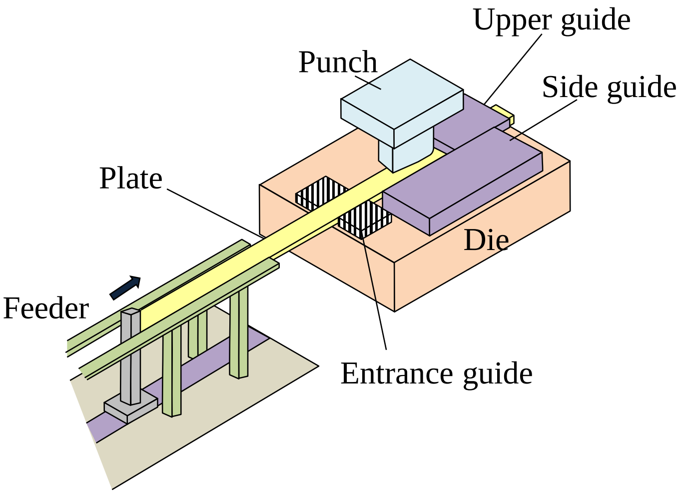


Fig. 2. Experimental setup for incremental forging of long plate having inclined cross-section.

Two types of inclined punch were used in this experiment to investigate the effect of the punch shapes on the plate having an inclined cross-section. The flat and taper bottom punches are shown in **Fig. 3**. Both punches have a surface inclination of 5.7° for forming the plate into an inclined cross-section. The taper bottom punch has the inclined surface of 5° and the flat surface of 6 mm, while the flat bottom punch has a horizontal surface of 28 mm.

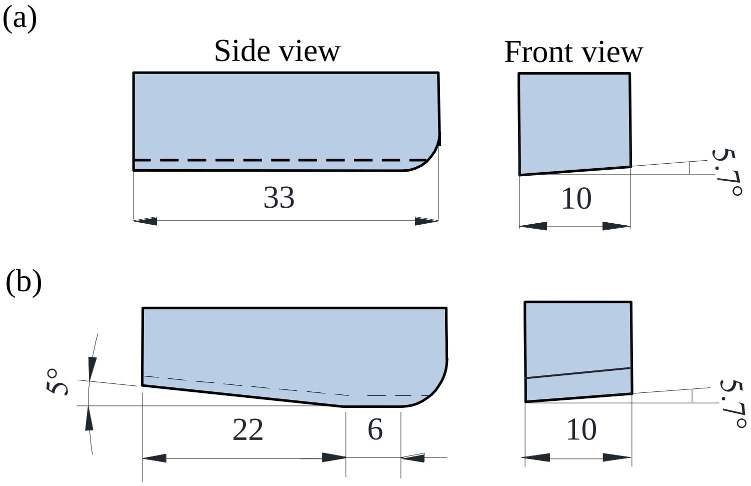


Fig. 3. Dimensions of (a) flat and (b) taper bottom inclined punches.

The pure aluminum A1050 and stainless steel SUS430 plates were used in the experiment. The conditions of plates used for the experiment are shown in **Table I**. The forging interval was varied to investigate its effect on the forging load and plate deformation behavior. The forging condition used for the experiment of incremental forging is given in **Table II**.

Table I
Plates used for experiment of incremental forging.

| Plate | Hardness<br>[HV 0.05] | Thickness *t* | width | length |
|---|---|---|---|---|
| Pure aluminum A1050 | 31.3 | 2.0, 3.0 mm | 8 mm | 500 mm |
| Stainless steel SUS430 | 122 | 1.9 mm | 8 mm | 500 mm |

Table II
Forging condition used for experiment of incremental forging.

| Conditions | Aluminum A1050 | Stainless steel SUS430 |
|---|---|---|
| Forging interval *f* | 3, 5, 10, 20 mm | 1, 3, 5 mm |
| Amount of feed | 200 mm | 200 mm |
| Average punch speed | 20 mm/s$^{-1}$ | 20 mm/s$^{-1}$ |
| Reduction in thickness at punch tip | 1.2 mm | 1.1 mm |

## 3. RESULT FOR LONG PLATE HAVING INCLINED CROSS-SECTION

The long plate having an inclined cross-section was incrementally forged with the flat and taper bottom punches for $t$ = 3 mm and $f$ = 5mm (**see Fig. 4**). Without the side guide, the plates is largely curved. For the flat bottom punch, waving on the plate sides and depression on the plate surface were caused. Waving and depression were prevented with the taper bottom punch. The curvature of the forged plate was large because of the different deformation rate of the plate during compression. The relationship between the radius of curvature and forging interval is shown in **Fig. 5**. The radius of curvature increases with increasing forging interval.

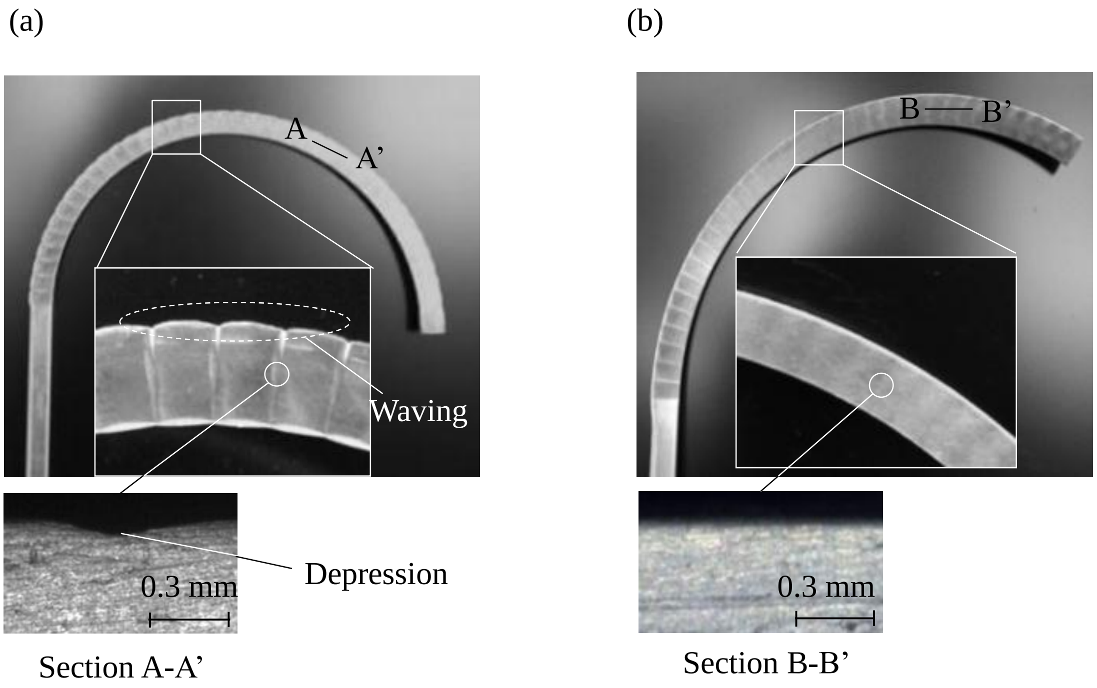


Fig. 4. Long plate having inclined cross-section incrementally forged with (a) flat and (b) taper bottom punches for $t$ = 3 mm and $f$ = 5mm.

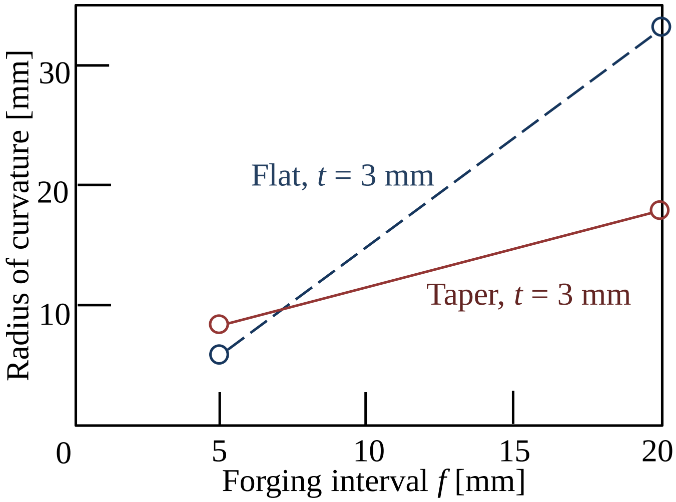


Fig. 5. Relationship between radius of curvature and forging interval.

A side guide was introduced to prevent the side curvature of the forged plate. The distance between the plate and side guide was 3 mm. The forged plates having an inclined cross-section with the side guide and taper bottom punch are shown in **Fig. 6**. The curvature of the forged plate having an inclined cross-section was reduced. For *f* = 3 mm, the reduction in thickness was larger than that of 5 mm.

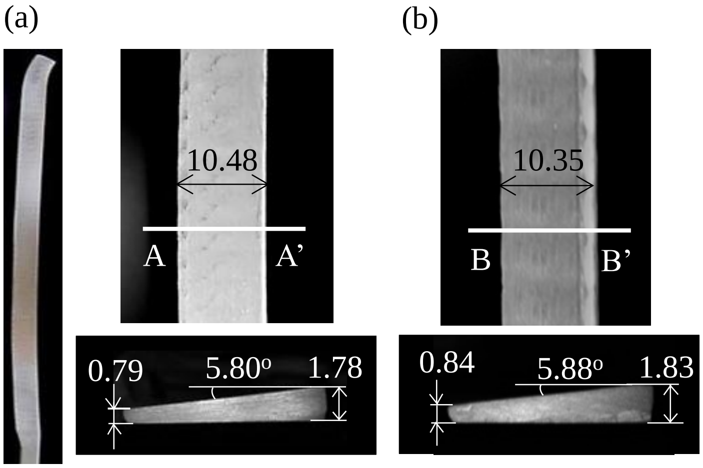


Fig. 6. Forged plates having inclined cross-section with side guide and taper bottom punch for (a) *t*= 2 mm, *f*= 3 mm and (b) *t*= 2 mm, *f*= 5 mm.

The degree of waving was defined as an average difference between the widths ($W_1$-$W_2$), where $W_1$ is the maximum width and $W_2$ is the minimum width in each 10 intervals of the forged plate. The relationship between the average width difference and the forging interval for the two punches is shown in **Fig. 7**. The width difference was reduced with the taper bottom punch and the small forging interval. The waving defect was reduced.

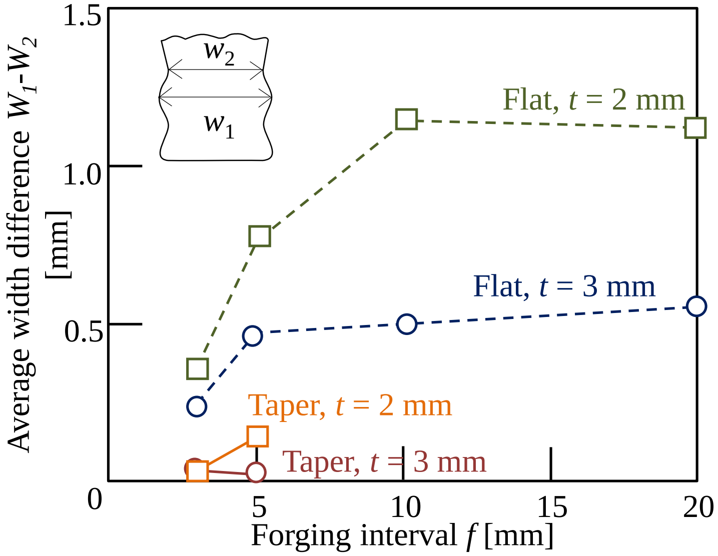


Fig. 7. Relationship between the average width difference and forging interval for two punches.

The relationship between the elongation in the longitudinal direction and the forging interval for the two punches is given in **Fig. 8**. As the forging interval decreases, the elongation of the compressed plate increases. The change in the width is small as compared to the length due to the large width-to-length ratio of the punch.

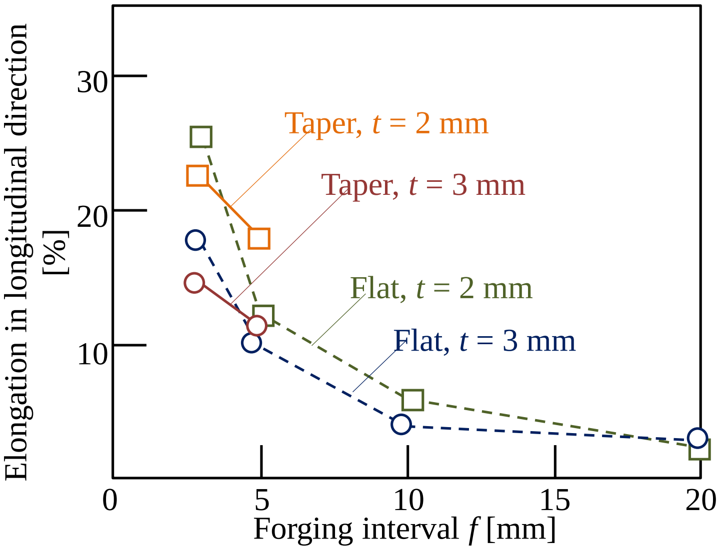


Fig. 8. Relationship between elongation in longitudinal direction and forging interval for two punches.

In incremental forging, the forging load is comparatively small due to repeated local deformation of the plate. The relationship between forging load and forging interval for two punches is given in **Fig. 9**. The forging load becomes small with the decrease in the forging interval with the flat and taper bottom punches. For the taper bottom punch, the forging load is smaller as compared to the flat bottom punch. Since the forging load decreases with a decrease in forging interval, small mechanical presses conventionally used in the forming industry can be used for a small forging interval.

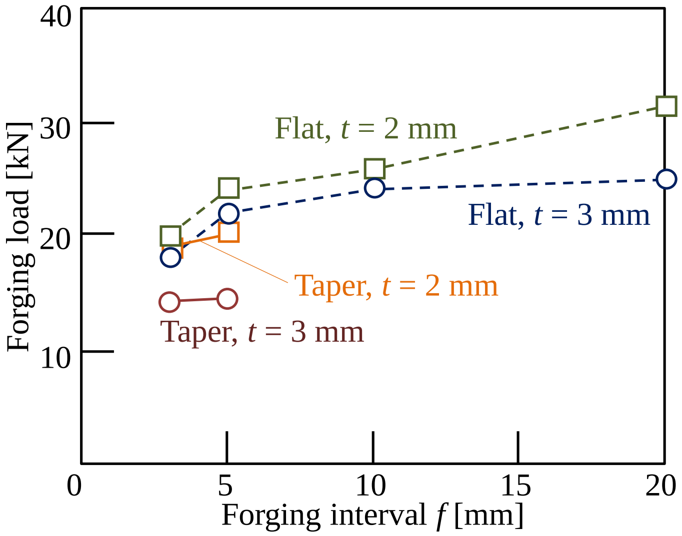


Fig. 9. Relationship between forging load and forging interval for two punches.

The relationship between reduction in thickness and forging interval is given in **Fig. 10**. The reduction in thickness of the plate having an inclined cross-section increases with decreasing forging interval. For a small forging interval, the load required is smaller as compared to that for a large forging interval. Therefore the elastic deformation of the press and tools is comparatively small, and thus the reduction in thickness is large. For a large forging interval, the large load causes a large elastic deformation, and the reduction in thickness becomes small.

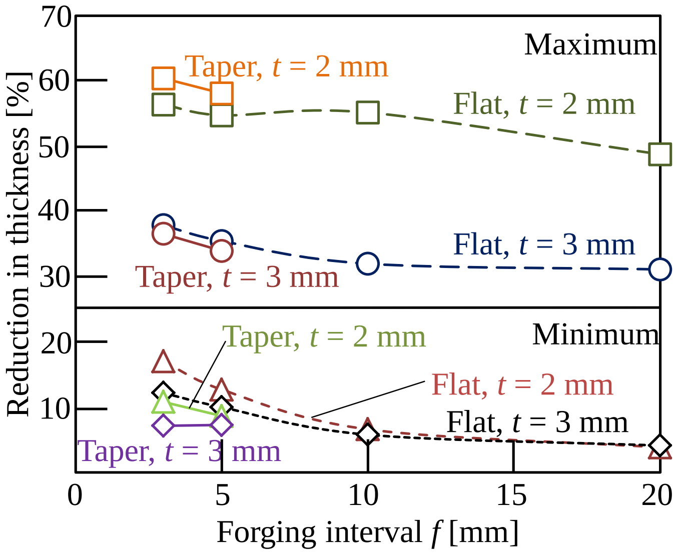
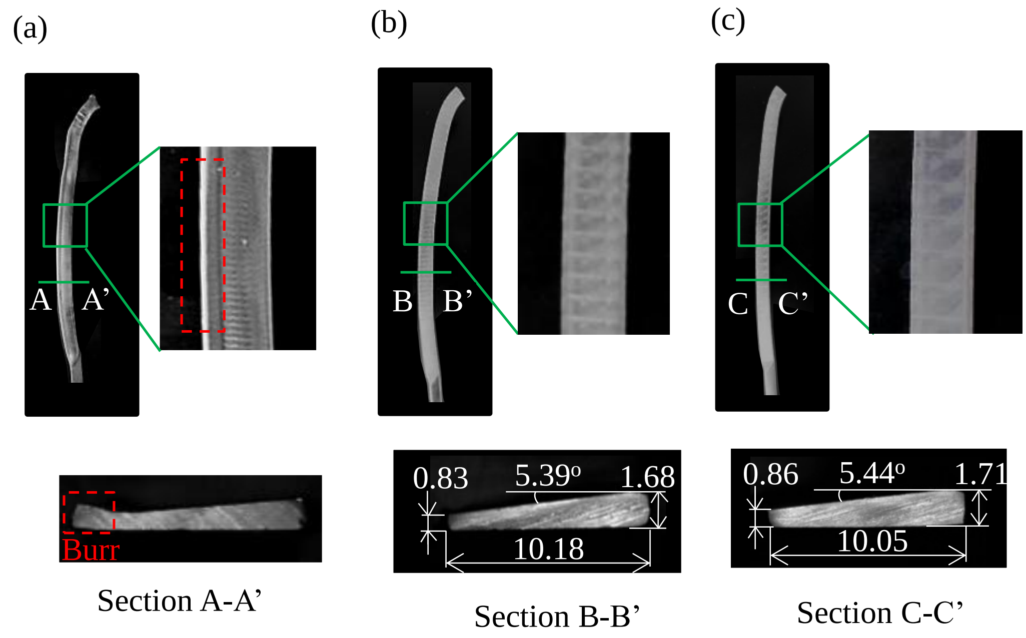


Fig. 10. Relationship between reduction in thickness and forging interval for two punches.

The incremental forging operations of stainless steel plates with a taper bottom punch and a side guide were carried out. The forging intervals were 1, 3 and 5 mm. The stainless steel plate having an inclined cross-section for different forging intervals are shown in **Fig. 11**. The plates showed minimum waving and depression. However, a slight curvature formed on these plates. For the stainless steel plate for *f* = 1 mm, a burr formed on one side of the plate.



Section A-A’ Section B-B’ Section C-C’

Fig. 11. Stainless steel plates having an inclined cross-section for (a) $f$ = 1 mm, (b) $f$ = 3 mm and (c) $f$ = 5 mm.

For a very small interval of $f$ = 1 mm, the curvature becomes large. The plate curved towards the side guide and shifted away from the forging area. As the plate shifted out, a burr is formed during the compression process. The burr formation on the side of the stainless steel plate having an inclined cross-section is illustrated in **Fig. 12**.

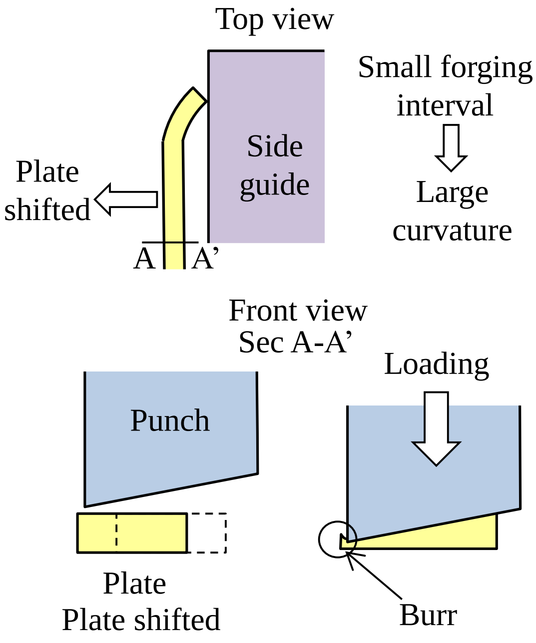


Fig. 12. Burr formation on side of stainless steel plate having inclined cross-section.

Deformation behaviors of the aluminum and stainless steel plates with the side guide have been examined. Although the side guide reduces the curvature of the forged plate having an inclined cross-section, the plates formed a burr for $f$ = 1 mm and a slight curvature. To overcome these problems, a grooved die was introduced. The grooved die is shown in **Fig. 13 (a)**. This die has a grooved width of 10.5 mm. The taper bottom punch and the upper guide were employed (see **Fig. 13 (b)**).

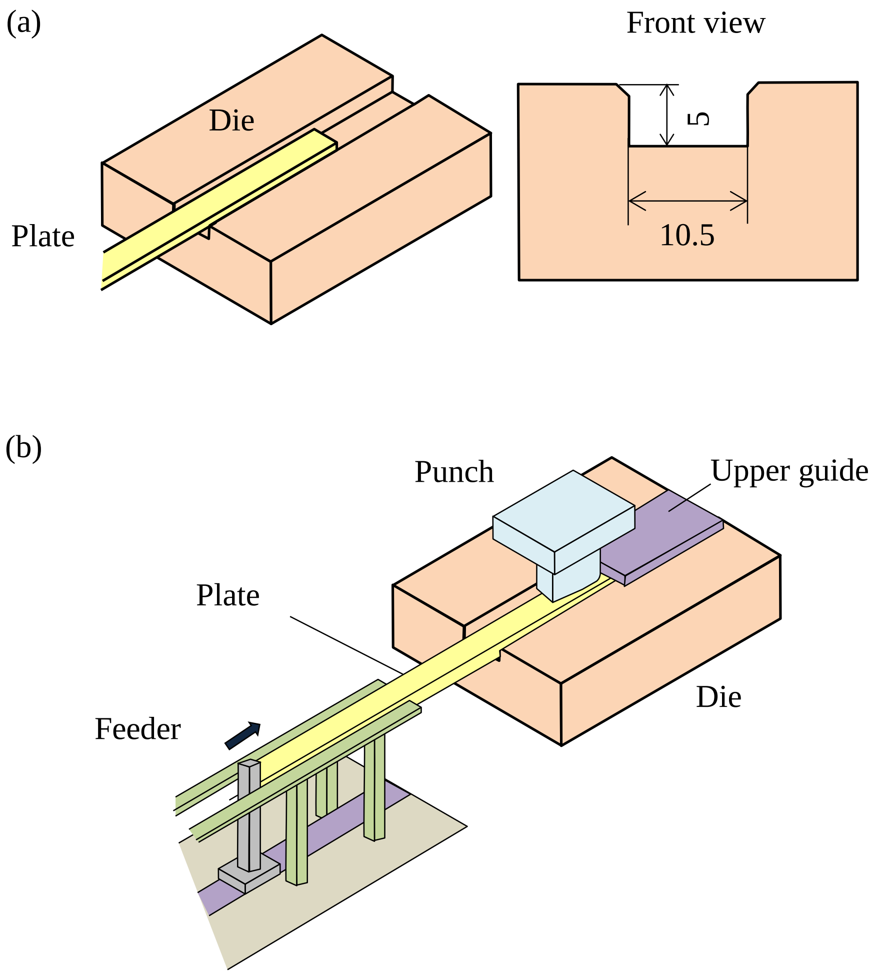


Fig. 13. (a) Grooved die for preventing curvature of formed plate (b) experimental setup with grooved die.

The resulting stainless steel plates having an inclined cross-section are shown in **Fig. 14**. For *f* = 3 mm and 5 mm, the curvature of the plates was further reduced. Since the taper bottom punch was utilized, wrinkling and depression were minimized. For *f* = 1 mm, burr was eliminated however waving on the sides of the plates was observed.

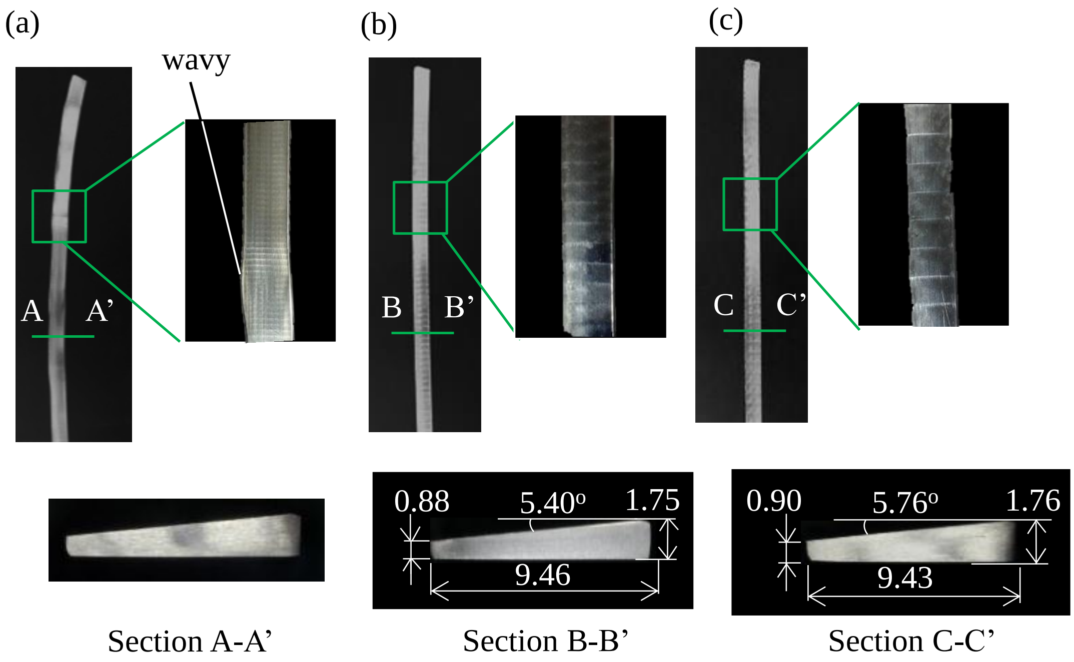


Fig. 14. Stainless steel plates having inclined cross-section for (a) *f* = 1 mm, (b) *f* = 3 mm and (c) *f* = 5 mm.

The relationship between the forging load of the stainless steel and aluminum plates and the forging interval is shown in **Fig. 15**. The forging load for each material was almost the same for *f* = 1, 3 and 5 mm using a taper bottom punch.

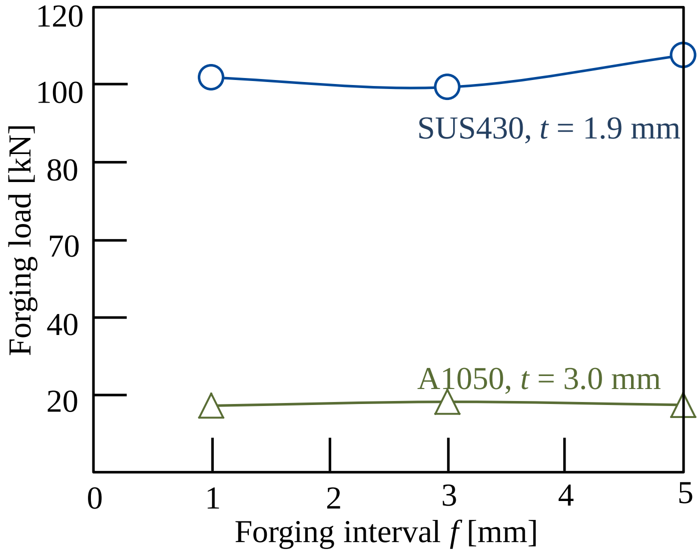


Fig. 15. Forging load for stainless steel and aluminum plates.

The relationship between the average width difference and forging interval for aluminum and stainless steel plates is shown in **Fig. 16**. The waving for both plates was minimized by the taper bottom punch.

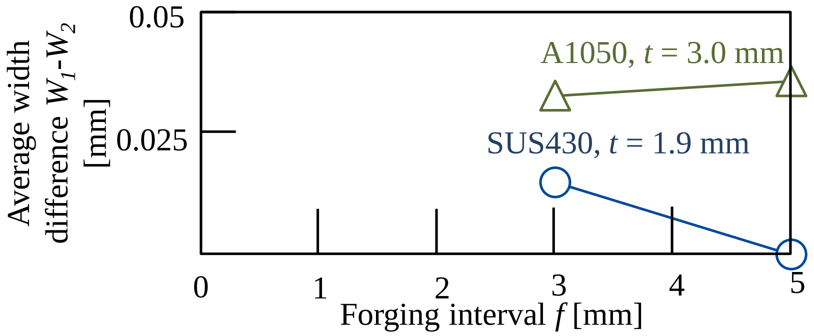


Fig. 16. Relationship between the average width difference and forging interval for aluminum and stainless steel plates.

## 4. BENDING AND COMPRESSION FOR FORMING LONG PLATE HAVING LOCAL THICKENING

The two-stage local thickening process of a long plate by incremental forging is shown in **Fig. 17**. In the beading stage, the long plate is compressed to form a beaded portion at the center of the plate. Then the plate is fed into the compression region. Both the end sides of the plate are constrained and thickening is formed by compressing the beaded portion. Although incremental forging reduces the forging load, the incremental forging process of long plate having local thickening is not easy to implement due to different deformations of plate under one stroke. Therefore in this chapter, the two-stage local thickening process was conducted on a plate with reduced in the length.

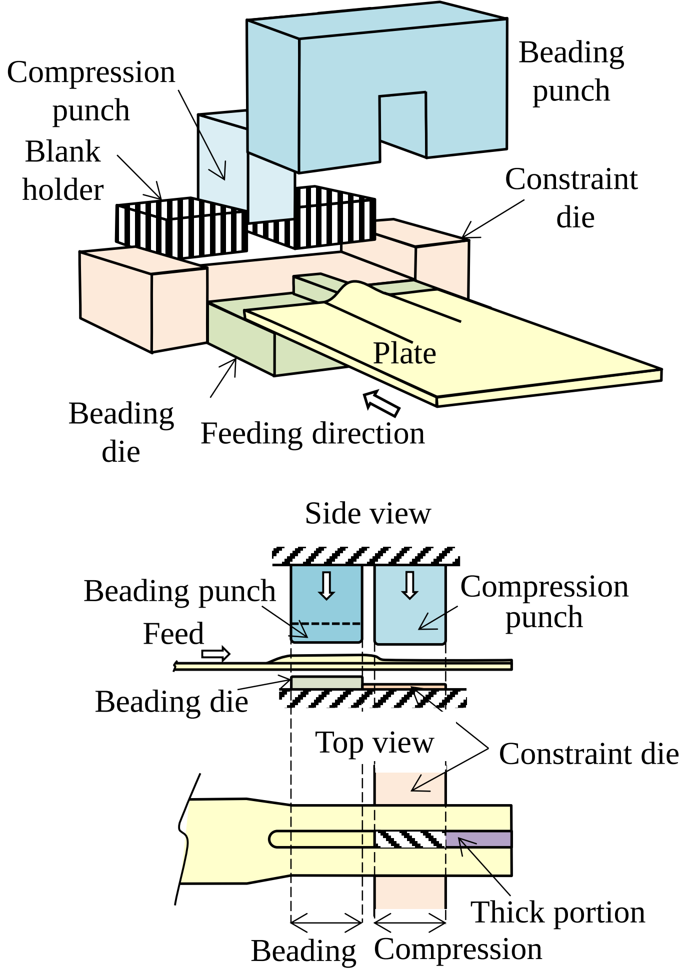


Fig. 17. Two-stage local thickening process of long plate by incremental forging.

Local thickening of plate by beading and compression is shown in **Fig. 18**. The center portion of the plate was beaded and compressed to form local thickening. In the 1st stage, the width of the plate was reduced and the beading die height was varied to control the amount of local thickening. During the 2nd stage, the width of the blank was confined while the beaded portion is compressed to obtain a local thickening at the center portion of the blank. The thick part possesses higher strength as compared to the thin part due to work-hardening.

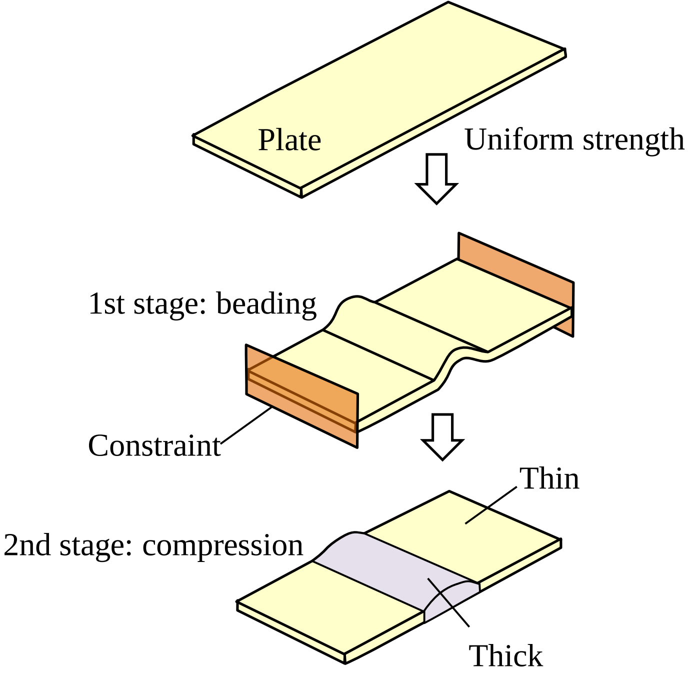


Fig. 18. Local thickening of plate by beading and compression.

The experimental setup for the plate having local thickening by beading and compression is given in **Fig. 19**. In the beading stage, a blank having a uniform thickness was beaded freely by a grooved punch. The plate width decreased during the beading process. In the compression stage, the flanges of the blank were restricted with the die. Springs were attached onto the blank holders and the blank holders were clamped onto both of the plate flanges to prevent wrinkling. The punch then compressed the beaded area to obtain local thickening. The floating die was supported by two springs which pushed the floating die up after compression to ease the plate removal. No change in the width of the plate occurred during compression.

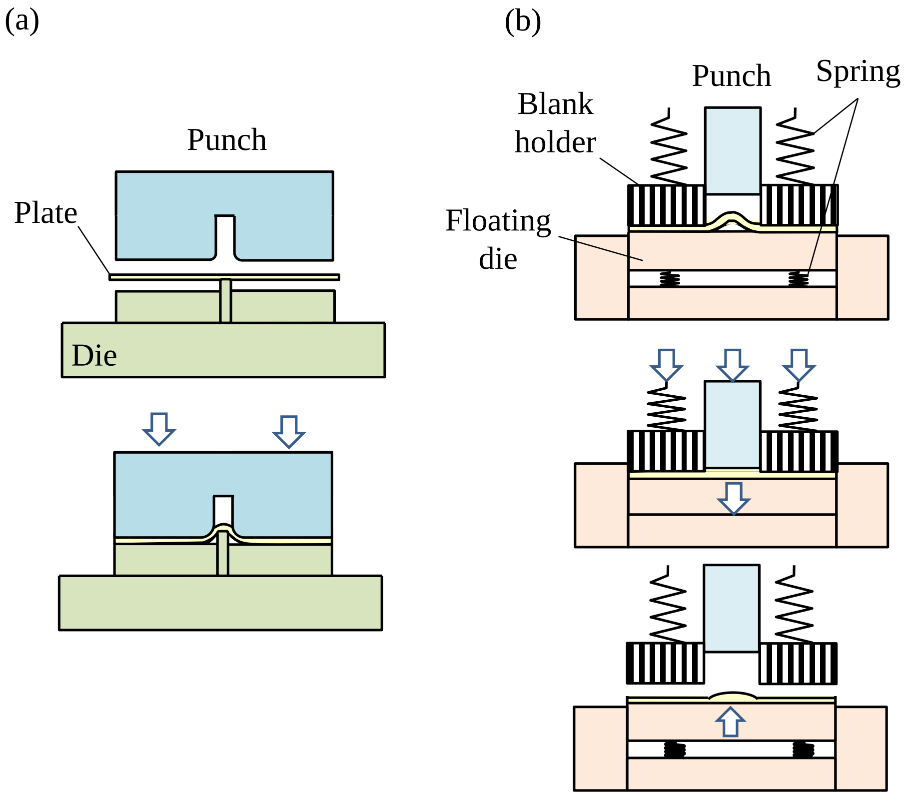


Fig. 19. Experimental setup for plate having local thickening by (a) beading and (b) compression.

The dimensions of the beading and compression dies are given in **Fig. 20**. The punches and dies were made of SKD11. The beading die height, *h* was varied between 3 and 8 mm. The angles of the beading die, $\alpha$ were $90^o$, $120^o$ and $180^o$. The corner of the beading die has a radius of 2 mm. The length of the confined area of the compression die was 100 mm.

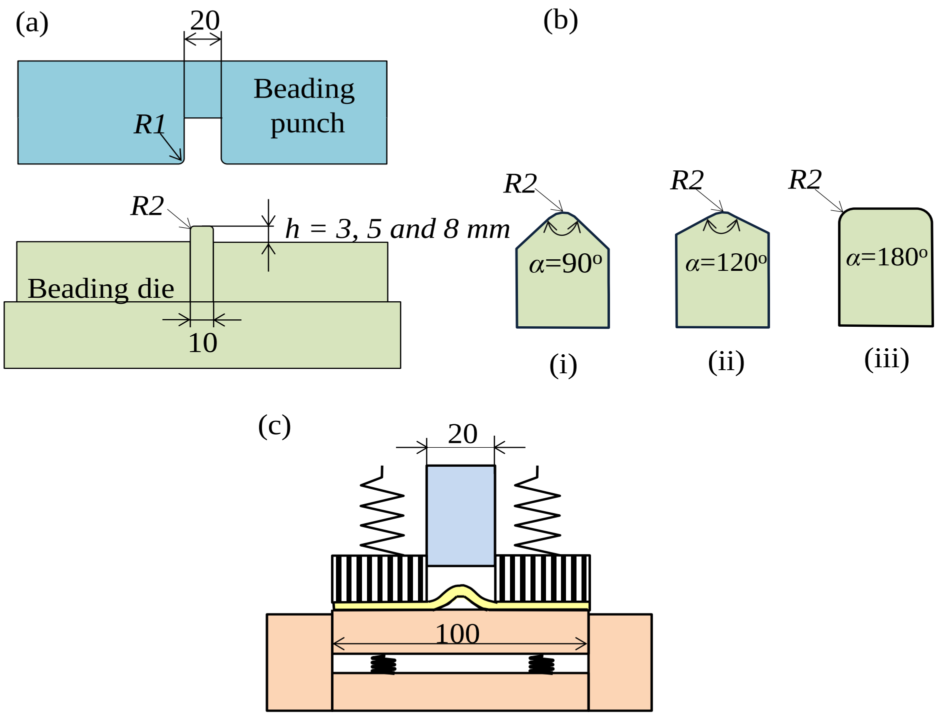


Fig. 20. (a) Beading die, (b) types of beading die and (c) compression die dimensions.

The conditions used for the plate forging of aluminum A1050 and SPCC plates are given in **Table III**. The thickness of the aluminum plate was 0.5, 1.0 and 1.5 mm while that for the SPCC plate was 0.5 and 1.0 mm. Since the beading height was changed, the plate widths were set to 101.0, 10.3.5 and 108.5 mm to obtain a constant plate width of 100 mm after the beading process. The plate length was the same for all conditions at 50 mm. No lubricant was used in the thickening process.

Table III
Conditions used for incremental forging of aluminum A1050 and SPCC plates.

| Plate | Aluminum A1050 | SPCC | |
|---|---|---|---|
| Tensile strength | 105 MPa | 334 MPa | |
| Hardness HV 200 | 31 | 95 | |
| Plate thickness *t* | 0.5, 1.0, 1.5 mm | 0.5, 1.0 mm | |
| Plate length | 50 mm | | |
| Plate width | 101.0 mm | 103.5 mm | 108.5 mm |
| Beading die height *h* | 3 mm | 5 mm | 8 mm |

## 5. RESULTS FOR PLATE HAVING LOCAL THICKENING BY BEADING AND COMPRESSION

### *5.1 Local thickening by beading and compression for aluminum plate*

The deformation behavior of the aluminum plate after beading and compression for different beading heights with $\alpha = 180^{o}$ is shows in **Fig. 21**. The thickness of the sheet was 1.0 mm. As the beading die height increases, the beaded portion increases. Local thickening was observed for *h*= 3 and 5 mm. However for *h* = 8 mm, folding occurred.

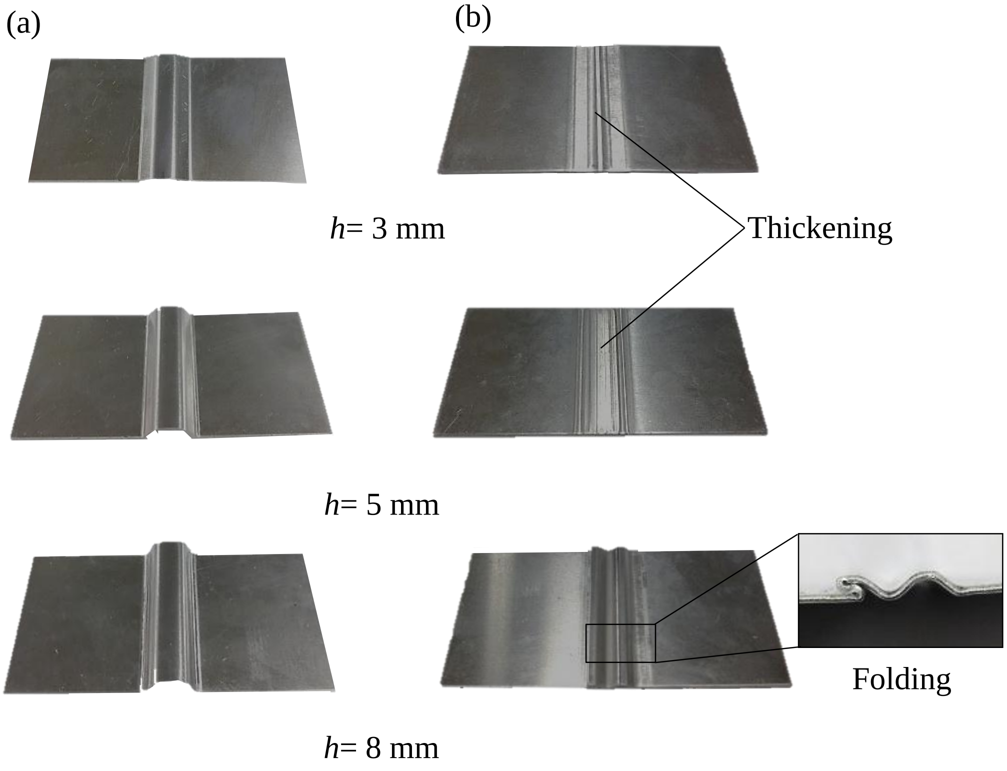


Fig. 21. Deformation behavior of aluminum plate after (a) beading and (b) compression for different beading heights for $\alpha = 180^{o}$.

The thickening behavior of aluminum plates was observed to investigate the formation of local thickening and folding during beading and compression. The thickening behavior for aluminum plates having a thickness of 1.5 mm for *h* = 5 and 8 mm is given in **Fig. 22**. A beading die of $\alpha = 180^{o}$ was utilized. The cross-sections of the plate were taken at different punch strokes. For *h* = 5 mm, the sidewall was inclined and local thickening formed at the beaded portion.

However as for $h$ = 8 mm, both sidewalls of the beaded portion were almost vertical as compared to $h$ = 5 mm. Therefore folding was observed.

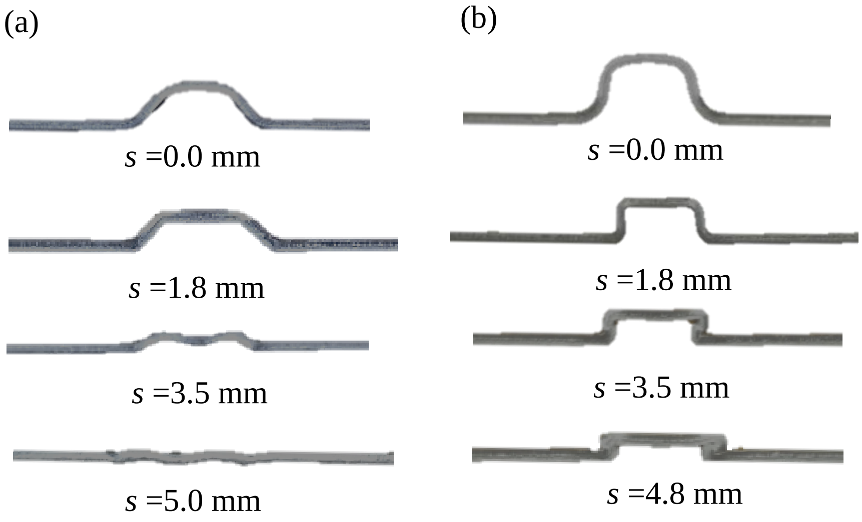


Fig. 22. Thickening behavior for aluminum plates having thickness of 1.5 mm for (a) $h$ = 5 and (b) $h$ = 8 mm and $\alpha$ = 180°.

The cross-sections of the local thickening area after beading and compression with $\alpha$ = 180° for aluminum plates are given in **Fig. 23**. No cracks were observed on the cross-section of the plate for $h$ = 5 mm. The thickening region shows an increase in thickness for $h$ = 5 mm. The increases in thickness for $h$ = 3 mm and 5 mm for a plate thickness 1.0 mm were 9% and 25%, respectively. As for $h$ = 8 mm, folding was observed.

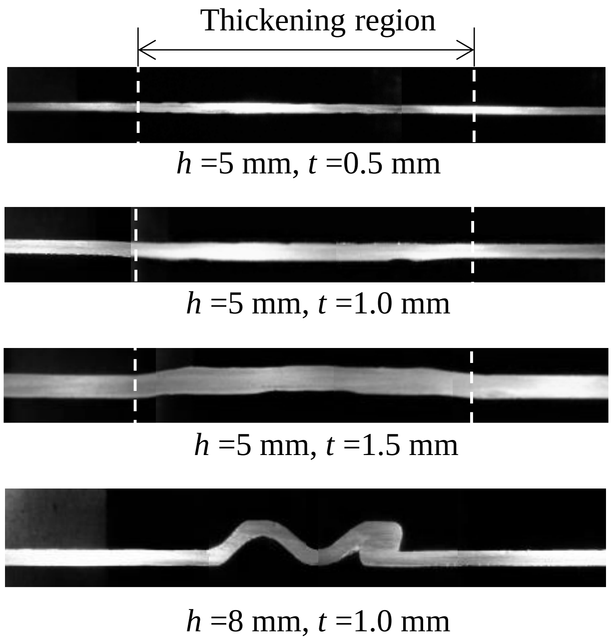


Fig. 23. Cross-sections of local thickening area after beading and compression with beading die $\alpha$= 180° for aluminum plates.

The thickness distribution for aluminum plates for $h$ = 3 mm before and after the local thickening process is shown in **Fig. 24**. The thicknesses of the plate before beading, after beading and after compression are compared. The original plate shows a uniform thickness distribution. Since the plate was beaded freely without a blank holder, the thickness distribution shows no thinning occur at the beaded portion after the beading process. After compression, thickening was formed with a peak thickness around the center of the plate.

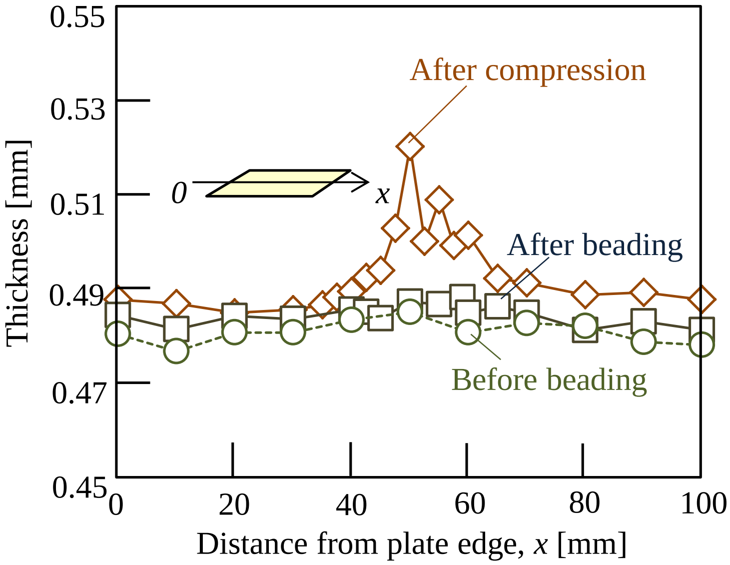


Fig. 24. Thickness distribution for aluminum plate for *h*= 3 mm.

*5.2 Local thickening by beading and compression for SPCC plate*

Since folding was formed for $h$ = 8 mm, the beading die angle was varied. From **Fig. 22**, the sidewalls of the beaded portion were almost vertical for $\alpha = 180^o$. To prevent the acute angle on the sidewalls, the angle of the beaded die was reduced. The effect of the beading die angle on the local thickening of the SPCC plate is shown in **Fig. 25**. For $h$ = 8 mm, local thickening was achieved with $\alpha = 90^o$. As the beading die angle increased, folding was formed.

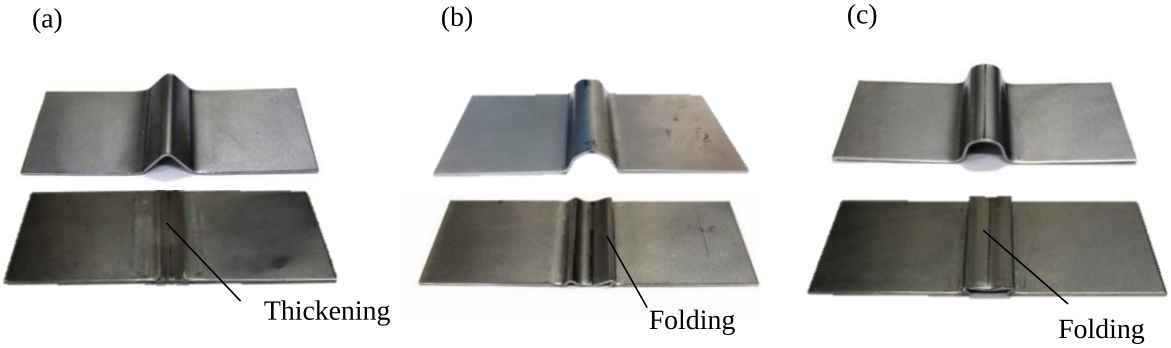


Fig. 25. Effect of (a) $\alpha = 90^o$, (b) $\alpha = 120^o$ and (c) $\alpha = 180^o$ on local thickening of SPCC plate.

The thickening behavior of SPCC plates for $\alpha = 90^o$ and $120^o$ are shown in **Fig 26**. The thickness of the plate was 1.0 mm for $h$= 8 mm. The deformation of the plates was observed at different punch strokes. For $\alpha = 90^o$, inclined sidewalls were formed. The sidewalls decrease as the punch stroke increases, and hence local thickening was observed. As for $\alpha = 120^o$, a dome-like shape beaded portion was observed. At a punch stroke of 3 mm, the sidewalls of the beaded area reduced and became almost vertical, producing a fold in the sidewall.

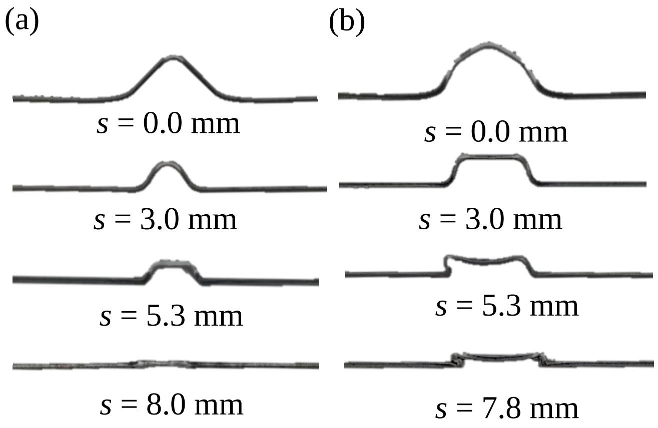


Fig. 26. Thickening behavior of SPCC plates for (a) $\alpha$= 90$^o$ and (b) $\alpha$= 120$^o$.

The distributions of thickness and strength for SPCC plates are given in **Fig 27**. The thickness of the plate was 1.0 mm. The beading die was varied between 3 mm to 8 mm. The beaded portion was formed with $\alpha$ = 90$^o$. The estimated strength of the material was calculated from the hardness values obtained at the cross-section of the SPCC plate. As the amount of local thickness increases, the hardness and strength of the plate increases.

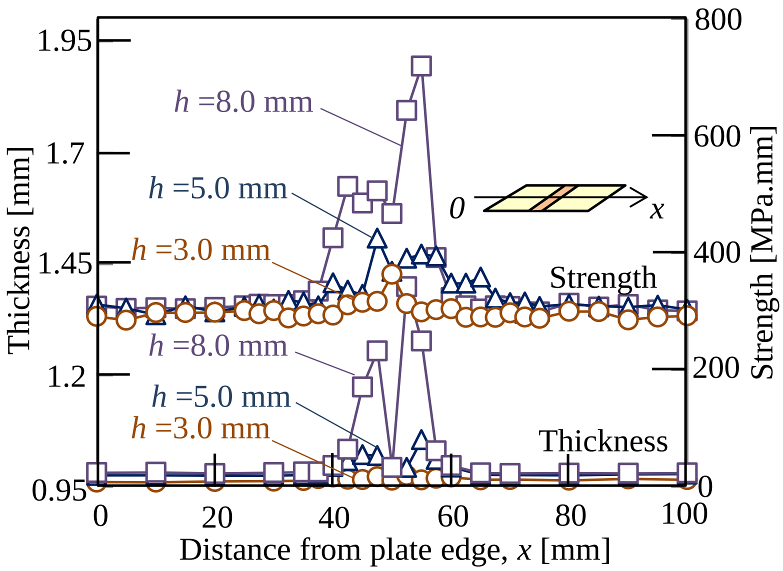


Fig. 27. Distributions of thickness and strength for SPCC plates.

The maximum change in thickness for aluminum and SPCC plates is given in **Fig. 28**. The forging of plate having local thickening using beading and compression was conducted for plate having thickness of 1 mm. When comparing between the beading die angles, $\alpha$ = 180$^o$ produced the largest local thickening for $h$ = 3 and 5 mm due to a large beading portion. However for $h$ = 8 mm, local thickening could not be achieved with $\alpha$ = 120$^o$ and 180$^o$. A beading die angle of 90$^o$ managed to produce local thickening with a 45% increase in thickness for both aluminum and SPCC.

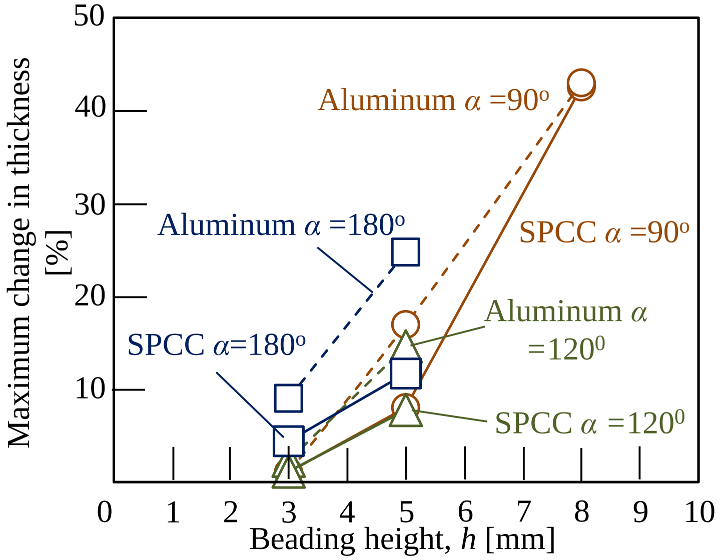


Fig. 28. Maximum change in thickness for aluminum and SPCC plates by beading and compression.

## 6. CONCLUSIONS

Plates having an inclined cross-section and thickness distribution were produced by forging. Although long plates are produced by rolling, the asymmetrical cross-section tends to cause wrinkling and curvature. On the other hand, plate forging is an attractive method to produce plates having an inclined cross-section due to its flexibility, whereas the forging load becomes large. An incremental forging process was developed to produce long plates having an inclined cross-section in this paper. Due to the small feeding interval and forging load, incremental forging is effective in forming of long plate. Small- and medium-size mechanical presses commonly employed in forming industry can be used because the forging load is greatly reduced by incremental forging. The inclined punch having a taper bottom has the advantage of minimizing waving and depression of the forged plates. The curvature and burr of the forged plate were prevented by the grooved die.

Tailored blanks having a thickness distribution are effective in reducing the weight of automobiles without compromising passenger safety. Although the tailored blanks are commonly produced by welding, the flexibility of distributions of thickness and strength is low. Although tailored-rolled blanks have high flexibility of thickness distribution, the supply is limited. The developed incremental forging process can produce blanks similar to tailor rolling by means of presses. Owing to the simple control scheme of thickness, common mechanical presses repeating the same ram motion are readily available for production. Only the feed is controlled to obtain a desired thickness by the effective use of elastic deformation of the press and tools. Accordingly, the production becomes more flexible, i.e. forming makers can produce the tailor-forged blanks and existing presses are reused.

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