Successive Forging of Quenchable Steel, Aluminium and Stainless Steel Sheets having Thickness Distribution and Inclined Cross-Section

（肉厚分布と傾斜断面を持つ焼入れ鋼,
アルミニウム，ステンレス鋼板の逐次鍛造）

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Doctor of Engineering

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Abstract

The use of tailored blanks having a thickness distribution increases in automobile body parts, because the tailored blanks offer substantial weight reduction, crash resistance and protection. The tailored blanks allow the use of an optimum thickness distribution in parts, and thus material utilisation is optimised and weight is reduced. Although the tailored blanks are generally produced by welding, joining of multiple sheets by welding is not easy and the sharp change in thickness induces stress concentration. Although stress concentration is reduced by gradual change of the thickness in the transient region for tailor-rolled blanks, these blanks are expensive.

A successive forging process of tailored blanks having a thickness distribution supplied for hot stamping was developed to overcome these problems. In this study, a blank having a uniform thickness was successively compressed with upper and lower punches. Since local deformation was repeated in successive forging, the forging load is comparatively small, and tailored blanks without joining are produced as well as to the tailor rolling process. The thickness was controlled only by the feed under a fixed stroke of the punch. As the feed decreases, the forging load decreases due to small contact area, and thus, the reduction in thickness of the blank becomes large for small elastic deformation of the press and tools.

During compression, the press ram is inclined by deflection of the press frame, and then tool marks were observed on the surface of the tailored blank. Finite element simulation was performed to obtain the shape of the punch to prevent the tool marks on the surface of the tailored blank. A die for correcting the upper punch inclination was proposed to reduce the tool marks. By inserting concave and convex plates into a C-frame of a press, the inclination of the upper punch was reduced and the misalignment between the upper and lower punches was decreased. Uneven surface of the tailor blank was minimised by using corner radius punch and also concave and convex plates.

Although aluminium alloys are attractive to reduce the weight of a car, car parts produced from steel are effective due to high strength and lower cost. High strength steel sheets however, are difficult to form. Hot stamping reduces the flow stress, forming load and produces parts strengthened by martensitic transformation. A tailored blank having two thicknesses was successively forged, and then hot-stamped into a roof rail miniature. The large curvature of the tailor-forged blank by successive forging was eliminated after the hot stamping process. The strength of the hot-stamped roof rail miniature increase significantly. A reduction of weight by 20% for the tailor-forged roof rail miniature was measured.

For tailor-rolled blanks, the thickness of the sheet is reduced and this portion is work-hardened. However, the strength required for the thin portion is small, whereas the strength is increased by work-hardening. Sheet forging having local thickening by beading and compression was developed to produce sheet having a strength distribution. A uniform thickness sheet was beaded and the sheet was then compressed to form thickening. As the beading die height increases, the degree of thickening increases. The effect of beading die shape was analysed to prevent folding for a large beading height. The produced tailored blank has high and low strengths for the thick and thin portions, respectively.

Sheet forging is widely used in metal forming industries to form sheets having a thin cross-section into various shapes and thicknesses. In this process, the forming load becomes high due to the large frictional restraint. For long parts, the forming load increases for large deforming area. Long sheets having a uniform cross-section are generally produced by rolling, whereas it is not easy to change tools and formed cross-sectional shapes are limited due to curvature and wrinkling. Long sheets are also produced by cutting, however this process results in a large amount of scrap. The use of long parts having an inclined cross-section is important in the printing industry to ensure smooth and high quality printing. These blades are used for cleaning and regulating toners in printers. In order to produce a long sheet having an inclined cross-section, a successive forging process was employed. Since only a small portion of the sheet was deformed at a time, a small load is required. The used of a taper bottom inclined punch minimised the formation of waving and depression of the forged sheet. A side guide was introduced to reduce the curvature of the sheet. However for a very small feeding, burr was formed on the side of the sheet due to a large curvature. The introduction of a grooved die eliminates the curvature of the forged sheet having an inclined cross-section.

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Introduction

1.1 An overview

1.1.1. Lightweight technology of automobiles

The weight of automobiles has grown steadily over the years to fulfil the risen demand of cars with high performance, safety structure, additional comfort and large space. The increase in the car weight leads to the increase in fuel consumption and global emissions. Automobiles emission issues have been widely addressed due to ecological and economical reasons [1, 2]. In the year 2000, the land transport took 72.3% of total CO_2 emission as compared to other modes of transportation [3]. For a better environment, production of lightweight cars has been a great challenge for car manufacturers. A reduction of car weight by 100 kg leads to a reduction of CO_2 emission by 9 grams per kilometre [4]. Technologies of producing lightweight automobiles to meet these requirements have been developed, for example light metals, design optimisation and advanced forming technology [5-7]. Fig 1.1 shows the pie chart of weight fraction of a passenger car. As the body-in-white contributes about 28% of the car weight [8], it offers a great potential for weight reduction.

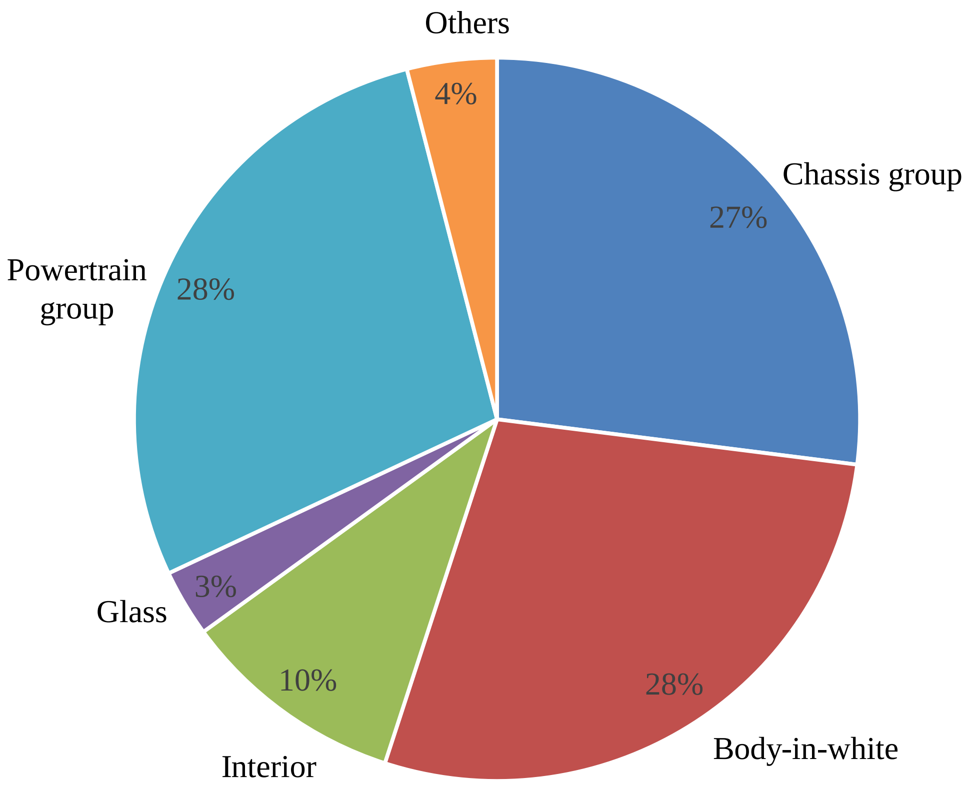


Fig. 1.1 Pie chart of weight fraction of passenger car [8].

Light metals such as aluminium alloys have been used extensively in automobiles engine block, chassis, body-in-white parts, etc. due to their high strength-to-weight ratio, good formability and corrosion resistance [9, 10]. As compared to steel, the density of aluminium and magnesium are much lighter by 66% and 78%, respectively [11]. In Japan, the use of aluminium alloys in car body panel started in 1985 [12]. Although aluminium and magnesium alloys are attractive in reducing the automobiles weight, the high cost of these materials as compared to steel becomes an obstacle for a large-scale and high volume production. The demand of lightweight vehicle has led the steel industry to the development of steel having superior mechanical properties and more cost-effective. Table 1.1 shows the tensile strength and specific gravity of various metals. The ultra-high strength steel sheets of tensile strength up to 1400 MPa provide excellent strength improvement and weight reduction of automobile body structure [13, 14]. As compared to aluminium alloys, the strength-to-specific gravity of the ultra-high strength steel is greater. To fulfil the demand of automobile parts having complex shape, the high strength steel sheets not only need to have strength characteristics, but also excellent press-forming capabilities.

Table 1.1 Tensile strength and specific gravity of various metals [15].

Sheet	Tensile strength	Specific gravity	Strength-to-specific gravity ratio
Ultra high tensile strength steel	980-1470 MPa	7.8	126-188 MPa
High tensile strength steel	490-790 MPa	7.8	63-101 MPa
Mild steel SPCC	340 MPa	7.8	44 MPa
Aluminium alloy A6061	310 MPa	2.7	115 MPa

1.1.2. High strength steel sheets

The use of high strength steel sheets is expanding to meet the demand for energy efficient vehicles. The replacement of conventional mild steel with high strength steel eliminates the needs of local reinforcement of parts, hence reduces the thickness and weight without reducing the strength. High strength steels are used strategically to increase the resistance to deformation and minimize intrusions into the passenger area in a case of collision [16]. Fig 1.2 illustrates the application of high strength steel in 2011 Honda CR-Z. During a crash, high strength steel parts provide excellent strength, durability and crashworthiness properties. However, stamping of high strength steel becomes difficult due to high strength, large forming load, low formability, large springback, etc. [17-19]. Conventionally, to prevent springback, the shape and geometry of the forming dies undergo several modifications during the trial process which result in additional die manufacturing cost, time and waste of materials.

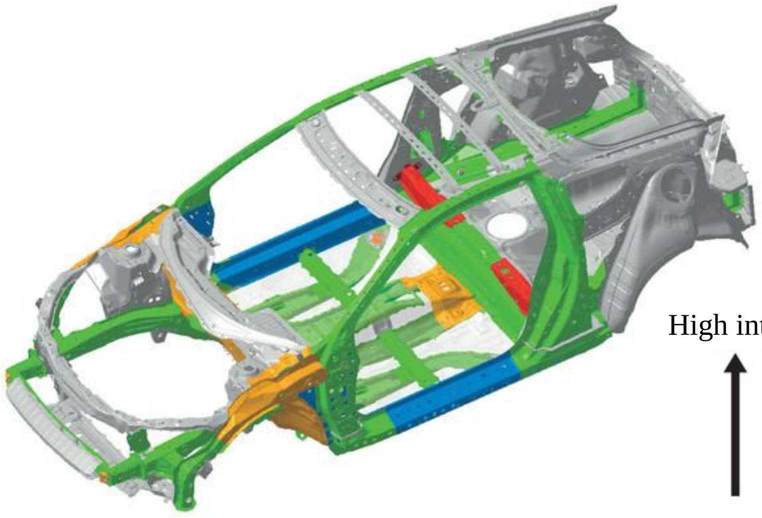


Fig. 1.2 Application of high strength steel parts in 2011 Honda CR-Z [20].

1.2. Tailored blanks

1.2.1. Tailor-welded blanks

Automobile parts having an optimum thickness distribution further improve the weight reduction of a vehicle. Semi-finished parts such as tailored blanks which provide local reinforcement at desired areas do not only reduce the weight of a stamped part but also increase the strength and improve the passenger safety [21]. Fig 1.3 shows the processes of producing stamped parts having a thickness distribution. Conventionally, the automobile body parts are produced by stamping different sheets of thicknesses and strengths individually before joining them together to form a single part having thickness and strength distributions. Tailored blanks on the other hand, are generally produced by joining two or more sheets together by welding and subsequently stamped into the final shape. This method suppresses the conventional one as it reduces the amount of stamping dies, scrap and additional welding [22]. In a sheet metal forming process, the formability of the tailor-welded blank is a concern to prevent failure during forming [23-25]. The sharp change in thickness induces stress concentration, and limits the formability of the tailor-welded blank. The different strengths in tailor-welded blanks on the other hand, cause non-uniform metal flow and weld line movement. The joining of sheet by welding changes the material properties at the weld area as well as the heat affected zone. These factors increase the tendency of fracture and tearing during stamping.

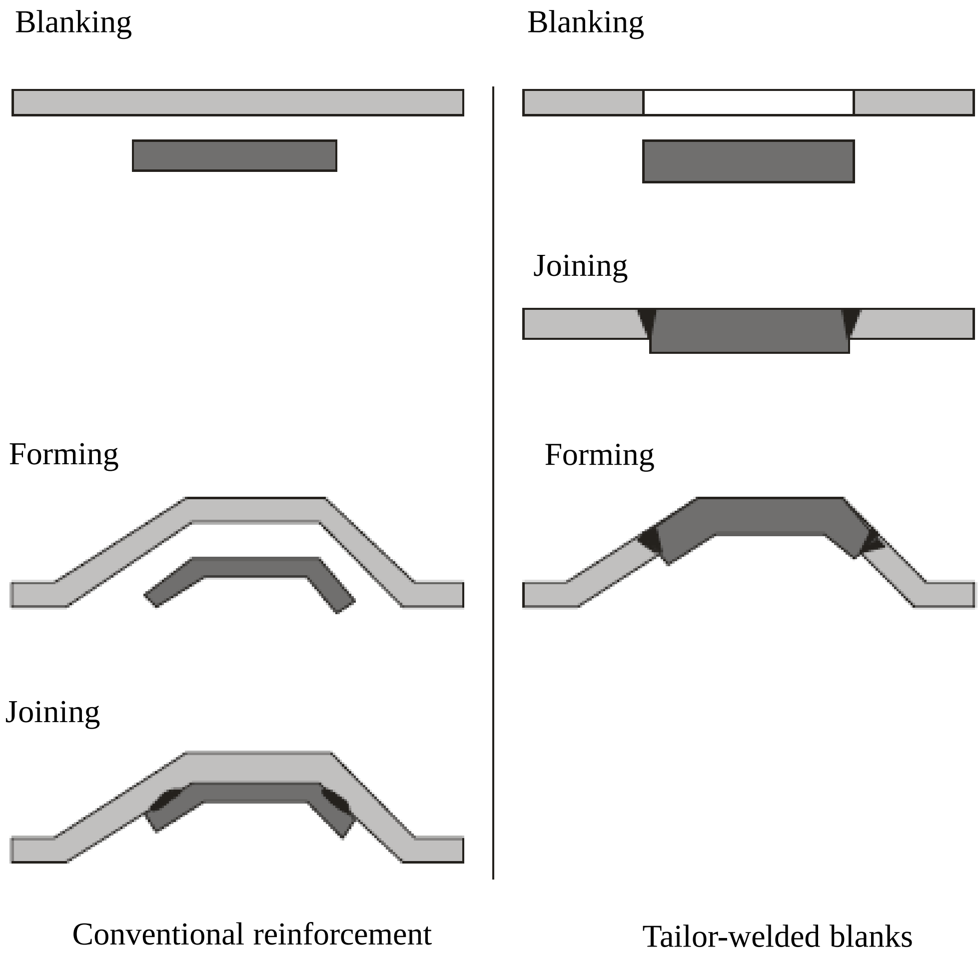


Fig 1.3 Processes of producing stamped parts having thickness distribution [26].

1.2.2. Tailor-rolled blanks

Tailored blanks having a thickness distribution without joining are produced by a rolling process. These blanks are named as tailor-rolled blanks. Fig. 1.4 illustrates the process of producing tailor-rolled blanks having a thickness distribution in the longitudinal direction. The thickness of the sheet is controlled by adjusting the roll gap between rollers [27, 28]. The thickness of the compressed sheet is measured directly during rolling and correction of the roll gap distance is conducted instantaneously to achieve the desired thickness. The gradual thickness changes in the transient region of the tailor-rolled blank reduces the stress concentration as in tailor-welded blanks. The thickness distribution of the tailor-rolled blank is more flexible and formability is improved [29, 30]. Due to the rolling process, the distribution of strength varies according to the amount of the reduction in thickness caused by different work hardening [31]. The thin portion of tailor-rolled blanks undergoes large reduction in thickness has higher strength as compared to the thicker portion which is opposite for cold stamping. In addition, the control system is not commonly available and the supply of tailor-rolled blanks is limited.

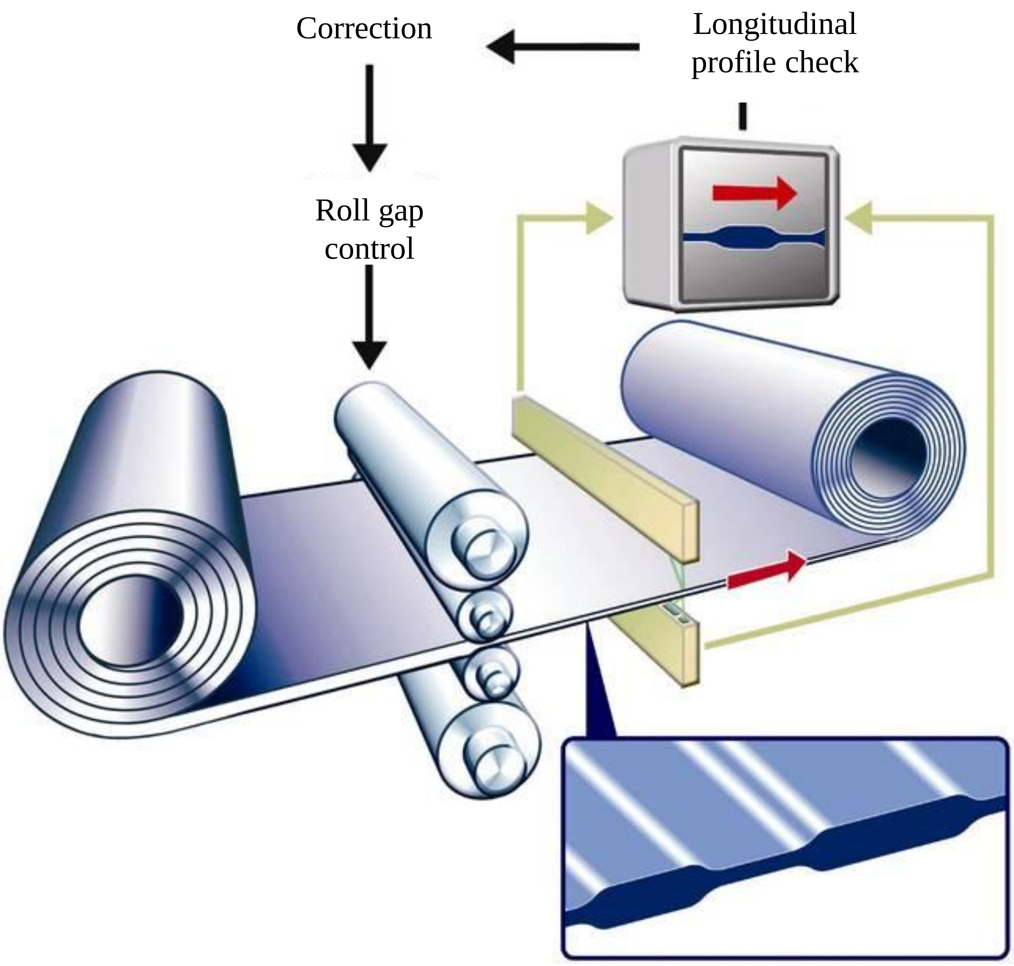


Fig. 1.4 Process of producing tailor-rolled blanks having thickness distribution [32].

1.3. Plate forging

In a sheet metal forming process, stamped parts are accurately produced, however the thickness distribution is not optimum and results in excessive weight and also failure. The wall thickness at the corners of the stamped part tends to decrease during stamping and leads to strength reduction. Plate forging is attractive in controlling thickness and strength distributions of automobile parts. To prevent tearing at the corners of the stamped parts without increasing the whole body thickness, local thickening of the blank was introduced by plate forging [33-35]. The local thickening of the blank increases the strength only at the desired area and hence improves the formability without increasing too much weight. Automobile parts having complex shape such as gear and seat recliner parts are also produced by plate forging [36, 37]. The formability of the forged parts is improved and high precision products are produced by controlling the metal flow [38]. Although plate forging is desirable, the large friction force between tools and blank increases the forging load. In order to reduce the forging load, plate forging process by using load pulsation has been introduced to allow re-lubrication of the sheet [39-42].

1.4. Incremental Forming

Incremental sheet forming is a process where sheets are formed locally into final desired shape and geometry by series of small deformation by a ballpoint or hemispherical tools under a predefined tool path [43, 44]. Fig. 1.5 illustrates the single point incremental forming process. In this process, the tool moves and follows the shape that has been described by the CAD data without the need of any supporting dies. Since the contact area between the tools and sheet is small the forming load is small. Although the elimination of die reduces the tooling cost, the production and the forming time is longer as compared to other conventional metal forming processes.

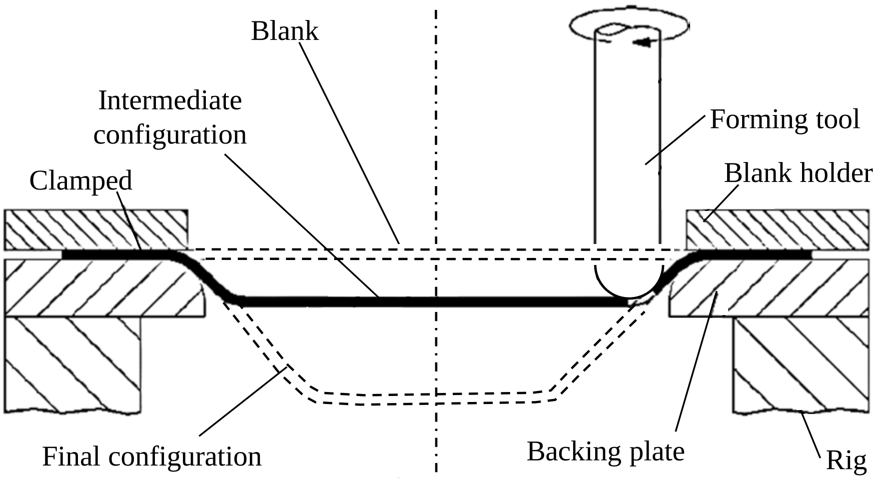


Fig. 1.5 Single point incremental forming process [44].

1.5. Successive forging

Successive forging is a compression process that deforms a small portion of the sheet sequentially and repetitively [45]. During successive forging the sheet is compressed by upper and lower punches. As compared to incremental forming, the punches are fixed during successive forging while the sheet are moved into the compression region. The feeding interval is control by a feeder machine that moves the sheet for compression. Since the deformation is small, the forging load is reduced and hence the successive forging process can be conducted by using small mechanical presses which are more commonly available in the metal forming industry [46]. In addition, by changing the amount of feeding, the elastic deformation of the press machine is linearly affected. The thickness distribution of the forged sheet is controlled by adjusting the feeding interval. A small feeding interval requires a small forging load and hence the elastic deformation of the press and tools is small. Therefore the reduction in thickness is large. For a large feeding, the elastic deformation is large and hence the reduction in thickness is small.

1.6. Hot Stamping

Safer and lighter cars have been produced by ultra-high strength steel and hot stamping. Hot stamping is effective to overcome the problems in forming high strength steel sheets [47-49]. Initially the sheet is heated in a furnace to an austenitic temperature (see Fig. 1.6). The sheet is then transferred to dies where forming and quenching processes are conducted simultaneously. Deformation of the sheet is carried out at high temperature and hence, the flow stress and forming load are reduced while the formability is improved [50-52]. Boron steel sheets having an original ferritic-pearlitic form are commonly used to produce automobile parts such as B-pillars and front bumpers due to its ability to fully transform into martensitic microstructure. The hot-stamped ultra-high strength steel reaches a tensile strength of 1.5 GPa after quenching between dies [53]. Although parts having high strength are produced by hot stamping, oxide scales are formed on the surface of the heated sheet while transferring the sheet from the furnace to the dies [54-56]. Additional process such as shot blasting is required to remove the oxide scales after hot stamping. Steel makers are introducing quenchable steels with Al-Si coating to protect the surface from oxidation and decarburisation at high temperature.

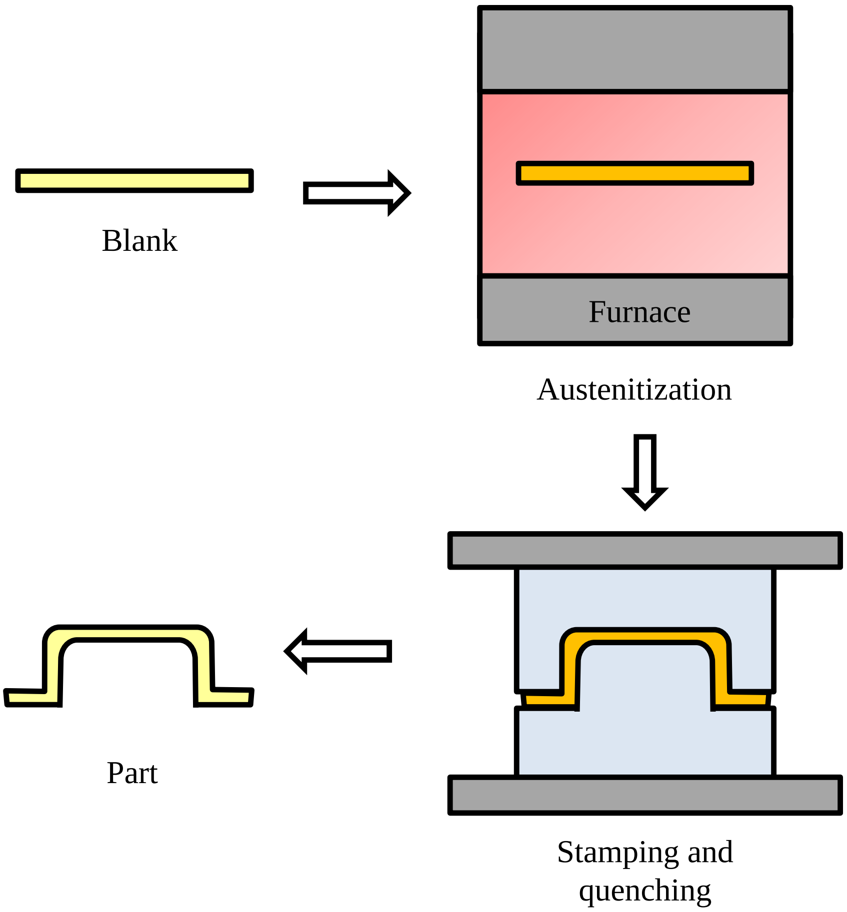


Fig 1.6 Process of producing hot-stamped parts.

Automobile structure body parts such as B-pillars requires high crash safety to protect the passenger during a collision. Although the whole body of stamped parts is generally die-quenched in hot stamping, increasing the strength of the whole parts is not sufficient. The balance of strength and ductility is required for automobile parts, and tailoring in hot stamping are useful. The B-pillar shown in Fig. 1.7 having a strength distribution is produced to fulfil the safety demands. The centre of the B-pillar have high strength to preserve the automobile structure and secure the passenger from intrusion while both ends have higher ductility for better energy absorption. Fig 1.8(a) illustrated the tailored die quenching process for producing parts having a strength distribution. Only the area requiring high strength is locally heated above the austenitic temperature before the whole body is die quenched [57, 58]. In contrast, the whole sheet is austenitised first, before quenching with a locally controlled cooling rate as shown in Fig. 1.8(b) [59, 60]. In a similar approach of tailor die quenching, parts having locally high strength are produced by quenching only portions in contact with the die [61]. Although the energy absorption of automobiles in the collision is improved by the tailored heat treatment, the thickness distribution of products effective for the weight reduction is not optimised.

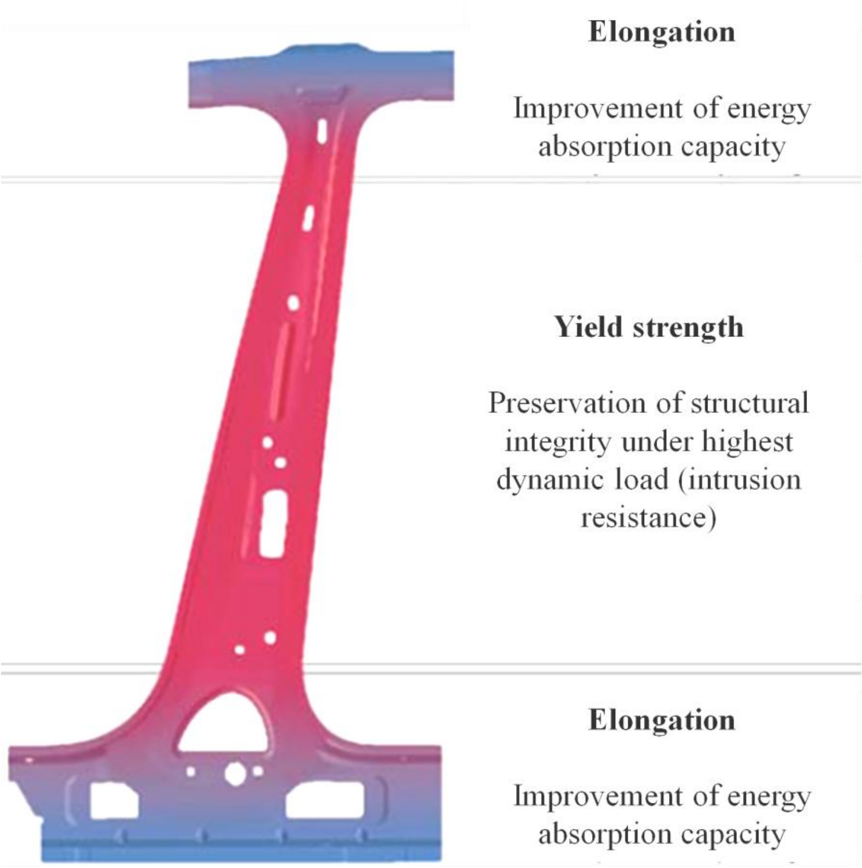
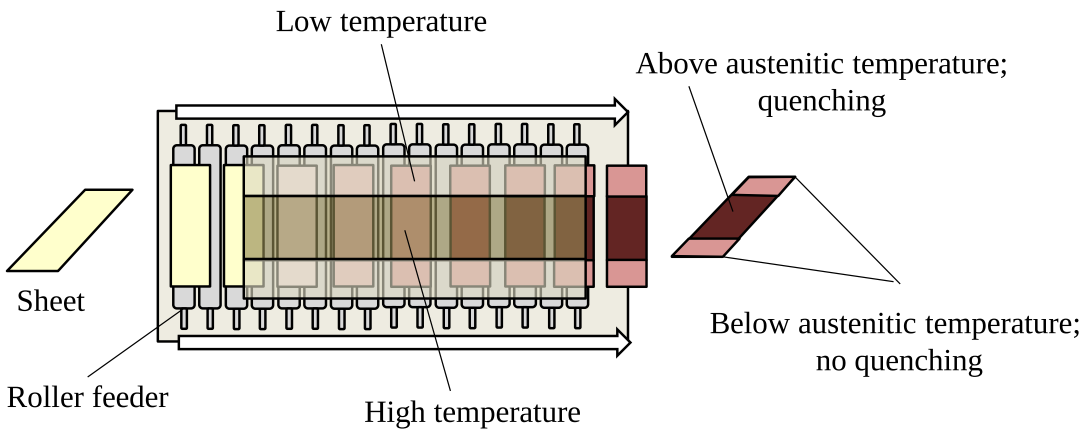
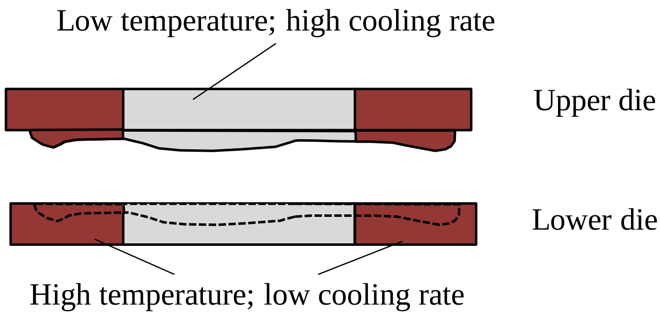


Fig 1.7 B-pillars having strength distribution [57].



(a) Tailored die quenching



(b) Tailored tempering

Fig 1.8 Tailoring in hot stamping.

Tailor blanks are not only cold-stamped but also hot-stamped to obtain products having an optimal thickness distribution for weight reduction [62]. Sheets of different materials and thicknesses are joined together by welding prior to the hot stamping process to produce parts having thickness and strength distribution. Automobile body structure parts are commonly joined of micro-alloyed steel and boron steel sheets to produce parts having high energy absorption as well as high strength [63, 64]. The weld area however, possess a weaker tensile strength as compared to the parent metals after quenching [65]. Joining Al-Si coated quenchable steels by laser welding dissolves the coating into the weld zone and causes non-homogenous martensitic formation after hot forming [66]. Since the quenchability of the weld is lower than that of the base metals, a higher cooling rate is required to prevent the drop in strength around the weld. Tailor-rolled blanks are hot-stamped to produce parts having a strength distribution. The variation of thickness affects the temperature distribution during quenching hence the strength distribution is controlled [67].

1.7. Research objectives

1.7.1. Control of thickness distribution in successive forging of tailored blank for hot stamping

The aim of this dissertation is to develop a method of producing tailored blanks having a thickness distribution supplied for hot stamping by successive forging. Tailor-welded blanks having a thickness distribution offer a substantial weight reduction and strength improvement, however joining sheets having different thicknesses and shapes are not easy and formability decreases. Although rolling produces tailored blank with improves formability and thickness flexibility, the equipment used is expensive. To reduce the investment cost, a method of producing tailored blanks having a thickness distribution by successive forging is developed. Under a constant punch stroke, the degree of reduction in thickness is adjusted by controlling the feeding interval. By reducing the deformation area, the amount of load is reduced. The tailor-forged blanks are then hot-stamped into a miniature of roof rails.

1.7.2. Successive forging of long sheet having inclined cross-section by adjusting the feeding interval

Long parts having inclined cross-section are generally produced by cutting, however the material loss is large. Rolling long sheet on the other hand causes wrinkling and curvature due to non-uniform sheet deformation. In this study a process of producing long sheet having an inclined cross-section by successive forging is developed. An inclined punch having a taper bottom surface and a grooved die are developed for preventing curvature and depression of the long sheet. The effects of forging interval on the forging load, reduction in thickness and waving of the long sheet having an inclined cross-section are investigated.

1.8. Outline of dissertation

This dissertation is about forming tailored blanks having a thickness distribution by controlling the amount of feeding. The produced tailor blank having two thicknesses by successive forging was then hot-stamped into a miniature of roof rail. The successive forging process was also applied to produce a long sheet having an inclined cross-section. Finally, forging of sheet having local thickening was carried out by beading and compression.

This dissertation has seven chapters as follows;

Chapter 2 presents the development of successive forging of tailored blank having a thickness distribution for hot stamping. In this process, the thickness of the blank is controlled by adjusting the amount of feeding. The reduction in thickness of the sheet is large for a small feeding due to small elastic deformation of the press and tools. A large feeding on the other hand produces a small reduction in thickness. The transient region connecting between the thin and thick area are control by the constant and variable feeding.

Chapter 3 presents the optimisation of the punch shape in successive forging to minimize the tool marks formed on the surface of the tailor-forged blank. The effect of punch shapes on the tool marking depth are investigated by finite element method. Convex and concave plates are inserted into the C-frame to reduce the upper punch inclination due to elastic deformation of the press. The tool marks formed on the surface of the tailored blank are compared between the tools with and without correcting inclination.

Chapter 4 presents the hot stamping of tailored blank having two thicknesses. The tailored blank is produced by successive forging by adjusting the amount of feeding. The strength of the blanks before and after hot stamping is investigated. The behaviour of Al-Si coating of the quenchable steel is examined to ensure no oxide scale formation during hot stamping. The properties of the uniform thickness and tailored roof rail miniatures are compared.

Chapter 5 presents a sheet forging process of producing tailor blanks having local thickening by beading and compression. The height of the beaded die is varied to examine the formation of the local thickening. The effect of beading die shapes is analysed to increase the degree of local thickening and to prevent folding. The hardness of the sheet after beading and compression is measured to obtain the strength distribution.

Chapter 6 presents a process of producing a long sheet having an inclined cross-section by successive forging. The long sheet is forged by inclined punches having flat and taper bottoms. The effect of feeding on forging load and reduction in thickness are investigated. A side guide and a grooved die are developed to prevent the curvature of the sheet due to different deformation of the material.

The concluding remarks and future perspective are presented in Chapter 7.

Chapter 2
Successive forging of tailored blank having thickness distribution

2.1 Introduction

The demand of high performance and spacious cars has increased the overall weight of an automobile. The increase in weight leads to the increase in fuel consumption and CO_2 emission [68, 69]. The reduction of car weight has been a challenge to car makers to produce lighter cars without risking the passenger safety. New materials, advanced forming processes and design optimisation have been developed to achieve this requirement [5, 7, 9, 70]. Lightweight metals such as aluminium and magnesium alloys have been applied in the production of car parts. However parts made from aluminium and magnesium alloys are more costly to produce. Steel on the other hand offers good strength, formability and weldability at a lower cost.

For the reduction in weight and improvement of crash safety of automobiles, the use of high strength steel increases. For automobile application, the ultra-high strength steel with tensile strength up to 1400 MPa has been introduced. High strength steels having high crash resistance provide great passenger protection during an impact [71]. Although high strength steel parts are useful, cold stamping of the sheets becomes difficult due to high strength, large springback, low formability, etc. [17, 19]. The optimisation of thickness distribution for body-in-white parts is effective in reducing the weight. The thickness of the parts for the required strength is controlled, i.e. the thickness is large for portions of requiring high strength, whereas that of portions requiring lower strength is thin.

Tailored blanks having an optimum thickness distribution offers great potential in weight reduction and strength improvement. Tailored blanks are mainly produced by welding and rolling. For tailor-welded blanks, sheets of different materials and thickness are joined together to obtain parts having different strengths and thicknesses. Reinforcement of a part is done only at the desired area hence excess weight is eliminated [21]. It is, however, joining multiple sheets of thickness is difficult. Stress concentration by the change of thickness between the welded sheets brings about the reduction in formability [23]. Tailor-rolled blanks having a thickness distribution on the other hand are produced without joining [28, 29, 32]. The stress concentration by the change of thickness at the weld is prevented by the gradual change in thickness for the tailor-rolled blanks, and a produced thickness distribution is more flexible than tailor welding. Since thin portions of the tailor-rolled blank have high strength by work-hardening for a large reduction in thickness, the distribution of the required strength becomes opposite for cold stamping [31]. In addition, the supply of tailor-rolled blanks is limited.

In the present study, a successive forging process of tailored blanks having a thickness distribution for hot-stamped products was developed. Since only a small portion of the sheet is forged at one time the forming load was reduced. The thickness of the sheet was controlled by adjusting the feed. The relationship between the thickness after compression and the feed was investigated. The final publication of this study is available at Springer via http://dx.doi.org/10.1007/s00170-016-9356-z.

2.2 Approach of successive forging of tailored blanks

A successive forging process was developed to optimise the thickness distribution of a blank supplied for hot stamping. The proposed successive forging of tailored blanks having a thickness distribution for hot stamping is shown in Fig. 2.1. The blank having uniform thickness was successively compressed with the upper and lower punches. Since local deformation is repeated in successive forging, the forging load is comparatively small. Tailored blanks without joining are produced as well as the tailor rolling process, and thus the stress concentration for the tailor-welded blanks is prevented. Although the tailor-forged blanks have higher strength in the thin portions by larger reduction in thickness, work-hardening, this effect is eliminated by heating during hot stamping.

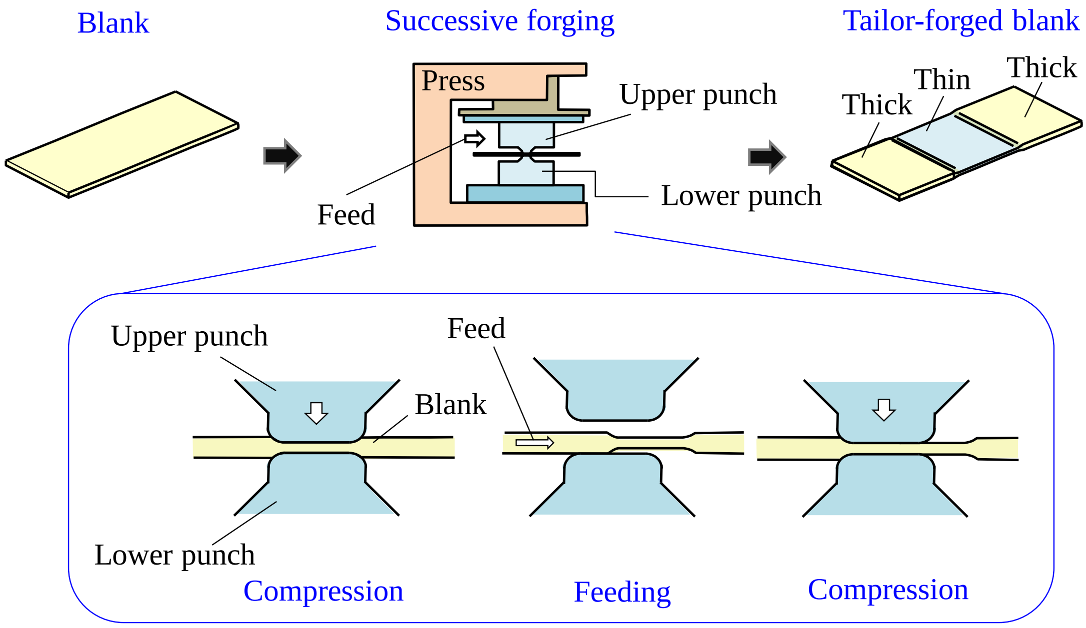


Fig. 2.1 Proposed successive forging of tailored blanks having thickness distribution for hot stamping.

The reduction in thickness of the sheet is influenced by elastic deformation of a press and tools as shown in Fig. 2.2. For a small feed, the forging load is low due to small contact area, and thus, the reduction in thickness of the blank becomes large for small elastic deformation of the press and tools. On the other hand, the reduction in thickness becomes small for a large feed. This leads to control of the reduction in thickness by the feed.

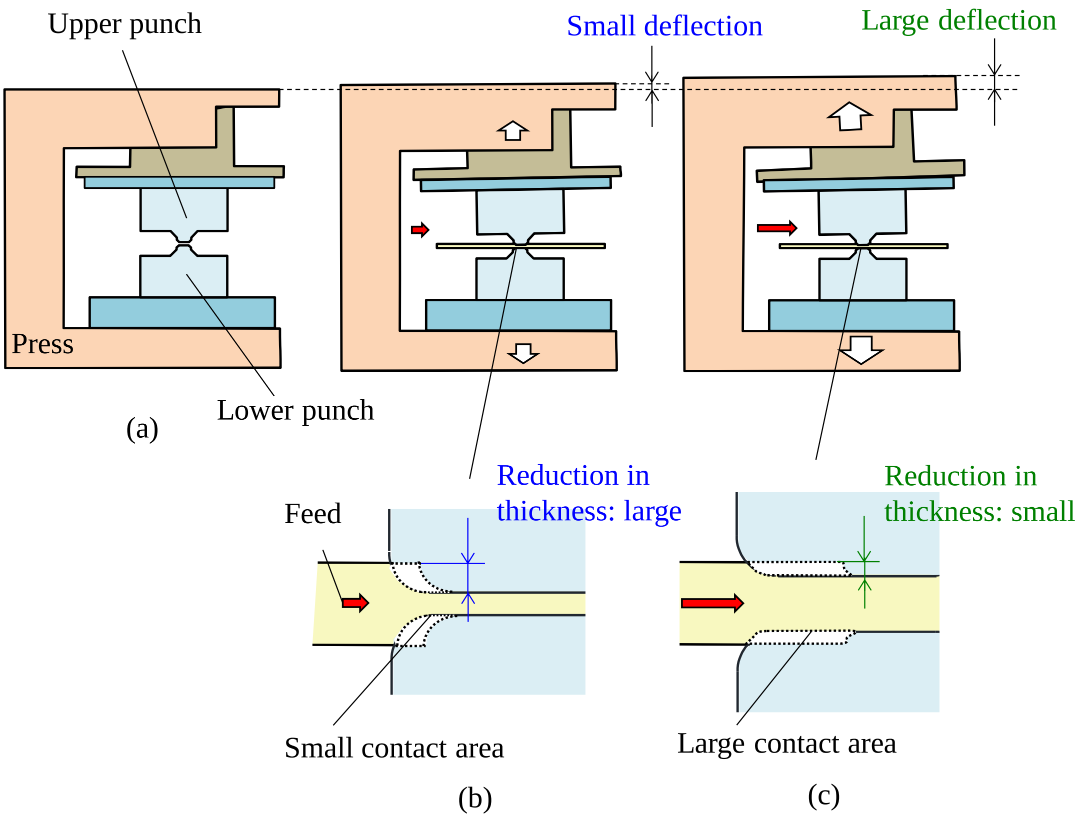


Fig. 2.2 Reduction in thickness of blank by elastic deformation of press and tools (a) without compression, (b) for small feed and (c) for large feed.

A 22MnB5 boron steel sheet was employed for the successive forging of tailored blanks having a thickness distribution. The length, width and thickness of the blank were 400 mm, 100 mm and 1.6 mm, respectively. The chemical compositions of the 22MnB5 boron steel sheet are given in Table 2.1. A 1500 kN mechanical servo press was employed in the experiment. A linear scale was employed as a feeder for moving the blank and the feed per one strike was between 0.1 and 7 mm. The stroke of the ram of the press was fixed to be 2.1 mm. The blank was lubricated with water soluble press oil. The tools and dimensions for successive forging of tailored blanks are given in Fig. 2.3.

Table 2.1 Chemical compositions of 22MnB5 boron steel sheet [%].

C	Si	Mn	P	B
0.21	0.25	1.2	0.015	0.0014

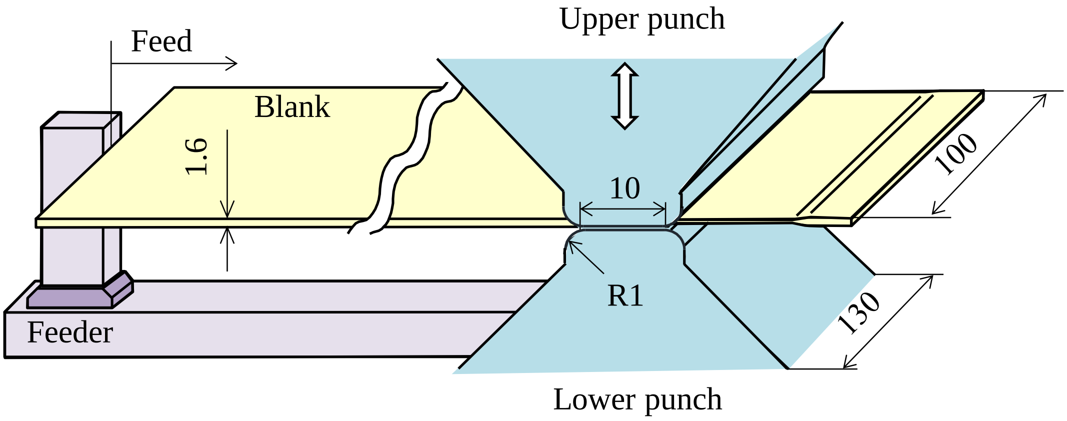


Fig. 2.3 Tools and dimensions for successive forging of tailored blank.

2.3 Results of successive forging of tailor blanks having thickness distribution with constant feeding

2.3.1 Tailored blank having two thicknesses

The tailored blank having two thicknesses produced by successive forging for constant feeding is given in Fig. 2.4, where the constant feed per one strike was $f = 1$ mm and the number of strikes was 130. Only the middle of the blank was compressed for the two thicknesses, i.e. one is that of the compressed region and the other is original. For a total feed of 130 mm, the compressed area is longitudinally elongated to 195 mm, and the width hardly changed due to the large width-to-length ratio of the punch. The successive-forged blank curved and had tool marks on the surface.

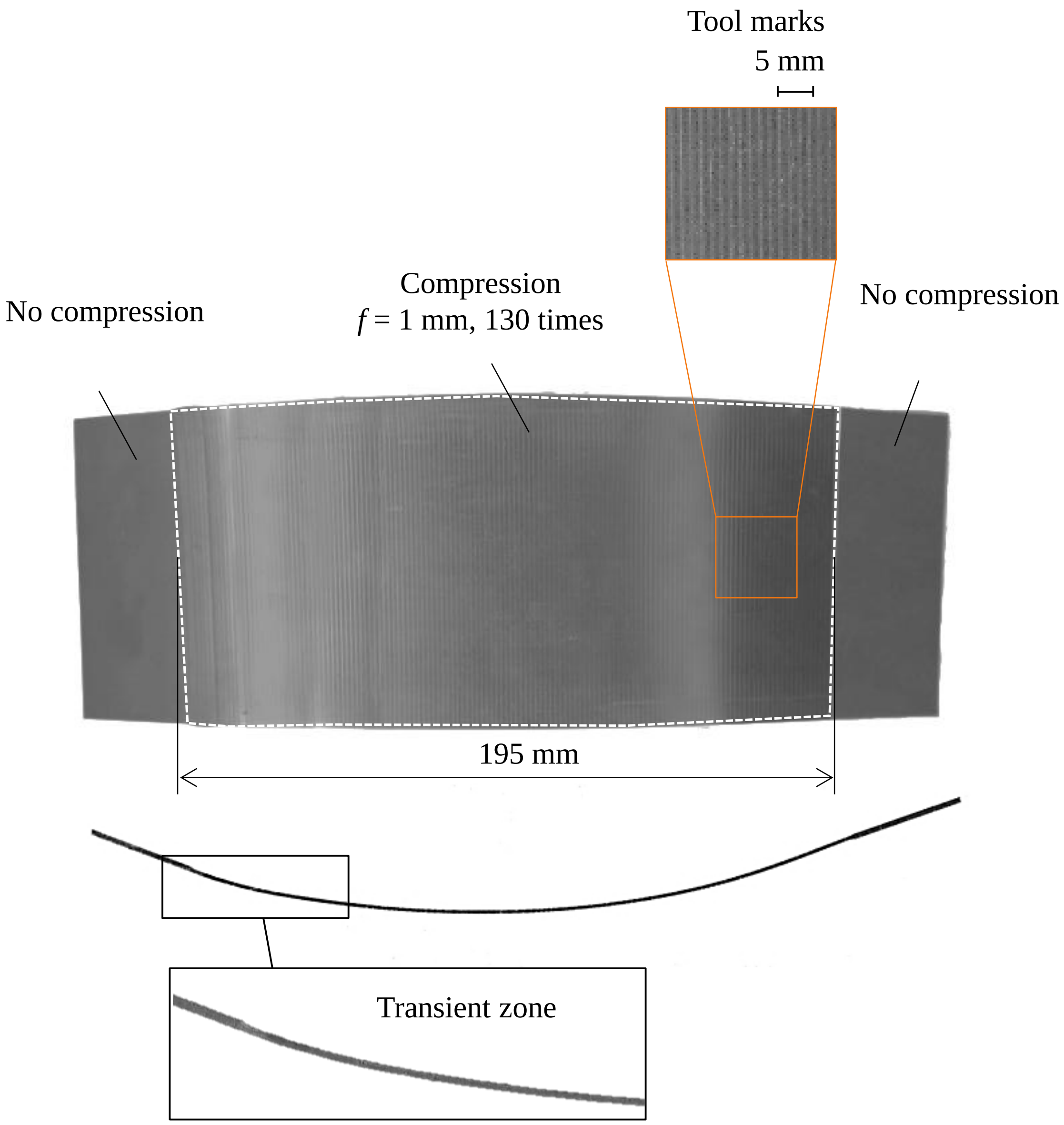


Fig. 2.4. Tailored blank by successive forging for f = 1 mm and number of strikes of 130 times.

The thickness distribution of the tailored blank having the two thicknesses is shown in Fig. 2.5. The thickness of the tailor-forged blank was measured along the two lines in the longitudinal direction 25 mm apart from the centre line of the blank, and the average of the measured values is shown. The thickness of the blank sharply changes at the start and end of compression. The thickness gradually decreases from the start of compression and attains a steady-state one. Because of elastic deformation of the press and tools, the steady-state reduction in thickness was r = 33% for a punch stroke of 2.1 mm.

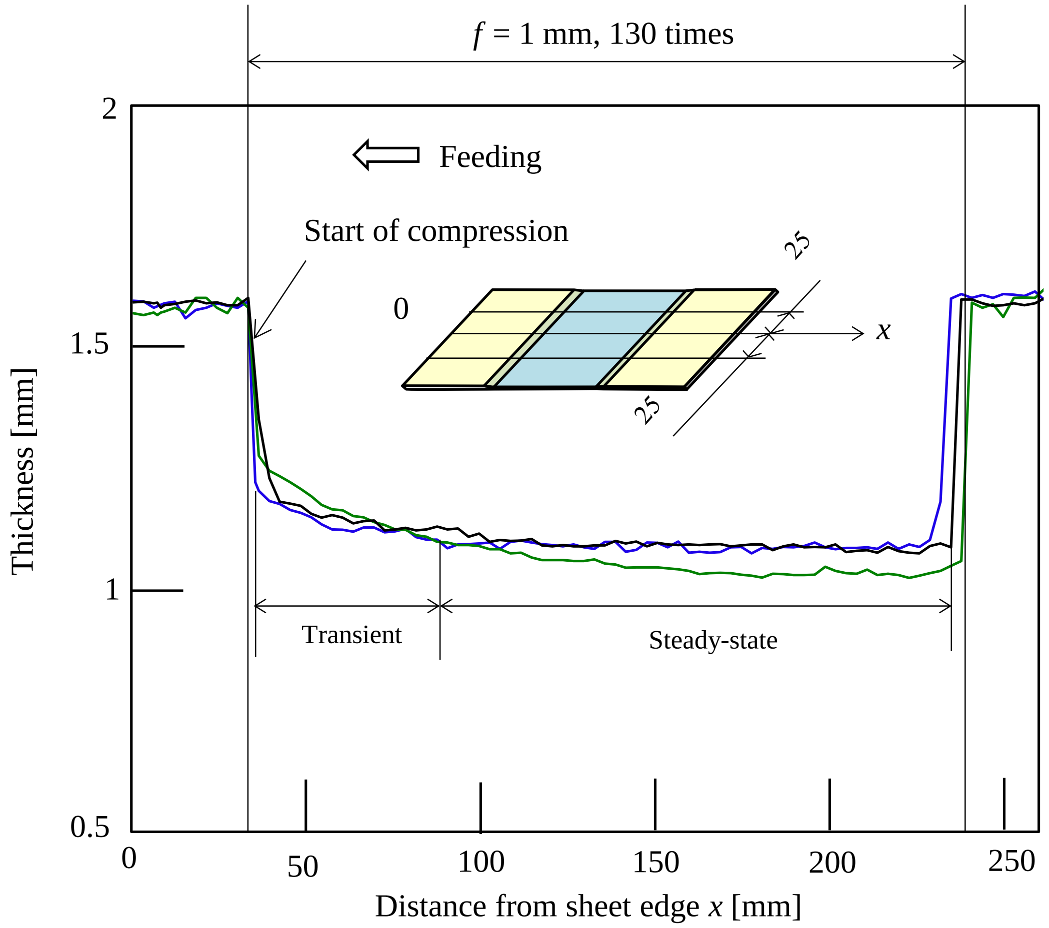


Fig. 2.5 Thickness distribution of tailored blank having two thicknesses with total feed for *f* = 1 mm and number of strikes of 130 times.

The variation of forging load with the total feed for *f* = 1 mm and number of strikes of 130 times is given in Fig. 2.6. The load gradually decreases and attains the steady-state one. The distribution of load shows a same pattern as the thickness distribution of the tailor-forged blanks.

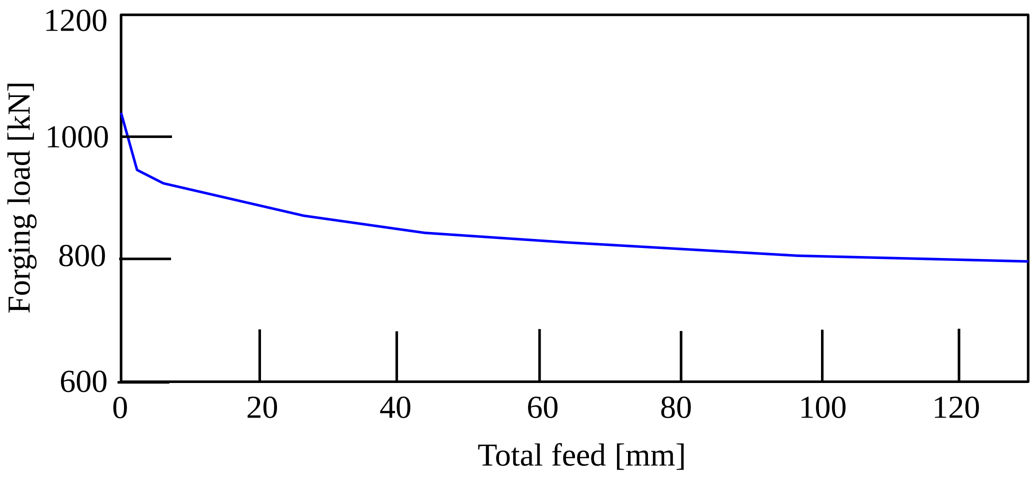


Fig. 2.6 Variation of forging load of tailored blank having two thicknesses with total feed for *f* = 1 mm and number of strikes of 130 times.

The thickness distributions of the tailor-forged blank in the transient zone and the length of the transient zone for different feeds are shown in Fig. 2.7 and Fig. 2.8, respectively. When the change in thickness for a length of 10 mm attains is ± 1%, the thickness is judged to attain a steady state. As the feed increases, the length of the transient zone decreases.

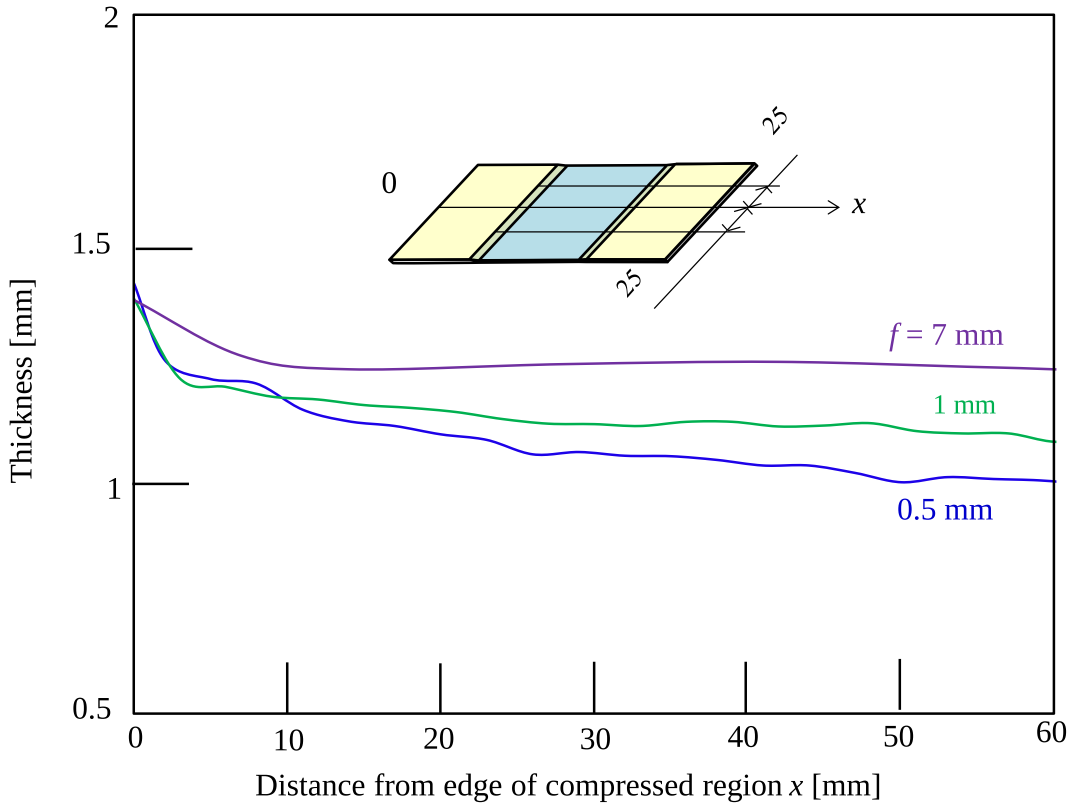


Fig. 2.7 Thickness distributions of tailor-forged blank in transient zone.

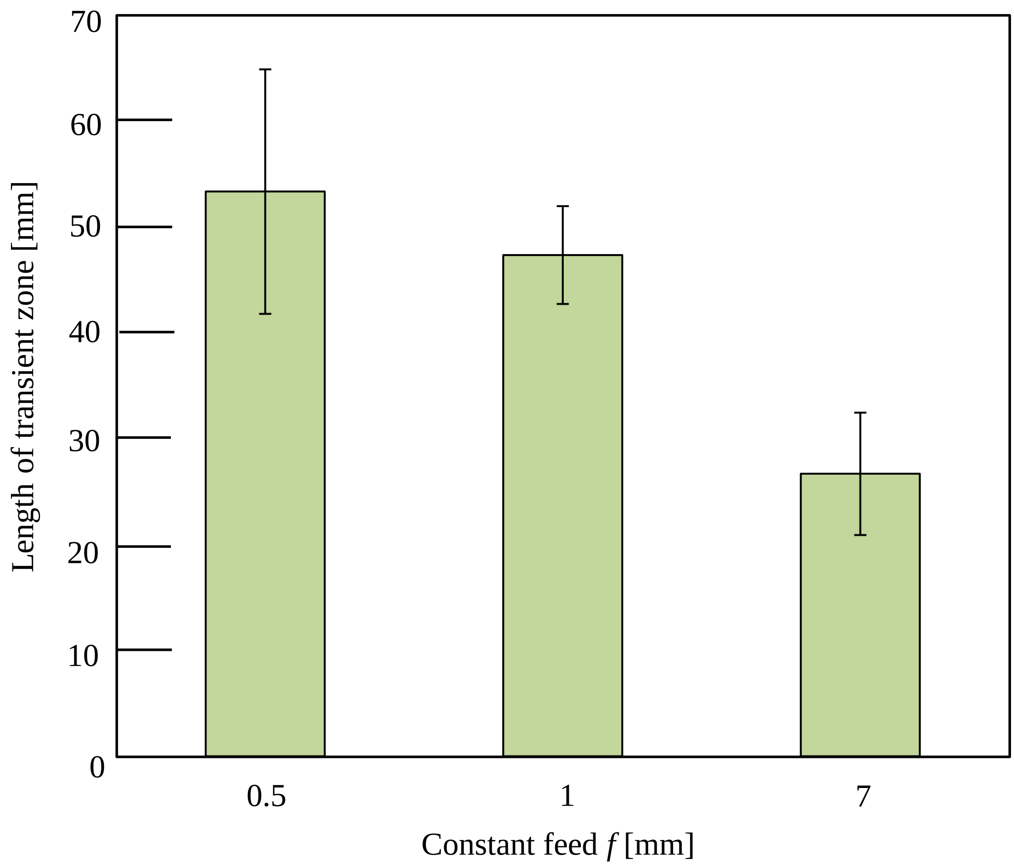


Fig. 2.8 Length of transient zone for different feeds of successive forging of tailored blanks.

The relationships between the steady-state reduction in thickness and the constant feed and between the steady-state forging load and the constant feed are given in Fig. 2.9. As the constant feed increases, the reduction in thickness decreases and the forging load increases. The steady-state reduction in thickness is almost linearly changed with the constant feed by elastic deformation of the press and tools as explained in Fig. 2.2.

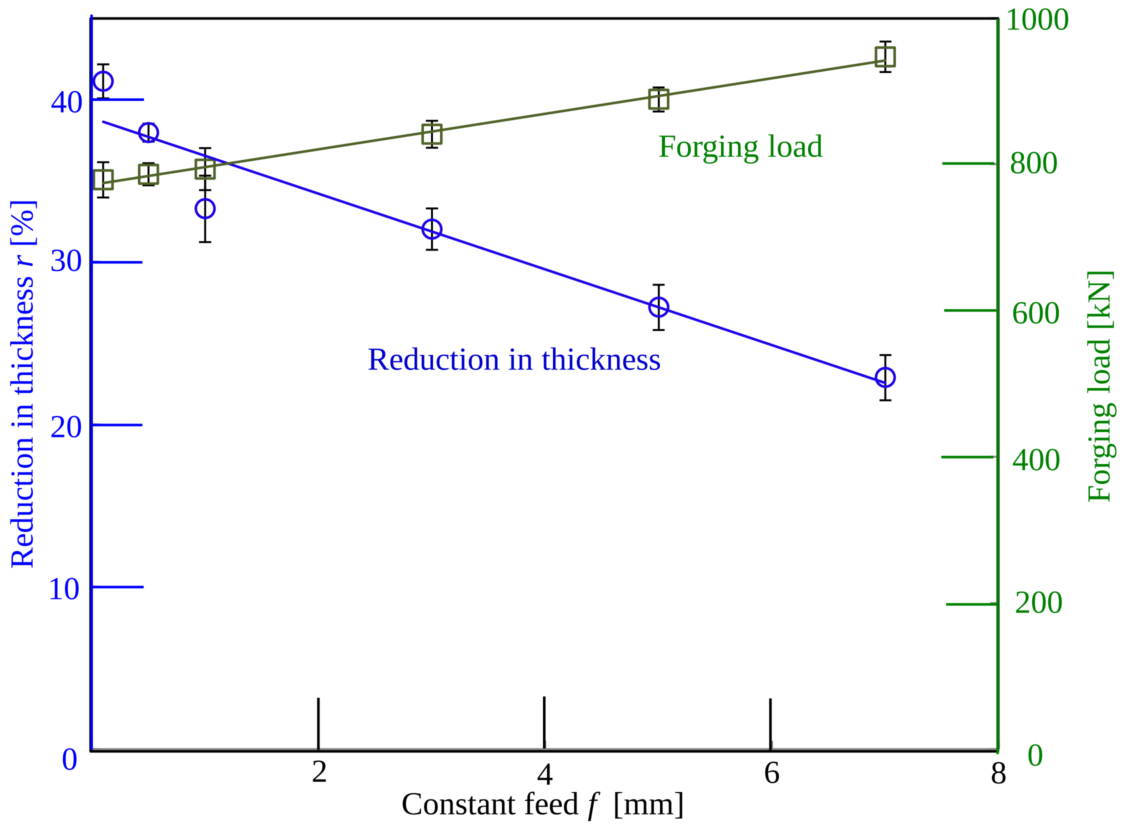


Fig. 2.9. Relationships between steady-state reduction in thickness and constant feed, and between steady-state forging load and constant feed.

From Fig. 2.9, the steady-state thickness t of the compressed blank is linearly approximated by

$$t = 0.046\ f + 0.96 \text{ mm.} \tag{2.1}$$

The thickness in a steady state can be controlled by a constant feed from Eq. (2.1). Since the thickness is controlled by only the feed under a fixed stroke of the punch, conventional mechanical presses having a comparatively low cost can be used by installing a feeder for the production of tailor-forged blanks.

2.3.2 Tailored blank having three thicknesses

The thickness distribution of tailored blank having three thicknesses are given in Fig. 2.10. A constant punch stroke of 2.1 mm was used. The tailored blank was forged for a combination of f = 1 and 7 mm. The transient regions connecting the thin and thick area are not symmetrical. The slope of the transient region for the decrease in thickness reduced gradually, whereas for the increase in thickness changed rapidly. In order to achieve an optimum thickness distribution for weight reduction, these transient regions need to be controlled. The excess material due to the gradual change in thickness increase the weight.

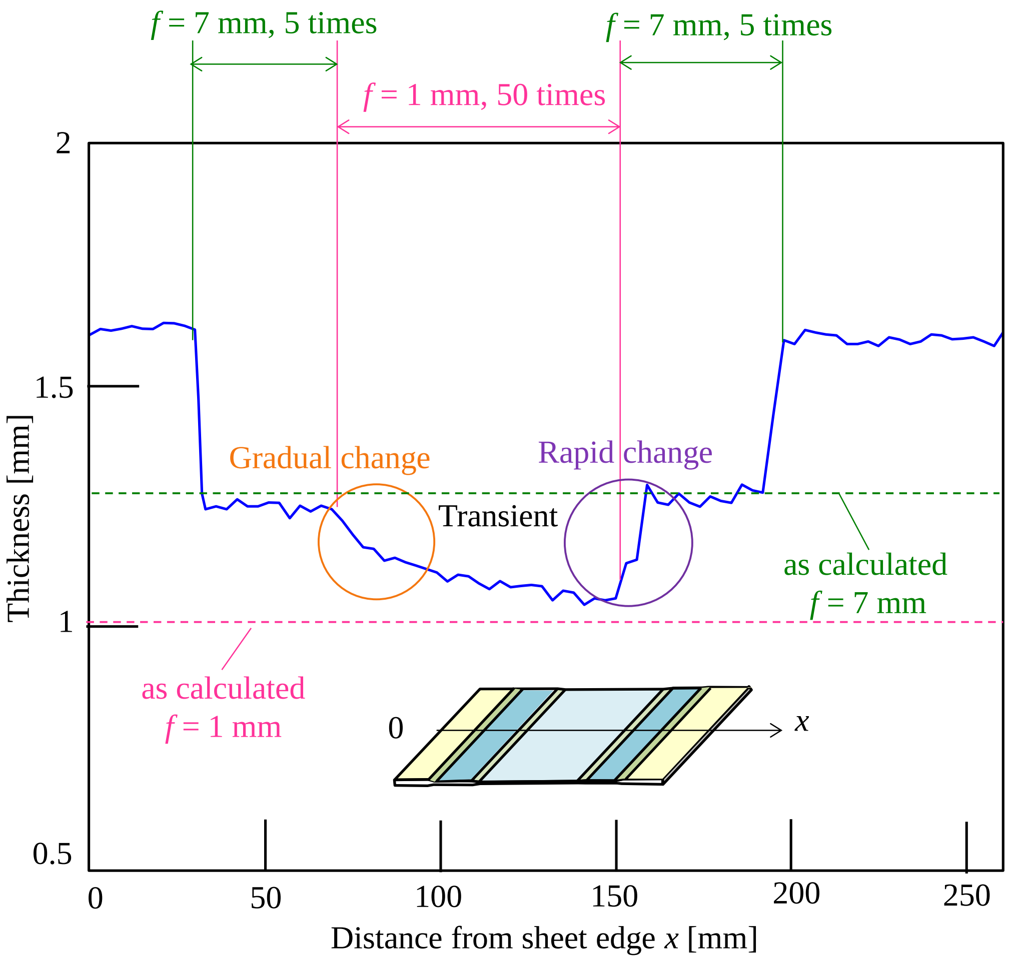


Fig. 2.10. Thickness distribution of three thicknesses tailored blank after successive forging.

The mechanism for decrease and increase in thicknesses of the transient region is explained in Fig. 2.11. For the decrease in thickness, the punch surface is fully in contact with the blank (see Fig. 2.11(a)). For every compression, the contact area between the punch and sheet is similar. Therefore the forging load and thickness reduced gradually. On the other hand, the contact area with the punch becomes rapidly small for the increase in thickness and thus the thickness distribution tends to become sensitive (see Fig. 2.11

(b)). Therefore a method for controlling the thickness distribution was proposed to adjust the gradual and rapid changes of the transient region.

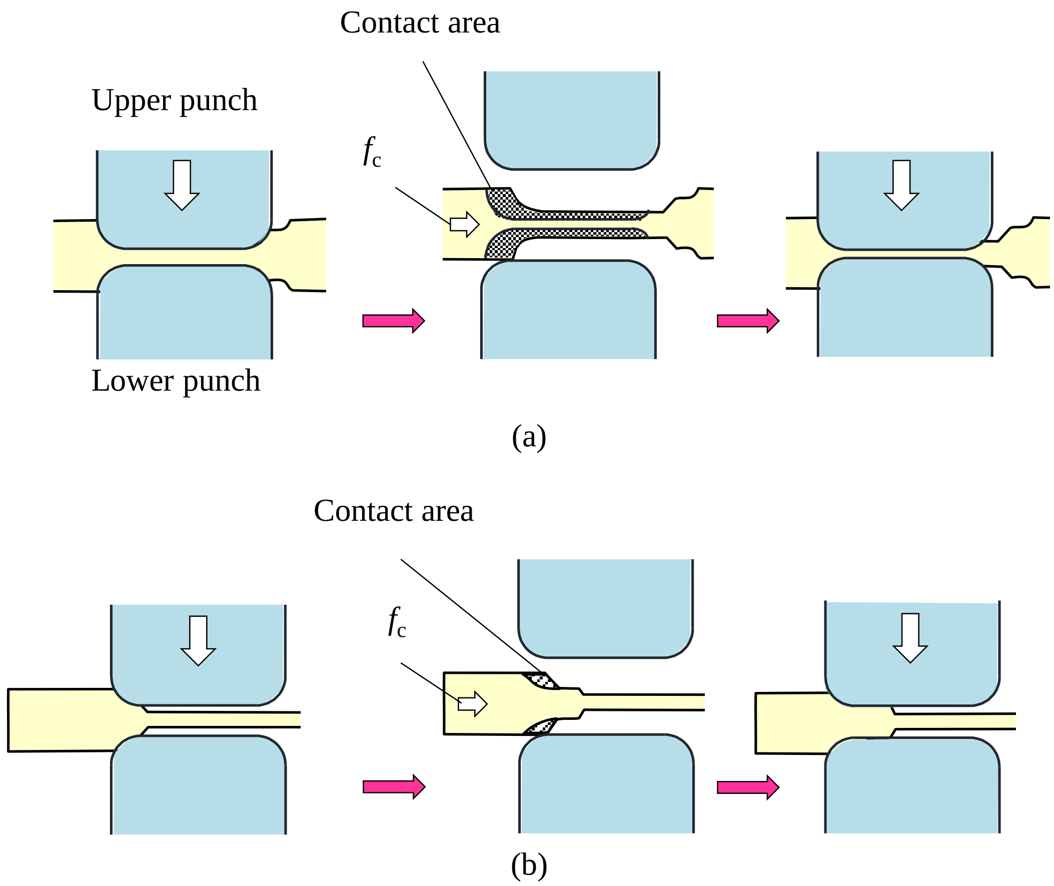


Fig. 2.11. Mechanisms for (a) decrease and (b) increase in thicknesses of transient regions.

2.4. Control of thickness distribution in transient regions

2.4.1. Control of decrease in thickness

In order to control the gradual change in thickness of the transient region, the constant feed was employed for the decrease in thickness. The change in thickness for the constant feed is shown in Fig. 2.12. For a small feeding, a gradual change in thickness was obtained, whereas for a large feeding a rapid change in thickness was caused. For a large feeding, the steady-state of the thickness was attained faster as compared to the smaller feeding.

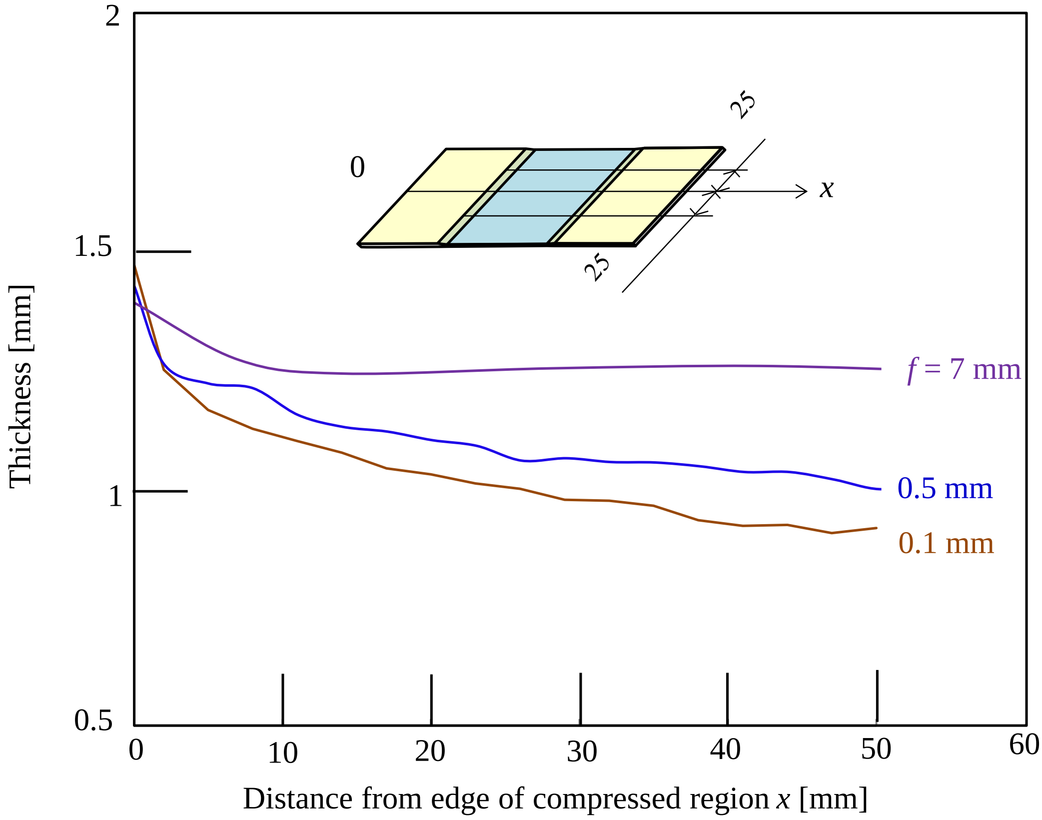


Fig. 2.12. Change in thickness for constant feed and f = 0.1, 0.5 and 7 mm.

2.4.2. Control of increase in thickness

For the increase in thickness, the variable feed, f_v was chosen to control the slope of the transient region. The feed per one strike for the variable feed is shown in Fig. 2.13. The feed starts with a minimum of 1 mm and the value increases until 7 mm. As the amount of feed increase, the contact area increases. As the contact area gets larger, the reduction in thickness reduces. Therefore the thickness of the sheet at the transient region was controlled.

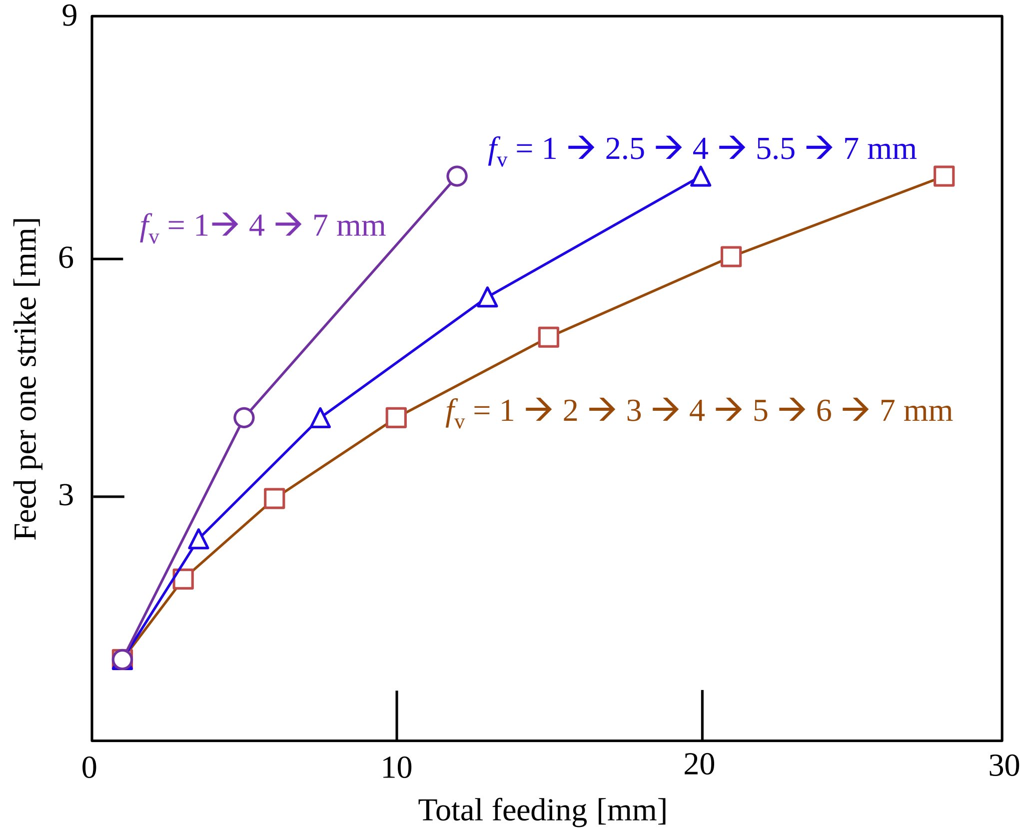


Fig. 2.13. Feed per one strike for variable feed and f_v = 1, 1.5 and 3 mm.

The change in thickness for the variable feed is given in Fig. 2.14. The thickness at the transient region increases as the feed increases. A small increment in feed results in longer and gradual transient region. Whereas for a large increment in feed, the change in thickness becomes rapid. Therefore thickness in the transient region is controlled by variable feeding.

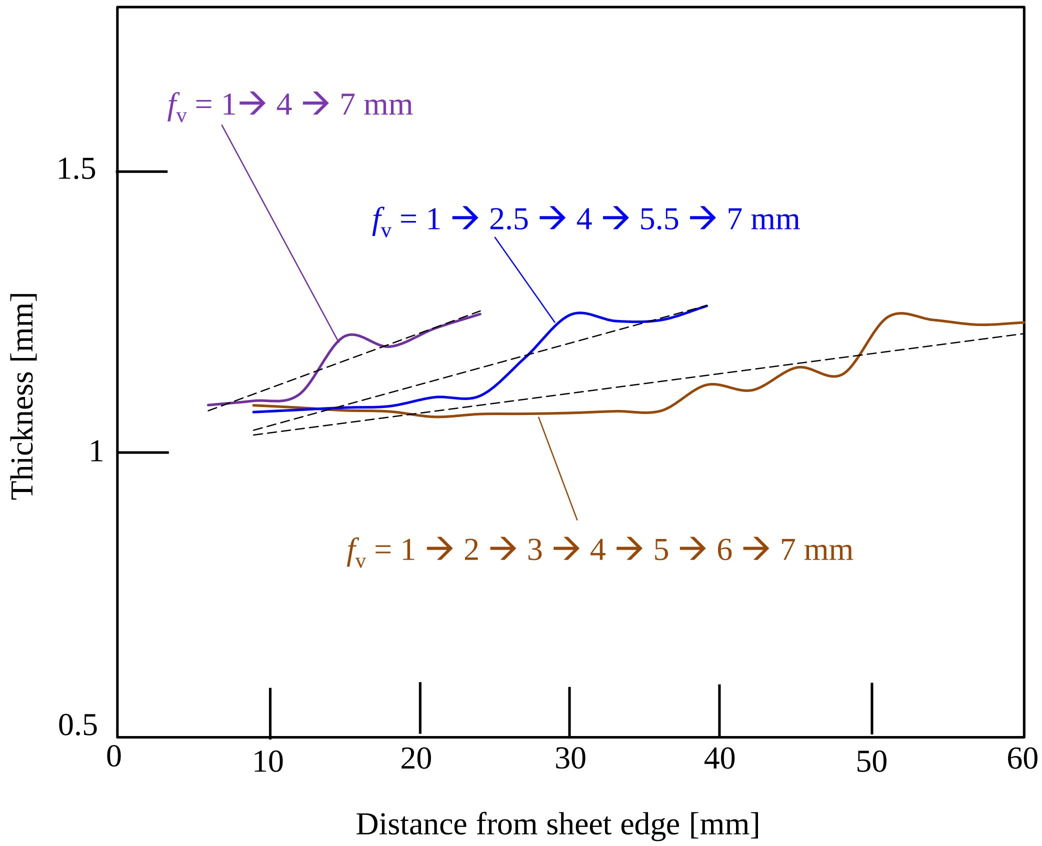


Fig. 2.14. Change in thickness for variable feed.

2.4.3. Thickness distribution of tailored blank with feeding control

The feed was controlled to produce a tailored blank having a thickness distribution. To obtain a symmetrical transient region, for the decrease in thickness, f = 0.1 mm was chosen while for the increase in thickness, fv with increment of 1.5 mm was selected. The tailored blank with feed control by successive forging is shown in Fig. 2.15. Tool markings were observed on the surface of the tailored blank. These markings were formed due to the inclination of the upper punch at the bottom dead centre.

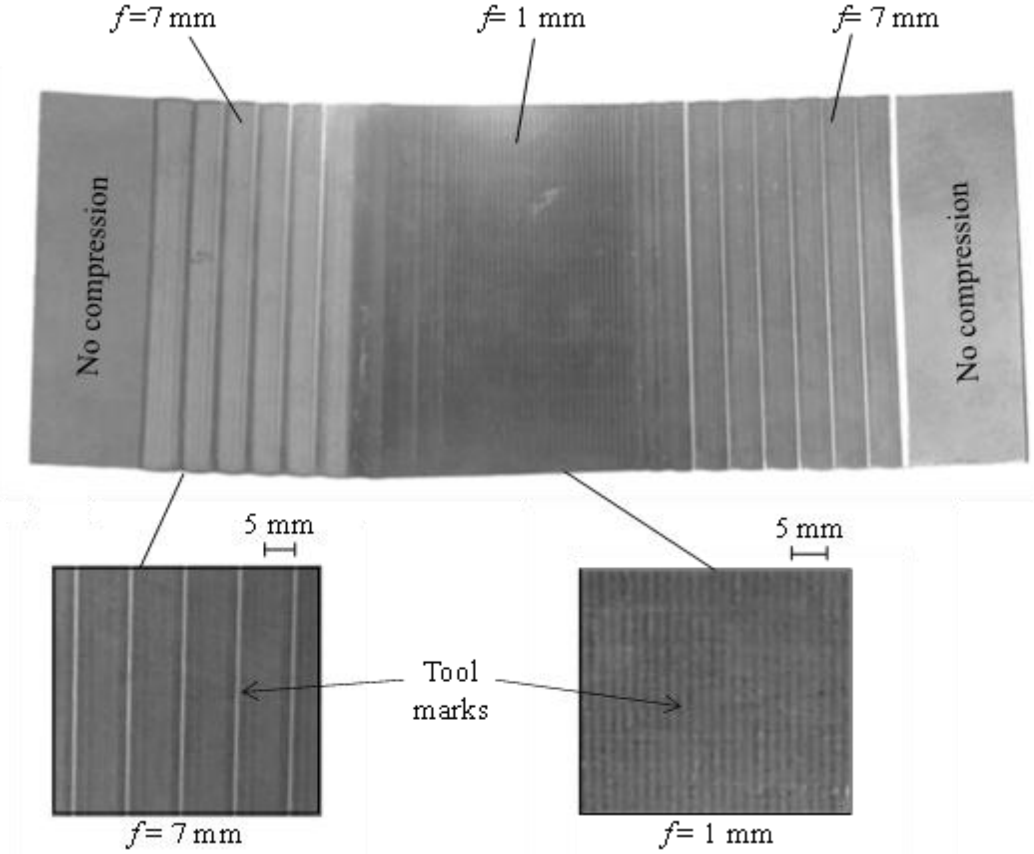


Fig. 2.15. Tailored blank with feeding control by successive forging.

The thickness distributions for tailored blank having three thicknesses with and without feeding control are given in Fig. 2.16. Without feeding control, the horizontal surface of 1 mm thickness was not achieved due to the long transient region at the decrease in thickness. With the control feeding, the thickness distribution is agreeable to the target thickness. For successive forging with feeding control, both of the transient regions were more symmetrical.

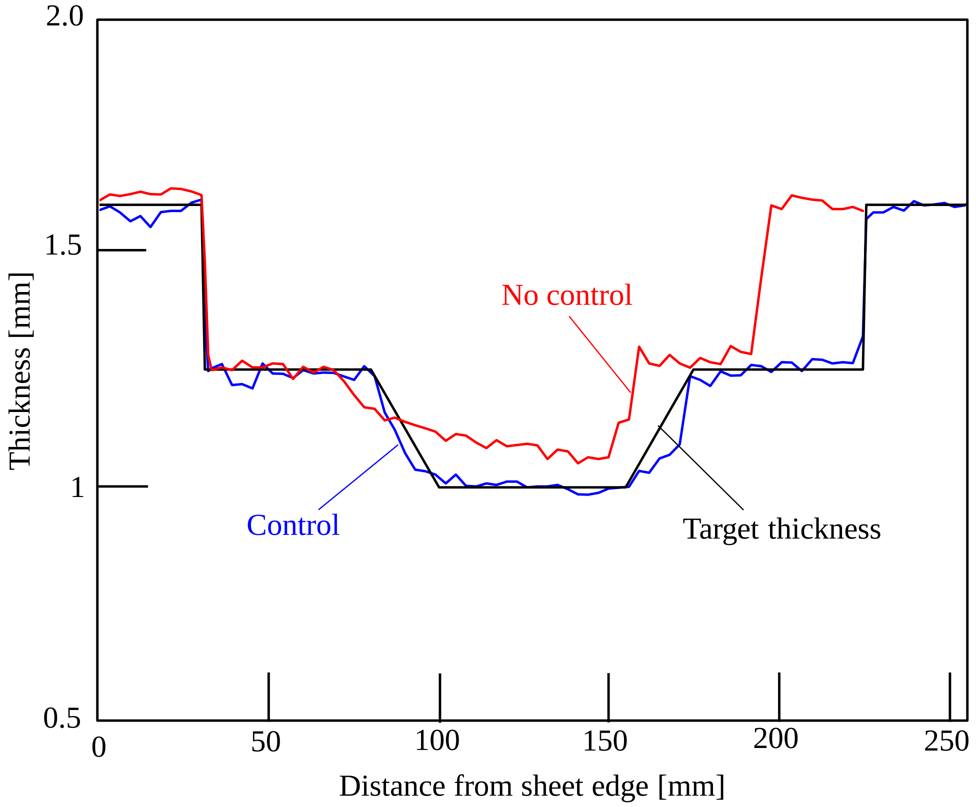


Fig. 2.16. Thickness distribution of tailored blank with feeding control.

The feed paths with and without control for tailored blank having three thicknesses are shown in Fig. 2.17. For the feed path with control, overshoot of the feeding reduces the gradual change of thickness of the transient region. In order to obtain a symmetrical thickness changes for both the transient regions, for the increase in thickness, the variable feeding, f_v was chosen.

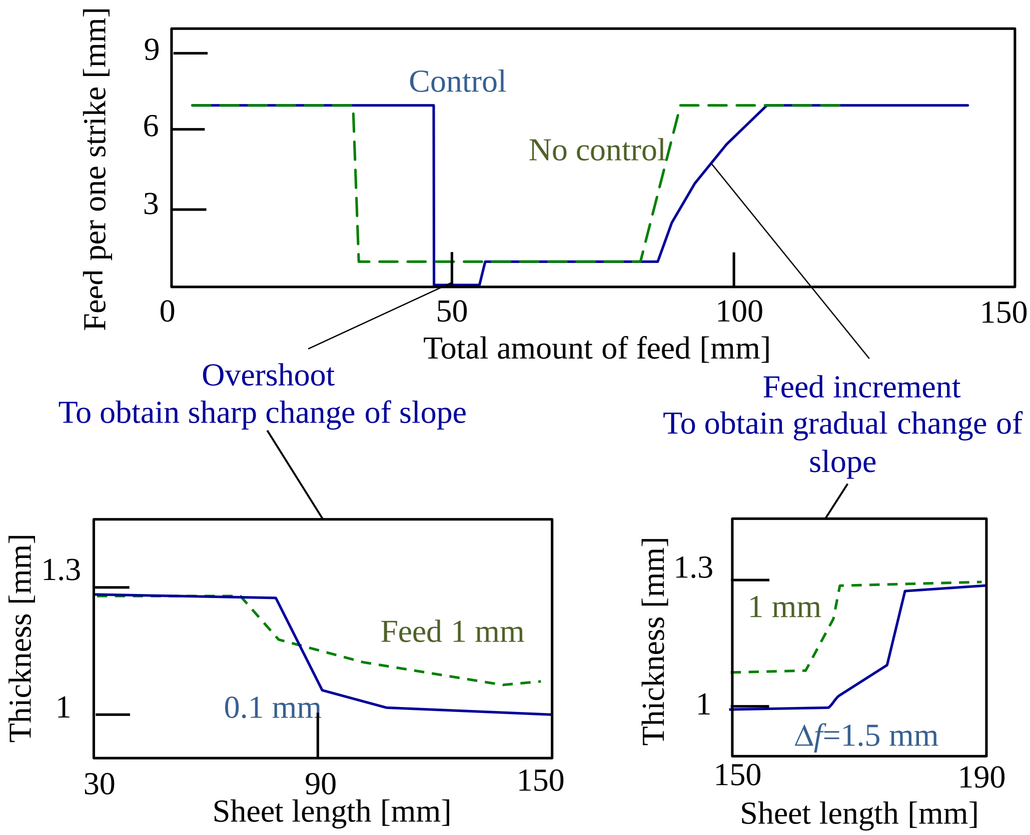


Fig. 2.17. Feed paths with and without control for tailored blank having three thicknesses.

2.5. Conclusions

Tailored blanks having distributions of thickness and strength are effective in reducing the weight of automobiles without compromising the passenger safety. Although tailored blanks are commonly produced by welding, flexibility of distributions of thickness and strength is lack because of the increase in weld length. Although tailored-rolled blanks have high flexibility of thickness distribution, the supply is still limited because the blanks are produced by special mills for controlling the roll gap during rolling.

The developed successive 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 available for the production. Only the feed is controlled to obtain a desired thickness by effective use of elastic deformation of a press and tools. The production becomes flexible, i.e. forming makers can produce the tailor-forged blanks and existing presses are reused.

Chapter 3

Improvement of surface quality of tailor-forged blank produced by successive forging with optimised punch

3.1 Introduction

The used of tailored blanks in car body in-white is important as car manufacturers are able to locate material with the best properties at the desired area precisely. Due to different strength requirement of the car body parts, the optimum thickness distribution is essential for the reduction in weight. Rather than increasing the thickness of the whole part, only a portion of the part is made thicker to increase the strength locally without increasing too much weight. Corners of stamped parts for example require higher strength to improve formability and prevent failure [33-35].

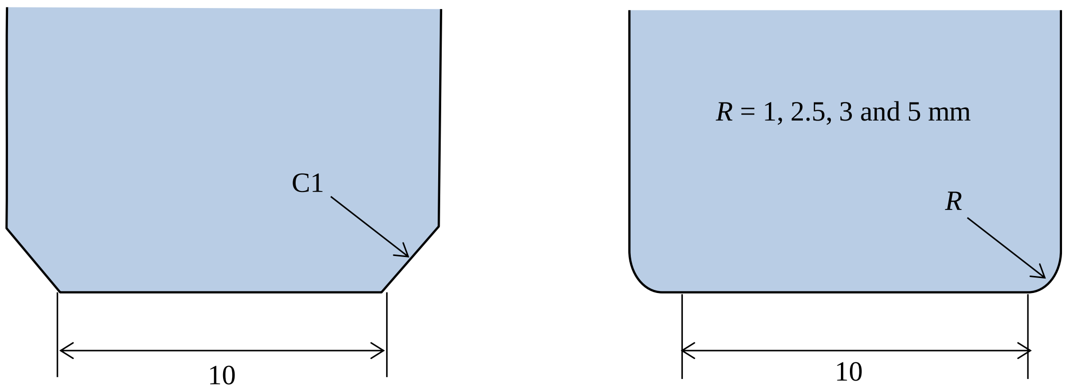
Although tailored blanks are useful in reducing the weight and improving the crash safety during a collision, the heterogeneity of materials and defect formation limit the ability and performance of the stamped parts. In tailor-welded blanks, the rough surface, imperfection and porosity of the weld metal reduce the ductility of the tailor-welded blanks [72, 73]. The weld line movement during forming due to different strength of materials decreases the formability and drawability [25, 74]. Tailor-rolled blanks on the other hand are produced without joining and therefore surface quality are improved. For the application in cold stamping, tailor-rolled blanks of different thicknesses have differing strength due to work hardening during rolling. Although successive forging have been employed to produce tailored blanks having a thickness distribution by adjusting the amount of feeding, the surface quality is problematic. The uneven surface profile of the tailor-forged blank induces stress concentration. During compression, the press ram is inclined by deflection of the press frame, and then markings are formed on the surface of the tailored blank.

In the present chapter, the punch shape was analysed to improve the tool marks formed on the surface of tailor-forged blanks. Tools for correcting inclination was also proposed to reduce the surface marking. The upper curved plate slides during compression to reduce the incline angle of the upper die.

3.2 Optimised punch shapes for successive forging of tailored blank

3.2.1 Finite element simulation of successive forging

Finite element simulation had been carried out to analyse the effect of punch shape on the deformation of tailor-forged blanks. The deformation behaviour and surface markings are calculated from the finite element simulation software ABAQUS. Two types of punch are chosen for this purpose. The punch shapes for optimisation is shown in Fig. 3.1. The chamfer punch has a sharp corner at the edges while the corner radius punch has round edges. The corner radius, R was varied from 1 mm to 5 mm while the chamfer is 1 mm. The upper and lower punches are treated as elastic and the coefficient of friction, μ is 0.1. Table 3.1 shows the conditions used for finite element simulation for successive forging of tailored blanks.



(a) Chamfer

(b) Corner radius

Fig. 3.1 Punch shapes for optimisation in successive forging of tailored blank.

Table 3.1 Conditions used for finite element simulation for successive forging of tailored blank.

Software	ABAQUS
Coefficient of friction	Upper punch and sheet：0.1 Lower punch and sheet：0.1
Punch	Elastic body
Sheet	Elasto-plastic body Young's modulus 210 GPa Poisson's ratio 0.3

The model of the finite element is shown in Fig. 3.2. Since successive forging involves feeding the sheet, two compression were carried out. The feeding was f= 5 mm. In this case, the sheet is made stationary while two sets of upper and lower punches were built to compress the sheet. To perform the feeding without moving the sheet, the second pair of punch were positioned 5 mm apart from the first pair. The thickness of the blank was 1.6 mm.

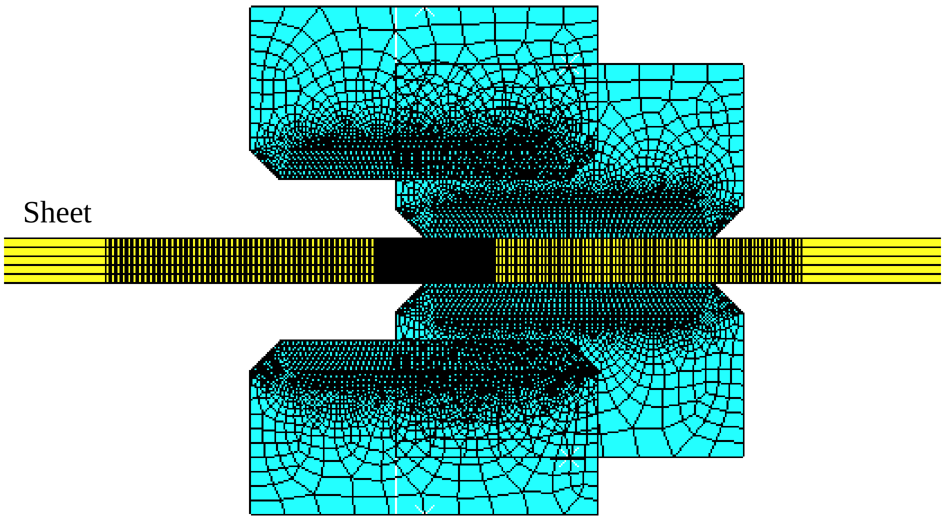


Fig. 3.2 Finite element model for successive forging of tailored blank.

The blank deformation and tool marks for different punches are shown in Fig. 3.3. In the first compression, the blank deformation is sharp with chamfer punch. However as with the corner radius punch, the blank deformation is gradual. As the radius of the punch increases, the change in thickness between the compressed and non-compressed area becomes more gradual. The tool mark was large for chamfer punch. Comparing between chamfer punch and corner radius punch of 5 mm, the tool marks reduces with the corner radius punch.

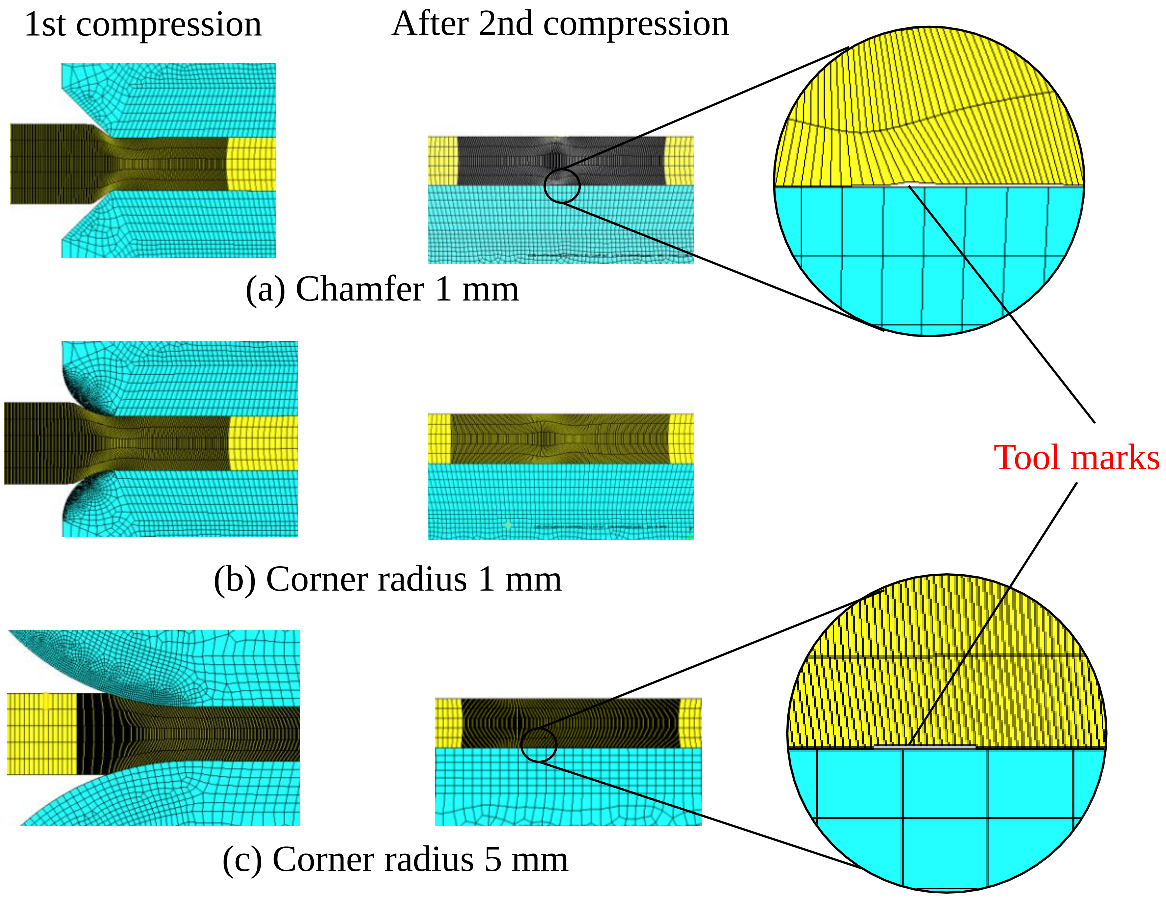


Fig. 3.3 Blank deformation and marking depth for different punches.

The relationship between tool marking depth and the punch radius is given in Fig. 3.4. For chamfer punch, the sharp edges causes tool marks of almost 0.012 mm. However as the punch radius increases, the tool marks decreases. For all the corner radius punch, the tool marking depth is almost constant. Therefore, a corner radius punch shows a better surface profile as compared to the chamfer punch. The length of the punch radius shows only a small effects on the tool marks.

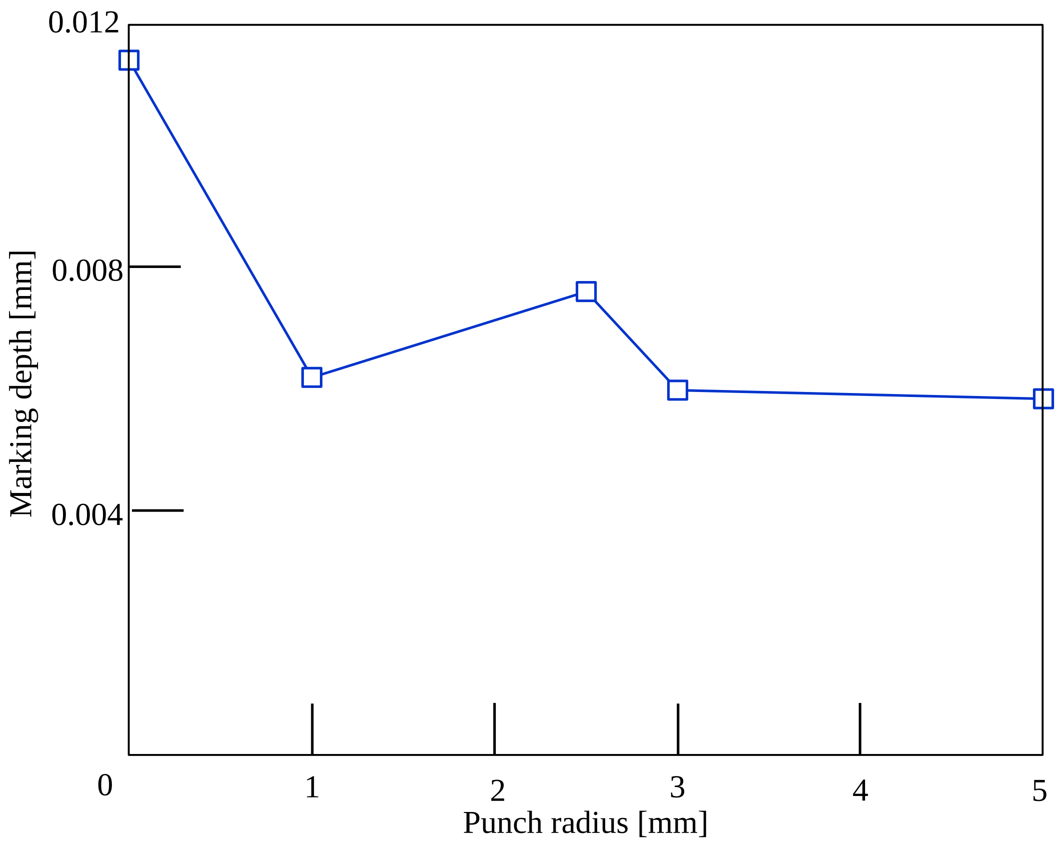


Fig. 3.4 Relationship between tool marking depth and punch radius for *f* = 5mm.

3.2.2 Experiment result

A successive forging process was carried with the corner punch radius to observe the tool marks formation. A corner punch radius of 1 mm was chosen to forge the blank with a constant feeding of 5 mm. The stroke was 2.1 mm. The surface profile of tailored blank for *f* = 5 mm are given in Fig. 3.5. However as compared to the calculation result, a large tool marks were observed with the corner radius punch. The large tool marks are caused by the elastic deformation of the press and tools during forging.

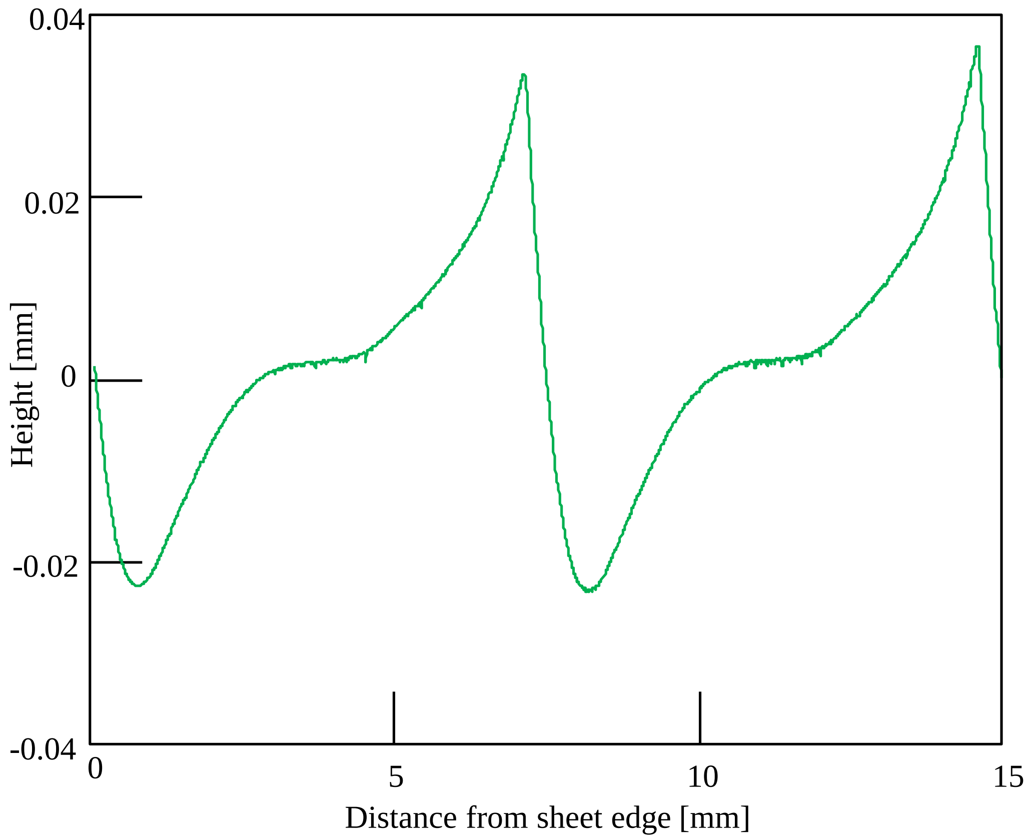
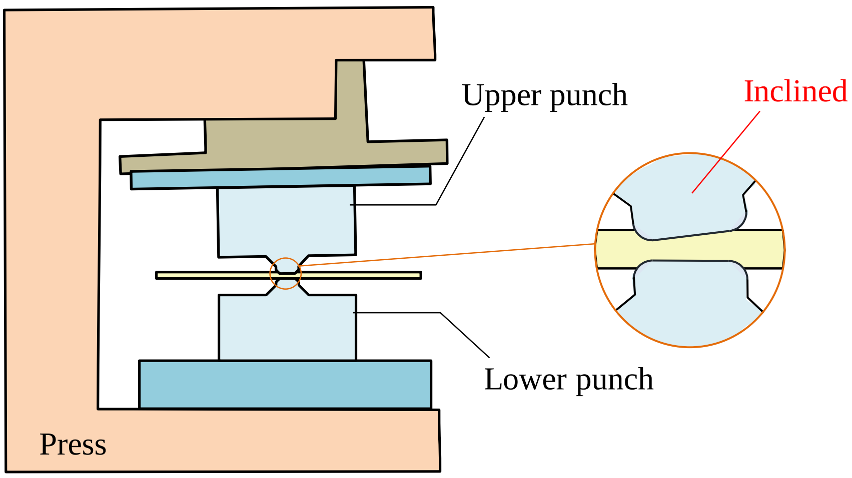


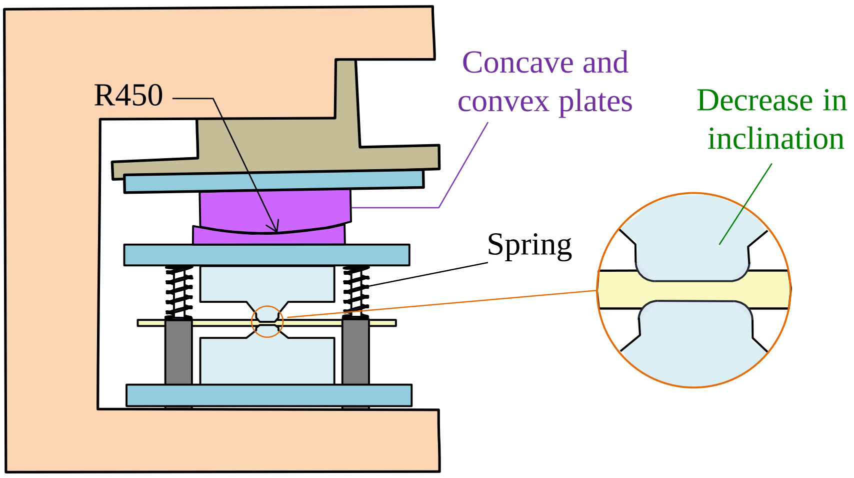
Fig. 3.5 Surface profile of tailored blanks for f = 5 mm with corner punch radius of 1 mm.

3.3 Improvement of surface quality of tailor-forged blank by tools for correcting inclination

The C-frame of the press deflects due to elastic deformation during successive forging, and the upper punch is inclined by elastic deformation (see Fig. 3.6(a)). The tool marks appearing on the surface of tailored blank shown in Fig. 3.5 were caused by repeated forging with the inclined bottom of the upper punch. To prevent the tool marks, concave and convex plates were inserted into the C-frame as shown in Fig. 3.6(b). The curved plate slid during compression, hence the inclination of the upper punch was reduced. Since the inclination was reduced, the contact area and forging load were increased. Therefore to obtain the same amount of reduction in thickness, the stroke was increased to 2.4 mm for correcting inclination tools.



(a)



(b)

Fig. 3.6 Dies (a) without and (b) with tools for correcting inclination in successive forging.

The die for correcting the incline in successive forging of tailored blank having a thickness distribution is shown in Fig. 3.7. The convex and concave plates having a radius of 450 mm were added between the upper and middle base plates. Springs were used to return the upper punch to its original position after each compression. A feeder was utilised to move the sheet into the compression region after each compression. 22MnB5 boron steel sheets having a thickness of 1.6 mm were used. The length and width of the sheet were 400 mm and 100 mm, respectively.

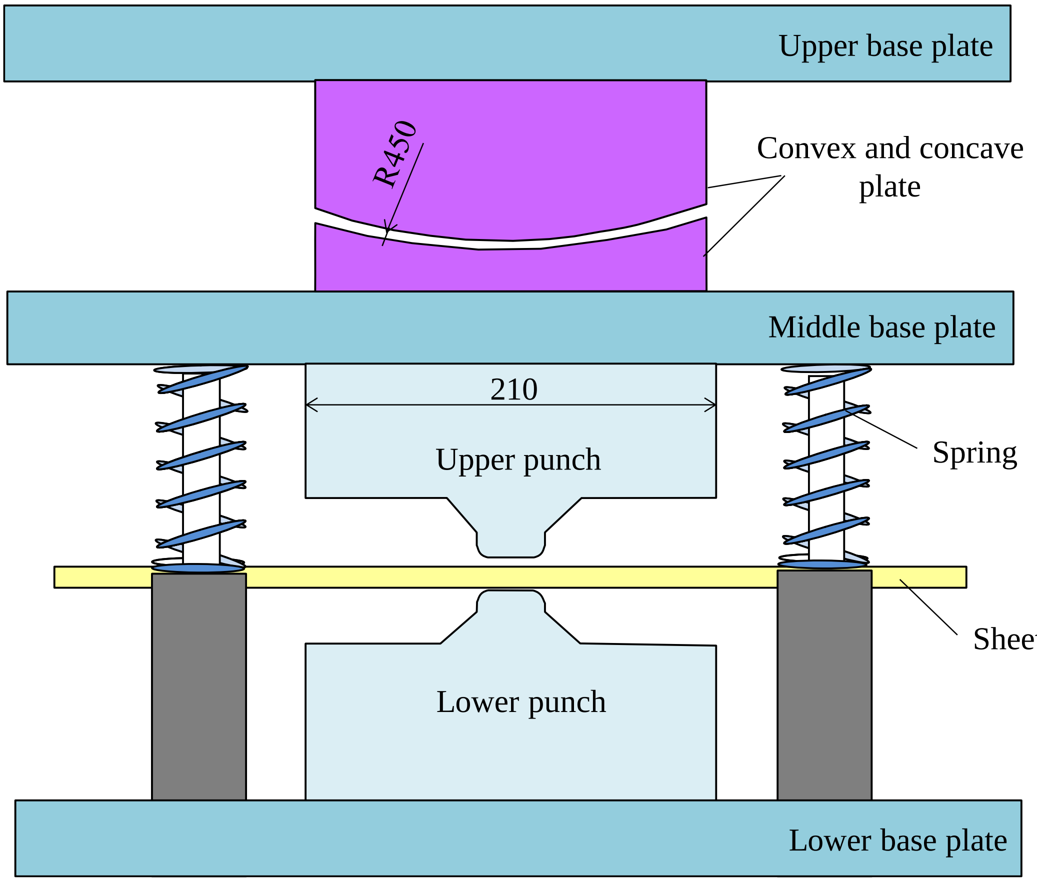
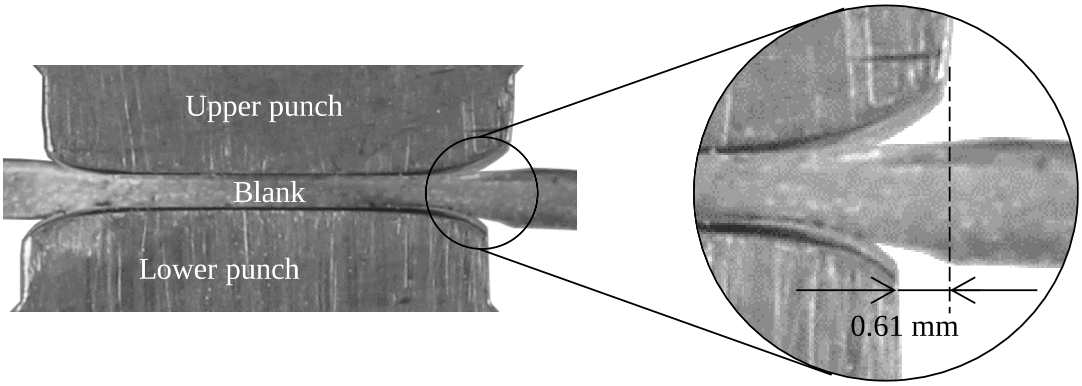
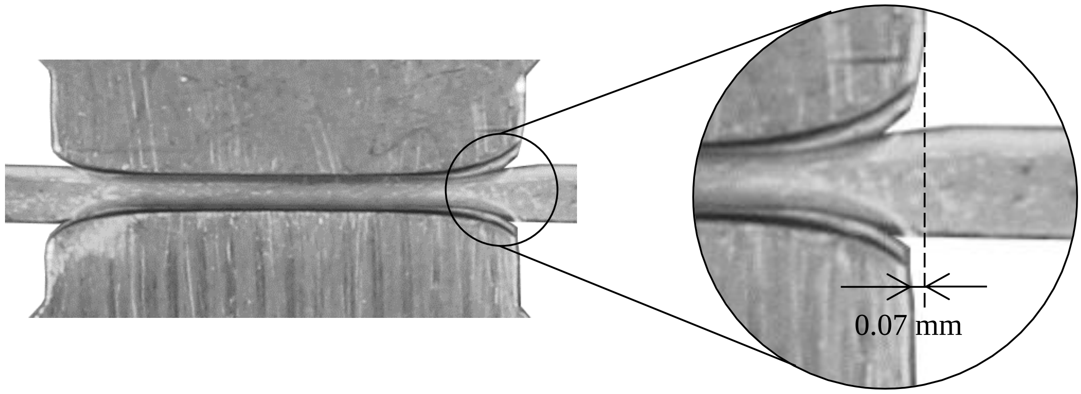


Fig. 3.7 Die for correcting incline in successive forging of tailored blank having thickness distribution.

The misalignment of the upper punch from the lower punch with and without tools for correcting inclination at the bottom dead centre is shown in Fig. 3.8. The stroke was 2.4 mm for both conditions. A corner radius punch of R = 1 mm was utilised. Without the incline correction, due to the incline of the press slide, there is a large misalignment of the upper punch from the lower punch. While with the incline correction on the other hand, the misalignment is small due to the small incline of the upper punch.



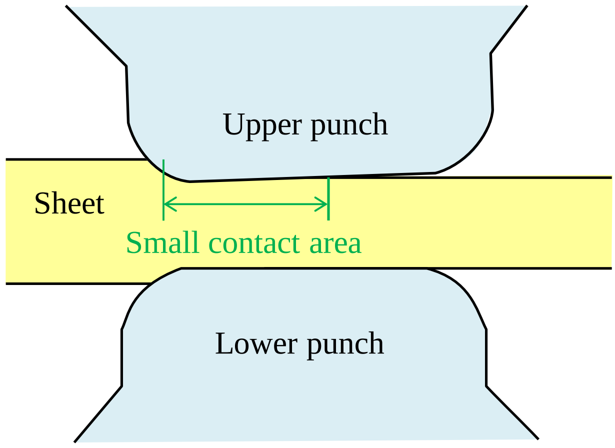
(a)



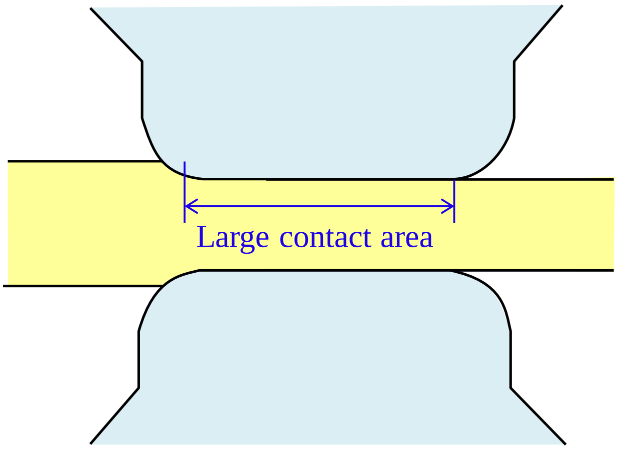
(b)

Fig. 3.8. Misalignment of upper punch from lower punch (a) without and (b) with tools for correcting inclination at bottom dead centre.

Fig. 3.9 illustrates the contact area between the upper punch and sheet during compression with and without the tools for correcting inclination. Comparing between both conditions, the contact area without the incline correction is smaller due to the inclination of the upper punch. Since the contact area is larger with the incline correcting die, the forging load increases.



(a) Without incline correction



(b) With incline correction

Fig. 3.9 Contact area between upper die and sheet during compression with and without incline correction.

With the inclination correction, the steady-state thickness t of the compressed blank is amended from Eq. (2.1) by

$$t = 0.045f + 0.97 \text{ mm}. \tag{3.1}$$

3.4 Surface quality for different punch shapes with tools for correcting inclination

3.4.1 Small corner punch radius

Fig. 3.10 shows the surface profile of tailored blanks with and without the incline correction for feeding 5 mm. A corner radius punch of R = 1 mm was employed. Without the incline correction, the surface marking depth is 0.06 mm. The large surface marking was reduced to 0.004 mm with the incline correction. A smoother surface was obtained. The experimental result with the tools for correcting inclination and a corner punch radius agrees with the calculated results.

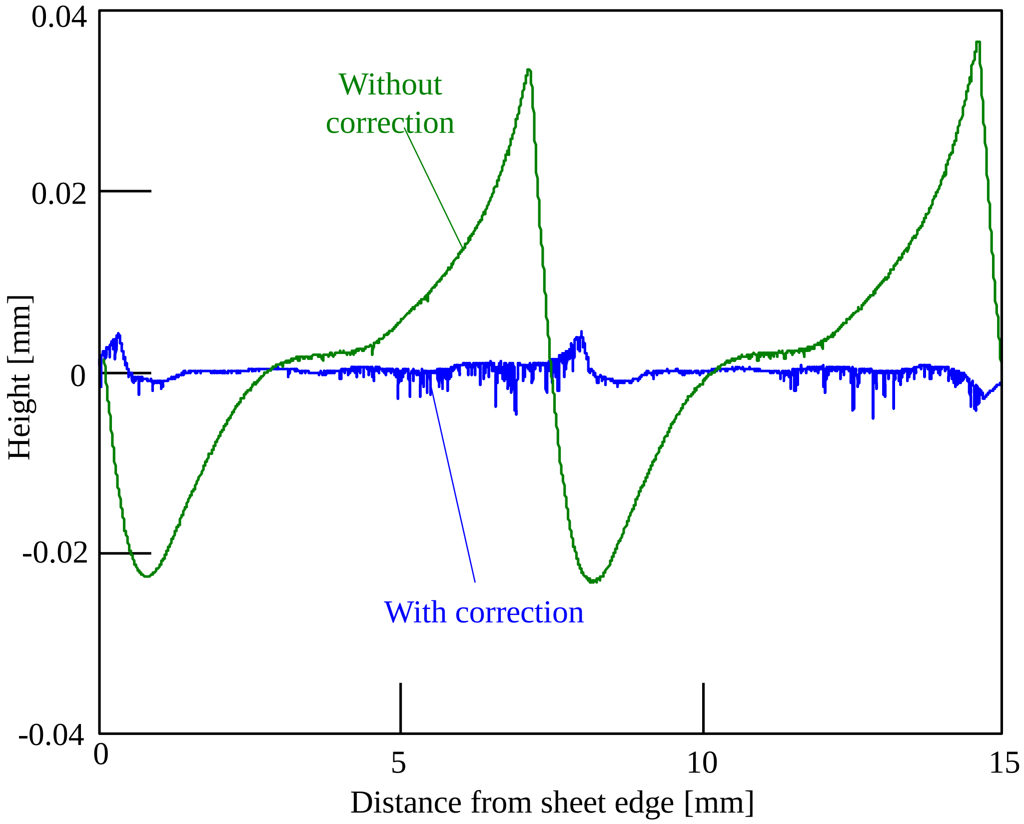


Fig. 3.10 Surface profile of tailored blanks with and without incline correction for feeding 5 mm with corner punch radius of $R = 1$ mm.

The reflected lines on the surface of the tailored blank with and without the incline correction are shown in Fig. 3.11. The feeding was 5 mm and the corner radius punch of 1 mm was utilised. The straight lines were drawn on a piece of paper and then reflected on the tailored blank surface. Without incline correction, the reflected lines were interrupted by the tool marks. On the other hand, with incline correction, the smooth reflected lines were observed. The tool marks of the tailor-forged blank with incline correction were reduced.

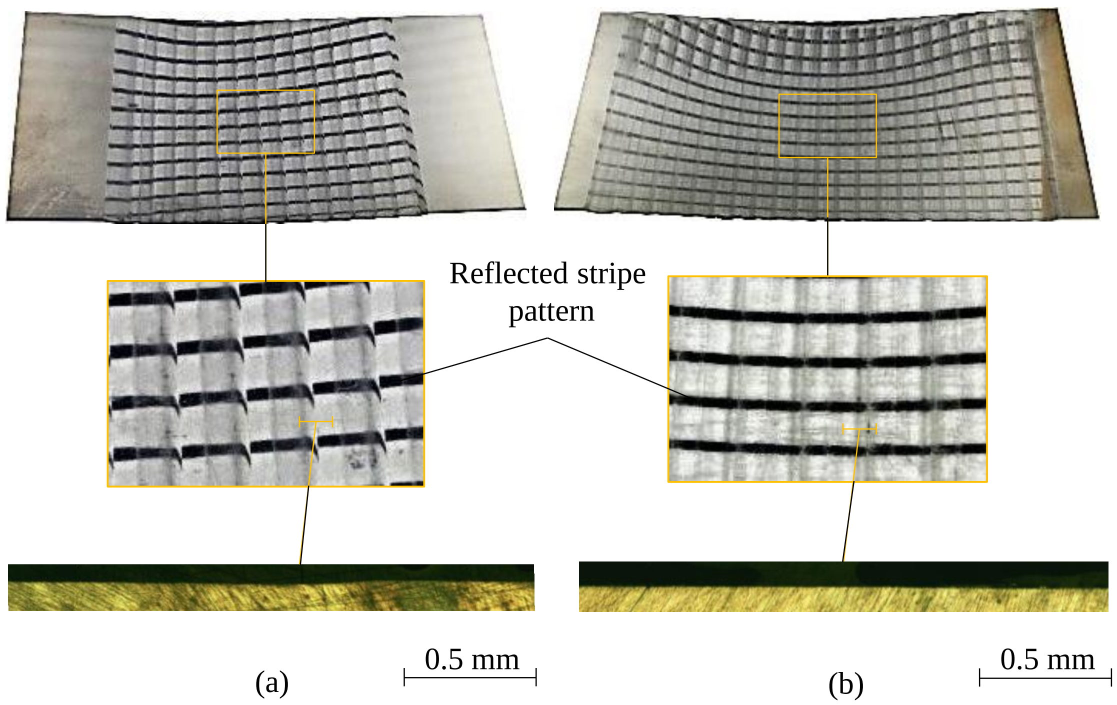


Fig. 3.11. Surfaces of tailored blank (a) without and (b) with incline correction for f = 5 mm.

3.4.2 Large corner punch radius

Since the calculated results show a small change in tool marking depth for different corner radius punches, a successive forging process was carried out with a corner radius punch of R = 3 mm to observe the tool marks formation. Fig 3.12 shows the surface profile of tailored blanks with tools for correcting inclination for feeding 5 mm with a corner radius punch of R = 3 mm. The surface profile of tailored blanks forged with a corner radius punch of R = 3 mm shows a marking depth of 0.006 mm. The tool marks formed using corner radius punches of R = 1 and 3 mm show a small difference.

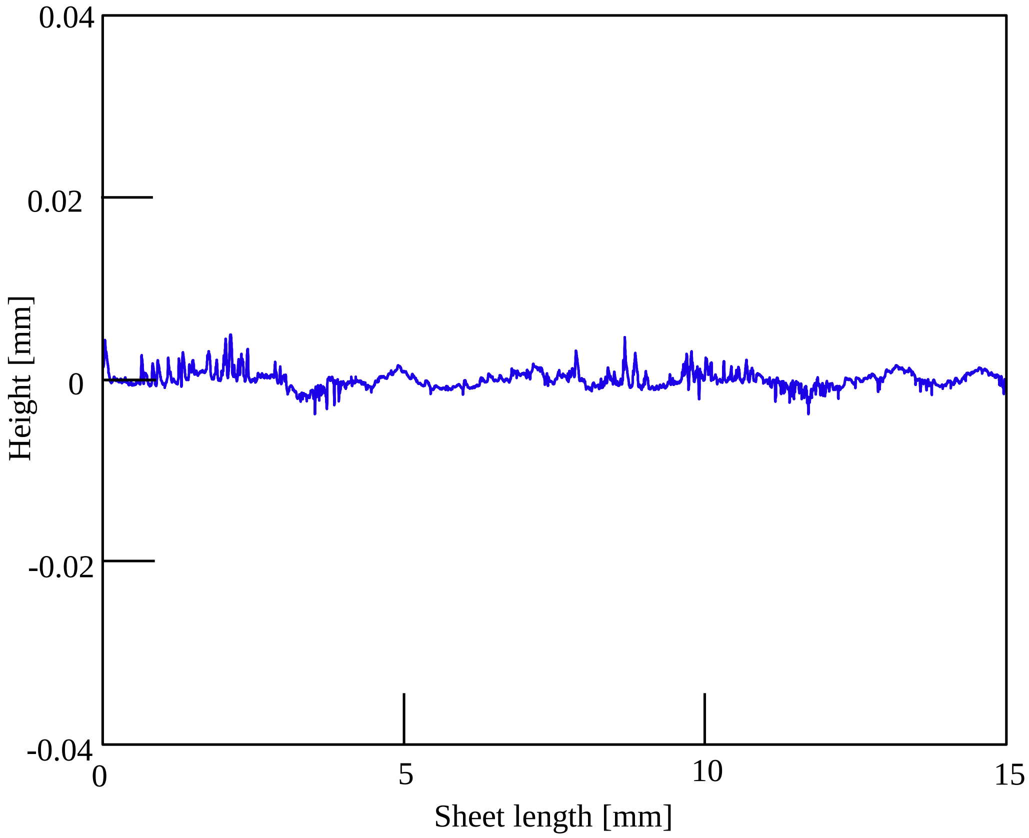


Fig. 3.12 Surface profile of tailored blanks with incline correction for feeding 5 mm with corner radius punch of R = 3 mm.

3.4.3 Chamfer punch

The surface profile of tailored blanks with incline correction for feeding 5 mm with a chamfer punch of 1 mm is given in Fig. 3.13. Although tools for correcting inclination was used, large tool marks were observed. The chamfer punch having a sharp edge at the corners produced a sharp change in the thickness as shown in Fig. 3.3.

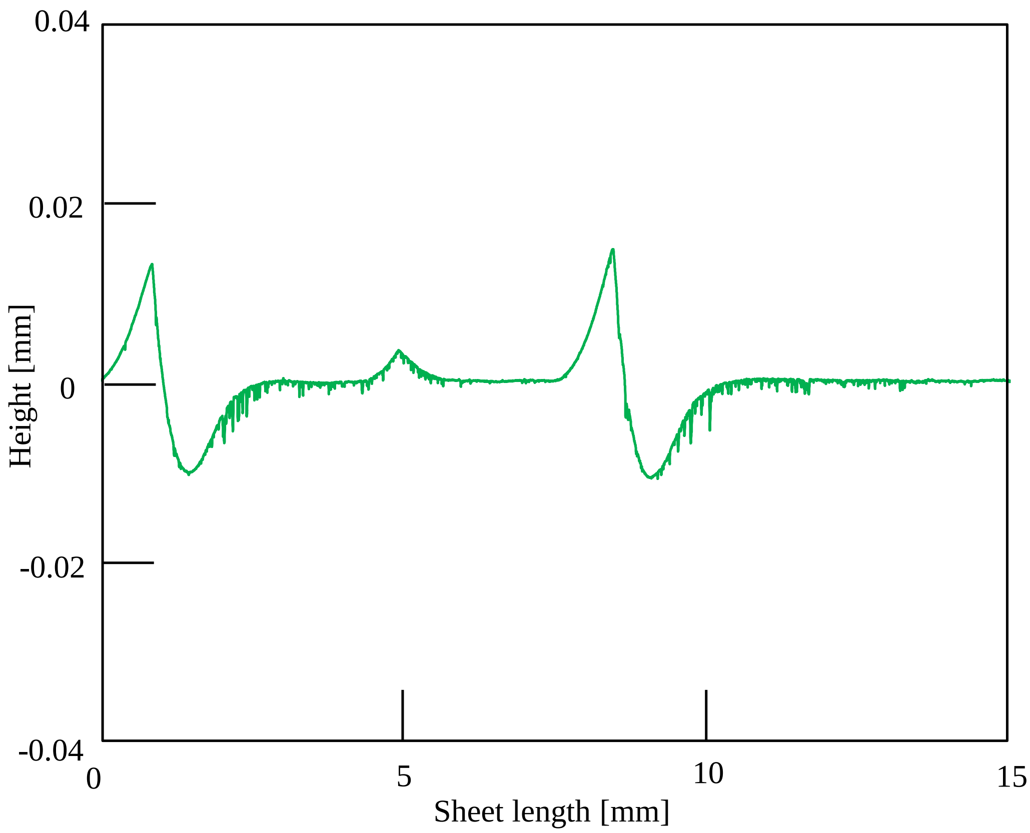


Fig. 3.13 Surface profile of tailored blanks with incline correction for feeding 5 mm with chamfer punch of 1 mm.

3.5 Conclusions

Automobile parts do not only need to have high dimension and shape accuracy but a good surface quality is essential. Although tailor blanks have been produced by successive forging, the surface quality deteriorates due to the tool marks formed during compression. The tool marks cause an uneven surface on the tailored blank which increase the stress concentration and reduce the formability. During successive forging, the press ram is inclined by deflection of the press frame and tool marks are formed.

Improvement of the surface quality for tailor-forged blank produced by successive forging for hot stamping was carried out. The die without incline correction produced tailored blank having thickness distribution with surface markings due to upper punch inclination. Corner radius punch improved the surface quality as compared to the chamfer punch. Tools for correcting inclination were proposed by inserting convex and concave plates into the C-frame. During compression, the plate slid and the upper punch inclination was reduced. With the tools for correcting inclination, the misalignment of the upper punch from the lower punch was reduced and the surface quality was improved. Since the upper punch inclination was reduced, the tools for correcting inclination require a larger load to produce a sheet with the same thickness due to the larger contact area.

Chapter 4
Hot stamping of roof rail from tailored blank having thickness distribution

4.1. Introduction

One of the challenges faced by car makers is the demand of lighter car with high safety standards. Lightweight metals such aluminium and magnesium alloys have been applied to achieve these requirements. Although these metals greatly reduce the weight of the car body part, low formability and higher cost as compared to steel has limited the application. The used of steel in automobile body structure increases due to its high strength and durability. Ultra-high strength steels of tensile strength exceeding 980 MPa are used on bumper beams, B-pillars, etc. where high strength is needed for optimum performance. The needs of local reinforcement in mild steel is eliminated with the high strength steel. Therefore, the strength of a part is improved without extra material.

Although high strength steel is favourable, stamping is not easy and formability is small. Large forming load and springback are some problems with high strength steels. Hot stamping has been developed to overcome these difficulties in forming high strength steels. By heating the sheet, the flow stress decreases leading to better formability and improve of springback. A 22MnB5 quenchable steel is vulnerable to surface oxidation when heating at 950^{o}C [17]. Steel makers have introduced a pre-coated quenchable steel with Al-Si layer as a prevention from oxidation during hot stamping [46].

A B-pillar for example requires for a balance of ductility and strength to increase the energy absorption and passenger protection during an impact [57]. Local heating and cooling of high strength steel produces stamped parts having a strength distribution in a tailoring in hot stamping process [58, 59]. Although the energy absorption of automobiles during collision is improved, the thickness distribution of products effective for the weight reduction is not optimised. Therefore, tailored blanks are hot stamped to produce parts having thickness and strength distributions.

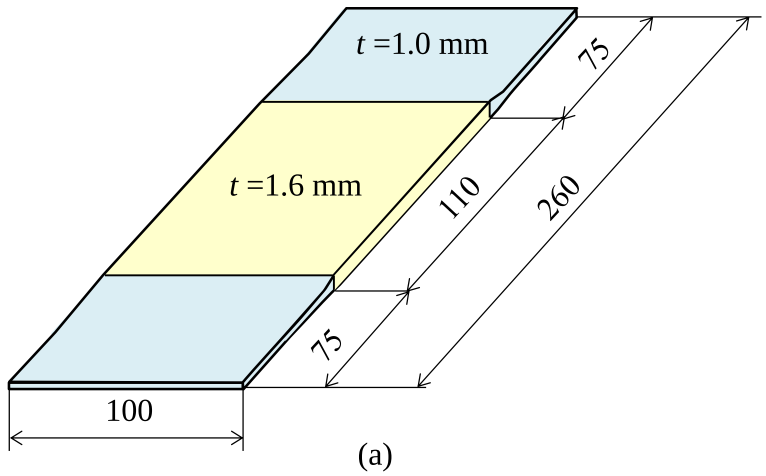
In the present study, a miniature of roof rail panel having a thickness distribution was hot-stamped from a successive-forged tailored blank. The blank was successively forged into a tailored blanks having two thicknesses. An Al-Si coated quenchable steel was employed to observe the coating behaviour after successive forging and hot stamping.

4.2. Procedure of hot stamping of roof rail from tailored blank having two thicknesses

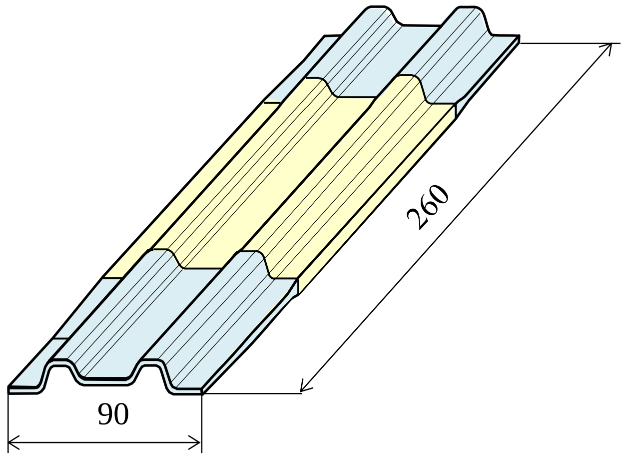
A tailored blank having two thicknesses was produced by successive forging. The tailored blank was made from an Al-Si coated quenchable steel sheet of 1.6 mm in thickness. The length and width of the blank were 400 mm and 100 mm, respectively. The chemical compositions of the quenchable steel sheet are given in Table 4.1. The tailored blank was hot-stamped into the miniature of roof rail. The shape and dimension of the tailored blank and hot-stamped roof rail miniature are illustrated in Fig. 4.1.

Table 4.1 Chemical composition of Al-Si coated quenchable steel [%].

C	Si	Mn	Al	B	Ti	Cr
0.23	0.27	1.22	0.04	0.0032	0.0037	0.2



(a)



(b)

Fig. 4.1. Dimension of (a) tailored blank and (b) hot-stamped rail roof.

Fig 4.2 shows the process of producing a miniature of roof rail panel having a thickness distribution by hot stamping. A uniform thickness blank was successively forged into tailored blank having two thicknesses. Prior to the stamping process, the tailored blank was heated in an electric furnace to an austenitising temperature of 910^{o}C for 240 seconds. The blank was then transferred by hand to the lower die in 5 seconds. The blank was formed and quenched simultaneously with dies to form a part strengthened by martensitic transformation. The tailored blank was hold within the dies at the bottom dead centre for 10 seconds. The die shape was manufactured to have different thickness distributions to cater for the thickness of the tailor-forged blank.

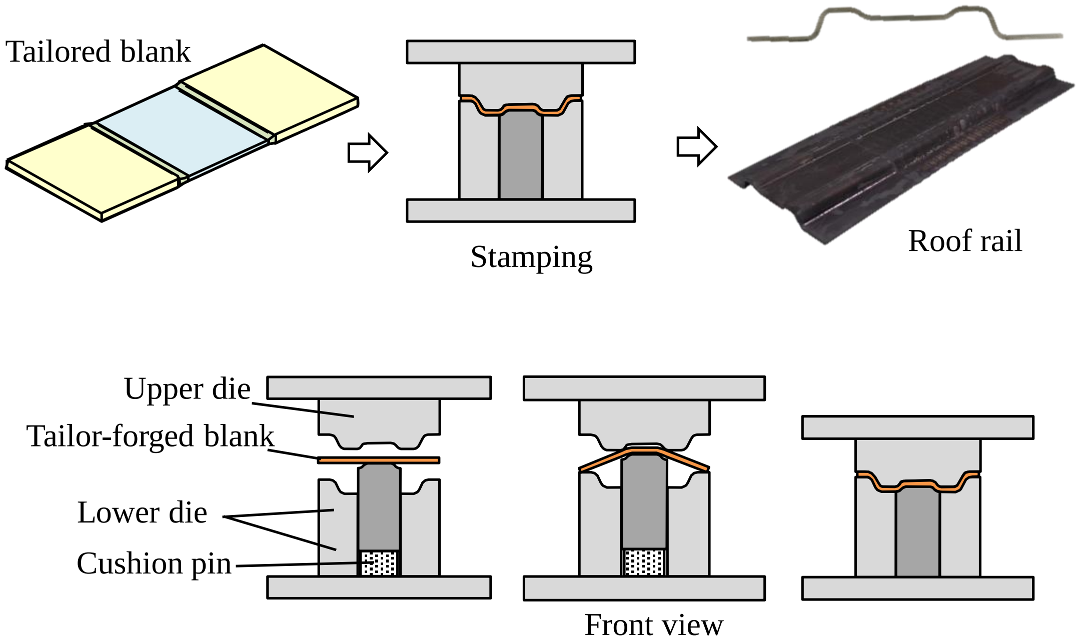


Fig. 4.2. Hot stamping of roof rail miniature from tailor-forged blank having thickness distribution.

4.3. Hot stamping of roof rail from Al-Si coated quenchable steel tailored blank

4.3.1 Shape and geometry

The thickness distributions of hot-stamped roof rail miniatures from the tailored blank and uniform thickness blank are given in Fig. 4.3. The roof rail having thickness distribution was successively forged for constant feeding of f = 0.5 mm to obtain a reduction of 38% at the steady-state thickness. The edges of the tailored blank was compressed while the centre portion was not compressed. The thickness was measured along the two lines in the longitudinal direction 20 mm apart from the centre line of the blank, and the average of the measured values is shown. The thickness distributions of the two compressed regions are different. In the front compressed region between x = 0 and 75 mm, the thickness is almost uniform, non-steady-state deformation appears in the rear compressed region between x = 185 and 260 mm. For a comparison, hot stamping of a roof rail made of a blank having uniform thickness was carried out.

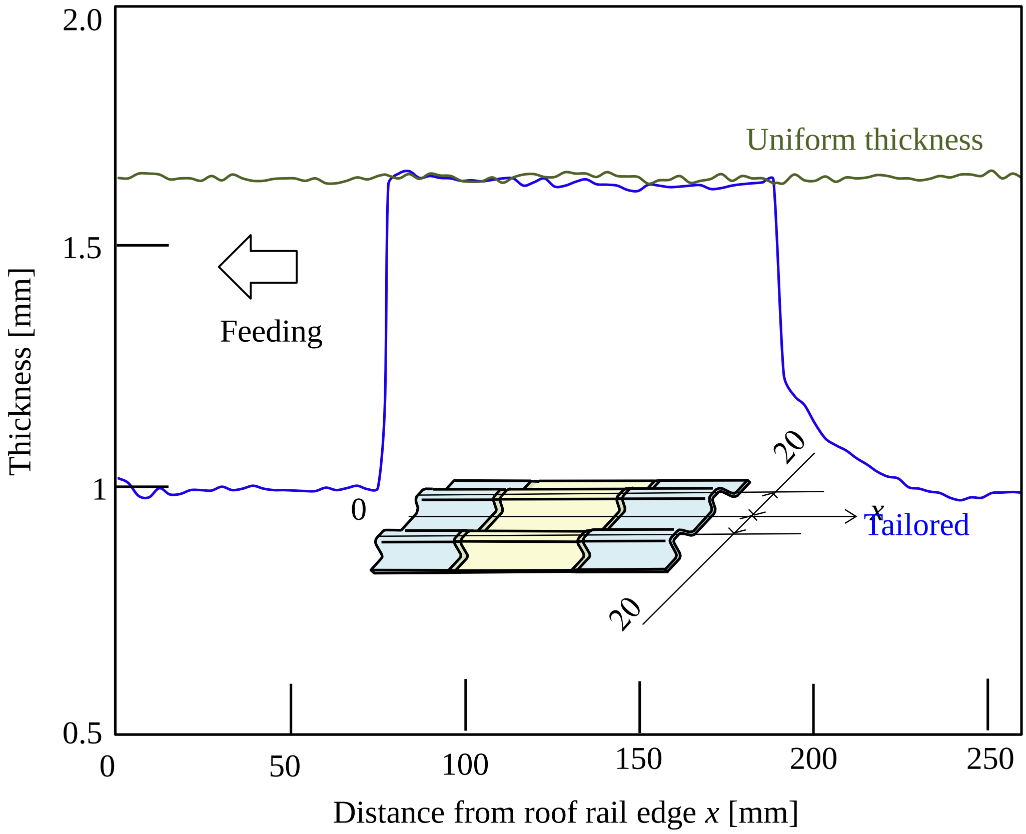


Fig. 4.3. Thickness distributions of hot-stamped roof rail miniatures from tailored blank and uniform thickness blank.

The roof rail miniatures of tailored blank and uniform thickness blank are shown in Fig. 4.4(a) and (b), respectively. The curvature of tailor-forged blank was reduced after the hot stamping process. The shapes of the roof rail miniatures of the tailored blank and uniform thickness blanks showed no significant different. The cross-sections of the roof rail miniatures are shown in Fig. 4.4(c). The surface for both of the roof rail miniatures shows no oxide scale formation.

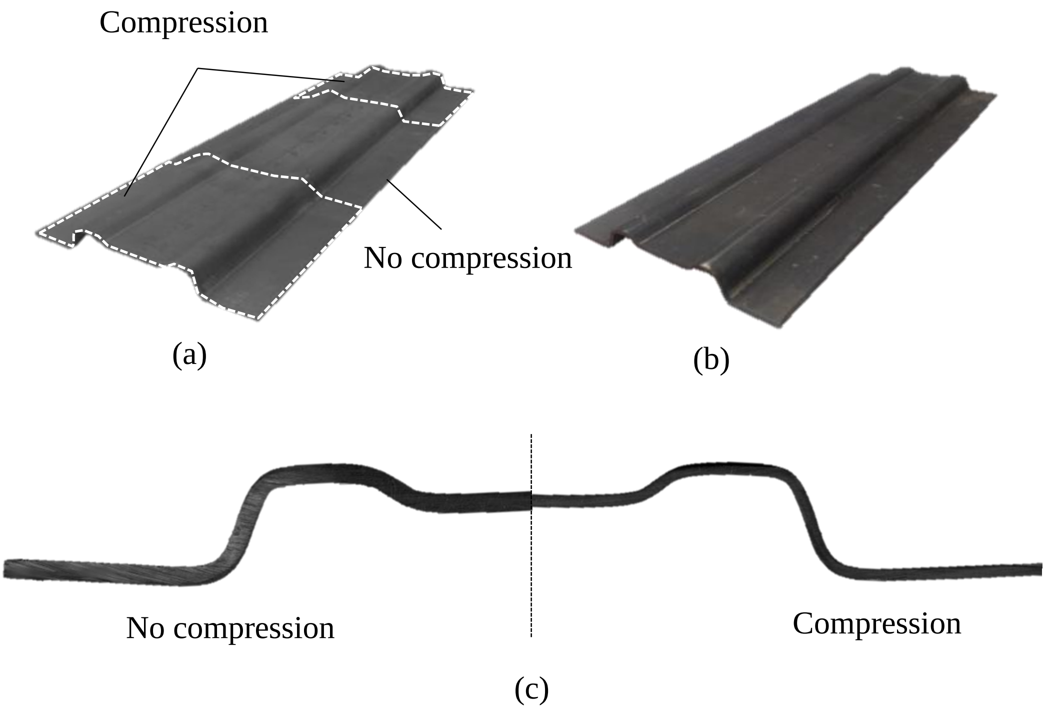


Fig. 4.4. Roof rail miniatures of (a) tailored blank and (b) uniform thickness blank and (c) cross-sections of roof rail miniatures.

Due to different deformation of the tailored blank during successive forging, large curvature was formed. The height of upper surface of tailored blanks before and after hot stamping was measured to investigate the reduction of the curvature. The height distributions of tailored-forged blanks before and after the hot stamping process are given in Fig. 4.5. Although a large curvature was observed from the tailored blank after the successive forging, the curvature was eliminated by hot stamping.

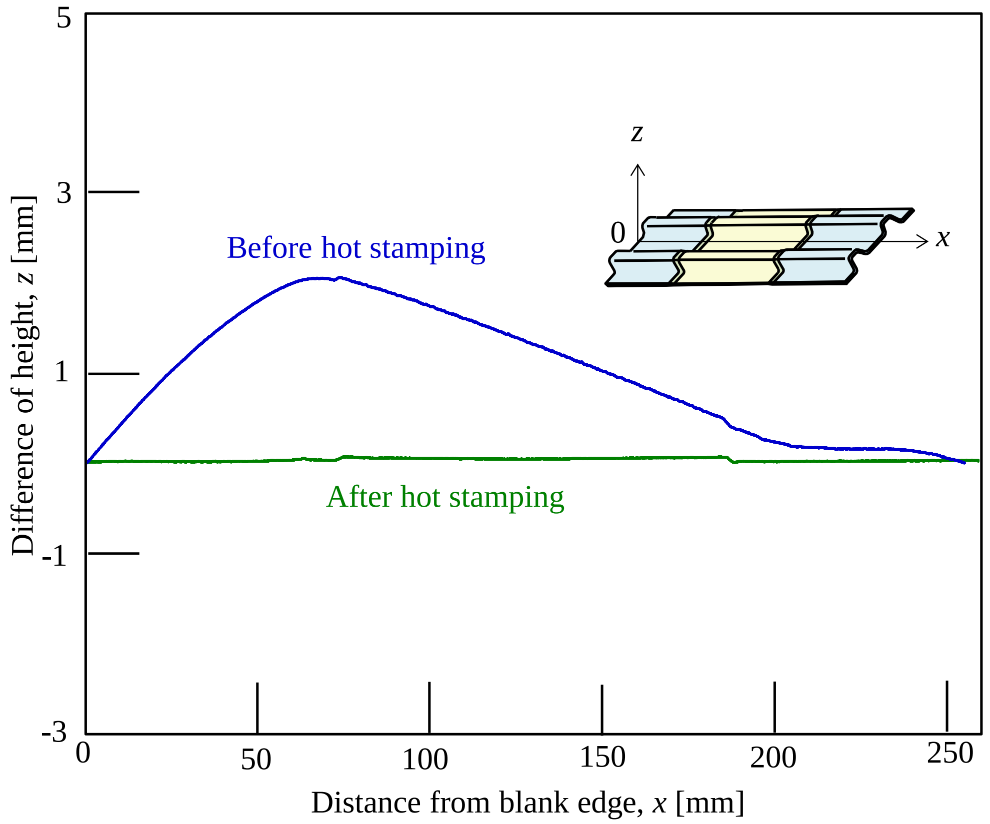
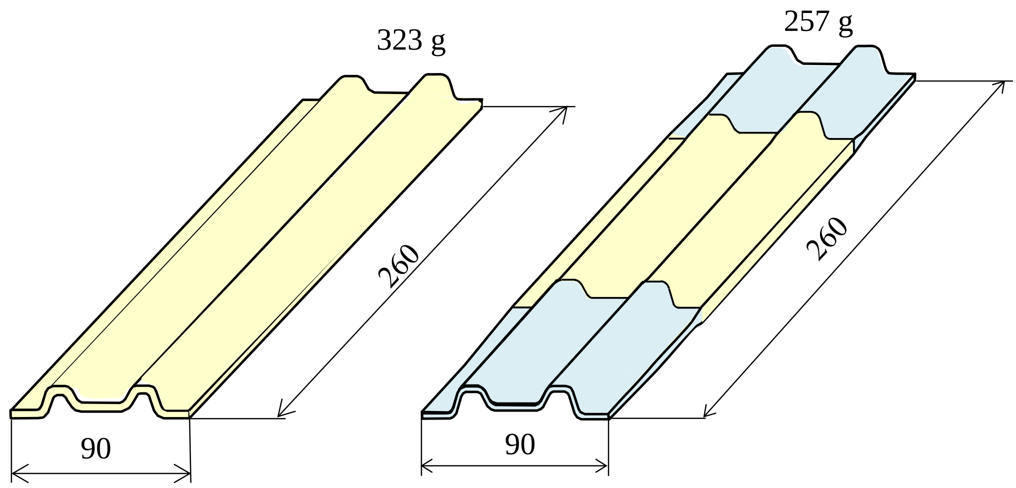


Fig. 4.5. Distribution of difference of height of upper surface in longitudinal direction before and after hot stamping.

Fig. 4.6 shows the weight for the roof rail miniatures of tailored blank and uniform thickness blank. The tailored blank roof rail has a smaller weight with a reduction of 20% from the uniform thickness roof rail.



(a) Uniform thickness (b) Tailored blank

Fig. 4.6 Weight for roof rail miniatures of tailored blank and uniform thickness blank.

4.3.2 Surface coating

Since the Al-Si coating is effective in preventing occurrence of oxide scale during hot stamping, the effects of compression and heating on the Al-Si coating were investigated. The cross-sections of the tailor-forged blank with and without compression are shown in Fig. 4.7. Even after successive forging, the coating layer remains intact on the surface of the tailored blank. The compressed area of 1 mm thickness has a thinner coating as compared to that of the non-compressed area of 1.6 mm (see Fig. 4.7(a)). The thickness of the coating increased for both of the compressed and non-compressed areas after the hot stamping process (see Fig. 4.7(b)). During heating of tailored blank, iron was diffused into the coating, and hence the coating thickness increased. Since the Al-Si coating was not damaged by the forging process, oxide scale formation was prevented during hot stamping.

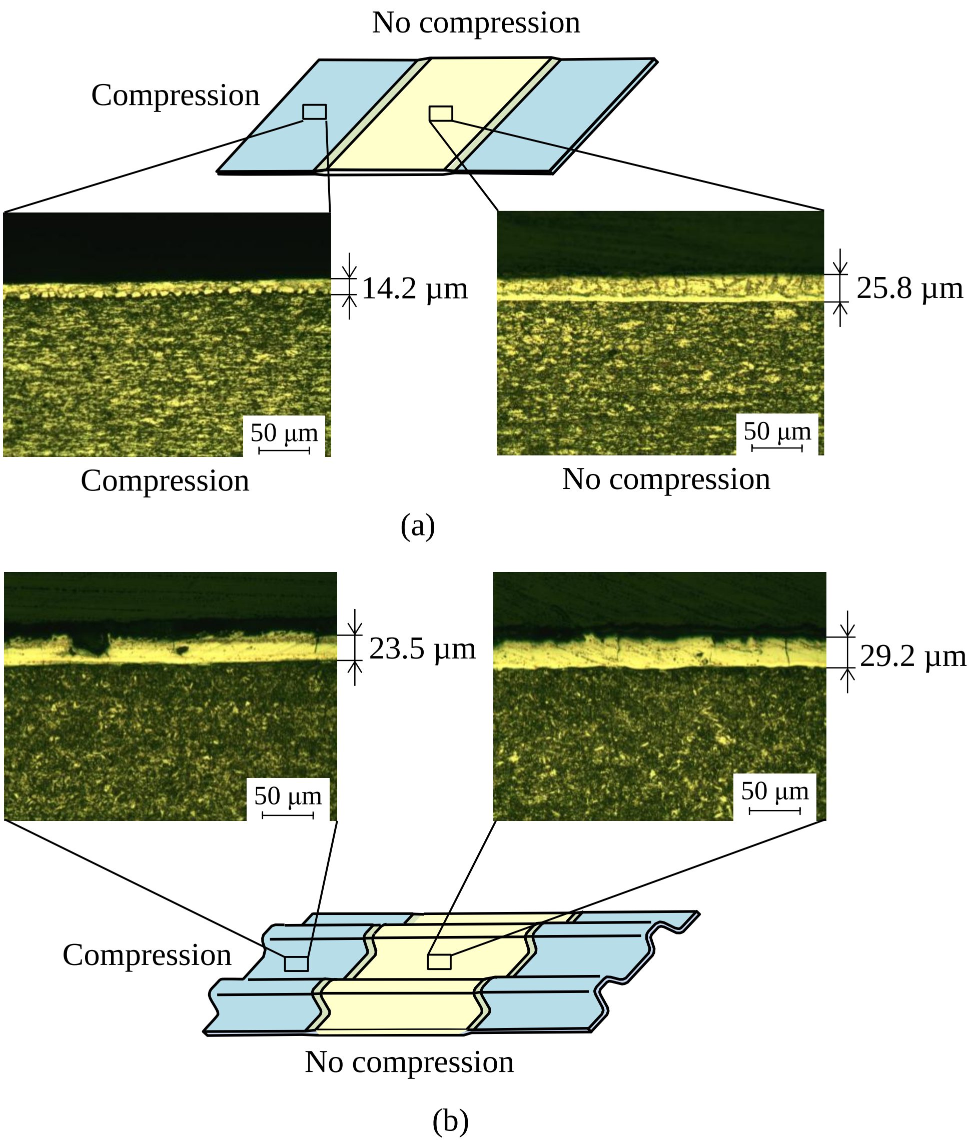


Fig. 4.7. Cross-sections of tailor-forged blank with and without compression (a) before and (b) after hot stamping.

4.3.3 Hardness

The distributions of Vickers hardness of tailored blanks before and after hot stamping are given in Fig. 4.8. For the compressed area of thickness 1.0 mm, the hardness is larger than that of the non-compressed area. Work hardening due to large reduction in thickness increases the strength at the thin area. The original hardness of the sheet was 195 HV20, and the hardness of the compressed area was increased to 250 HV20 by work-hardening.

The hardness of the tailored blank was significantly increased by hot stamping, and both hardnesses of the compressed and non-compressed areas were almost 460 HV20. Using tailored-forged blanks, hot-stamped parts have not only high strength but also reduced weight.

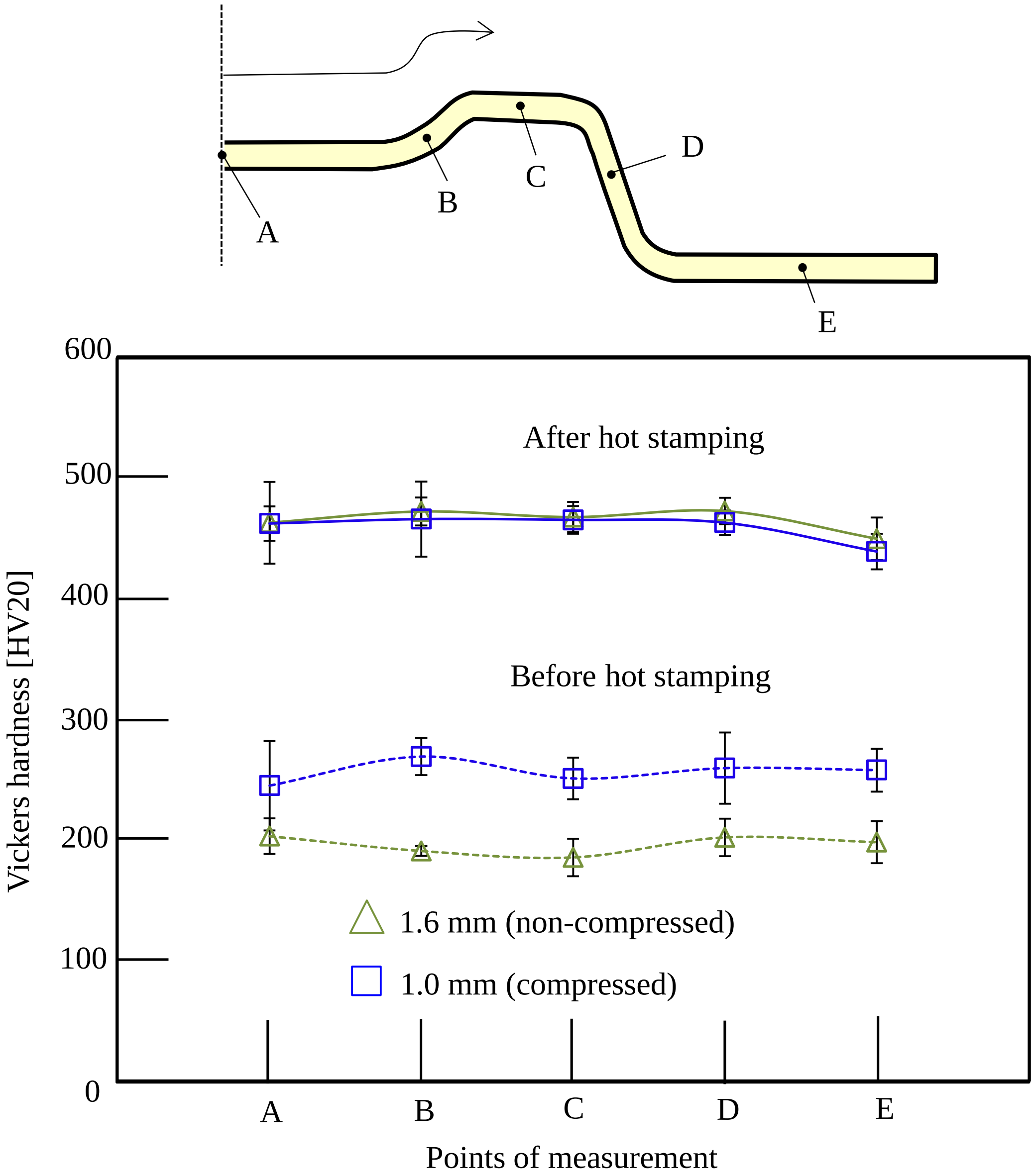


Fig. 4.8. Distributions of Vickers hardness of tailored blank before and after hot stamping.

4.4. Hot stamping of roof rail from non-coated 22MnB5 steel tailored blank

4.4.1 Shape and geometry

A hot stamping of roof rail from 22MnB5 boron steel tailored blank was carried out. The 22MnB5 blank was successively forged into tailored blanks having two thicknesses. The thickness, length and width of the blanks was 1.6 mm, 400 mm and 100 mm respectively. Fig 4.9 (a) shows the tailor blank having a thickness distribution after successive forging. Fig 4.9 (b) and (c) show the miniatures of roof rail from tailored blank and uniform thickness blank after hot stamping, respectively.

(a) Tailored blank

(b) Roof rail from tailored blank

(c) Roof rail from uniform thickness blank

Fig 4.9 Tailor blank and miniatures of roof rail from 22MnB5 tailored and uniform thickness blanks.

Fig 4.10 shows the thickness distribution of hot-stamped roof rail miniatures from tailored blank and uniform thickness blank from 22MnB5 steel. The uniform thickness blank was not forged while the tailored blank was successively forged at the middle portion. The feeding control was applied on the transient for increasing and decreasing thicknesses to obtain a symmetrical transient region. At the beginning of the compression, the thickness reduced gradually, followed by a constant thickness of 1 mm. The increasing in thickness at the transient region shows a gradual change in thickness.

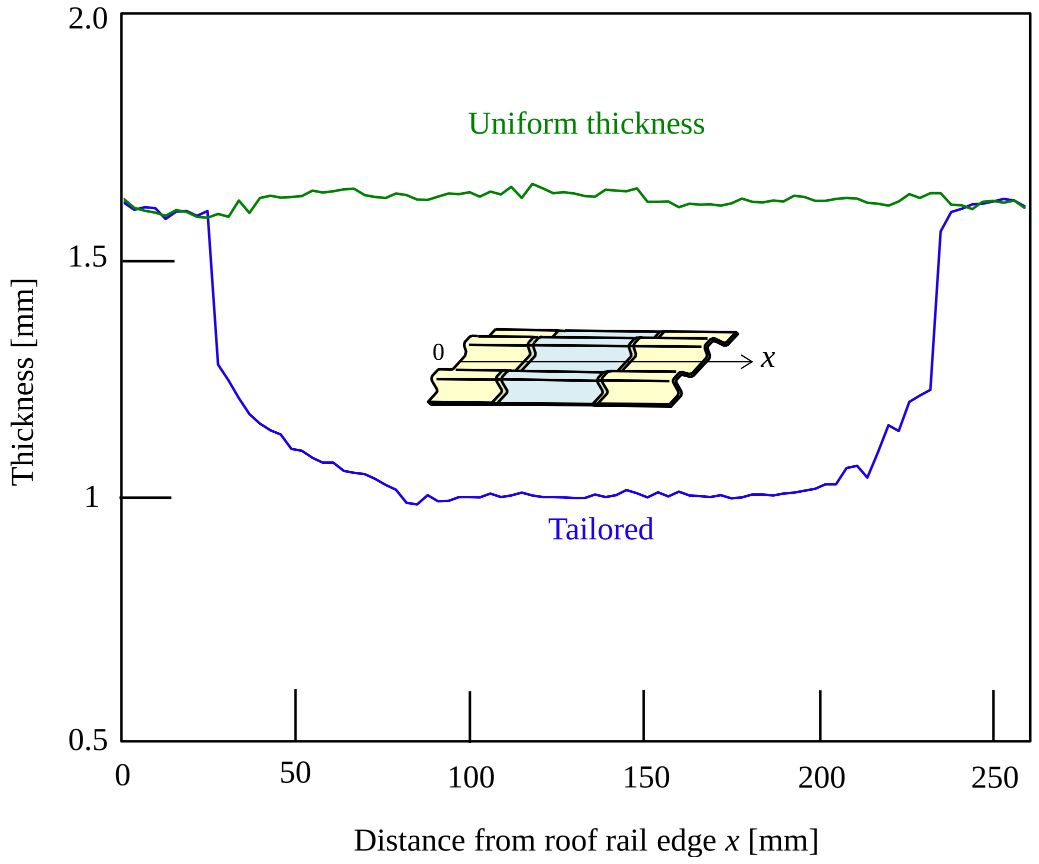


Fig 4.10 Thickness distribution of hot-stamped roof rail miniatures from tailored blank and uniform thickness blank from 22MnB5 steel.

The feed per one strike was controlled to obtain a tailor-forged blank having a thickness distribution. The feed per one strike used for producing this tailored blank is shown in Fig. 4.11. For the decrease in thickness in the transient region, constant feeding f = 0.5 mm was employed. For the increase in thickness, the variable feed, f_v of increment of 1 mm was chosen. With the control of feeding, both of the transient region were more symmetrical.

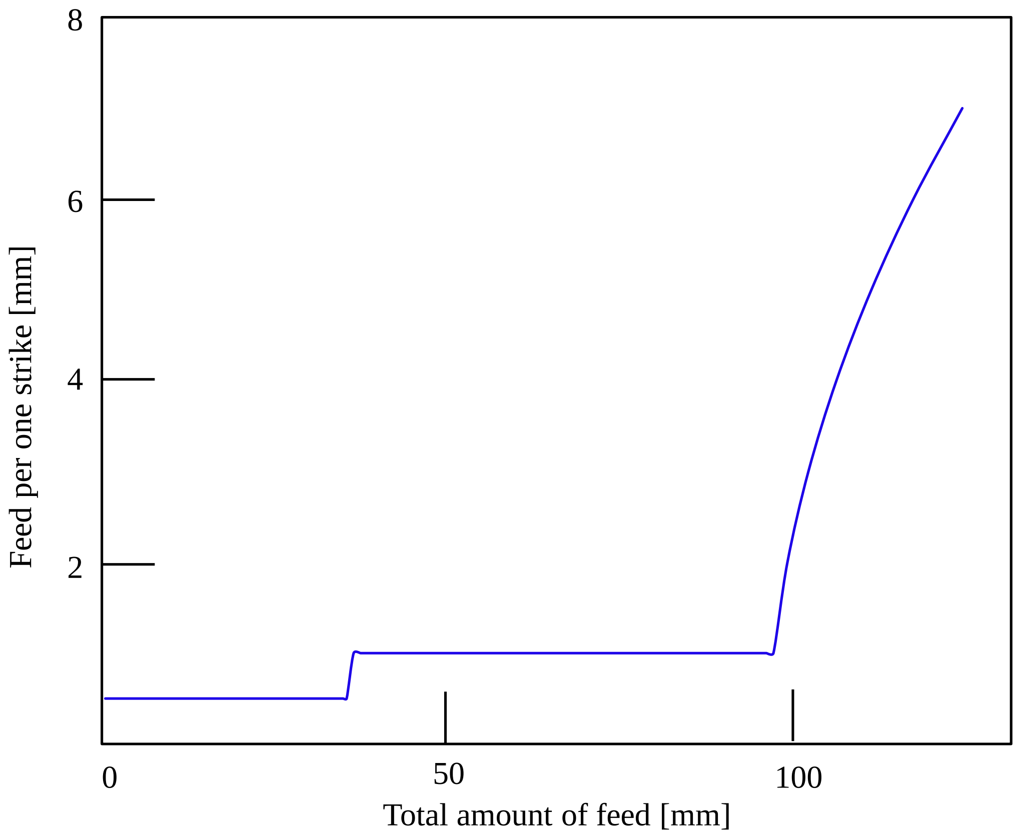
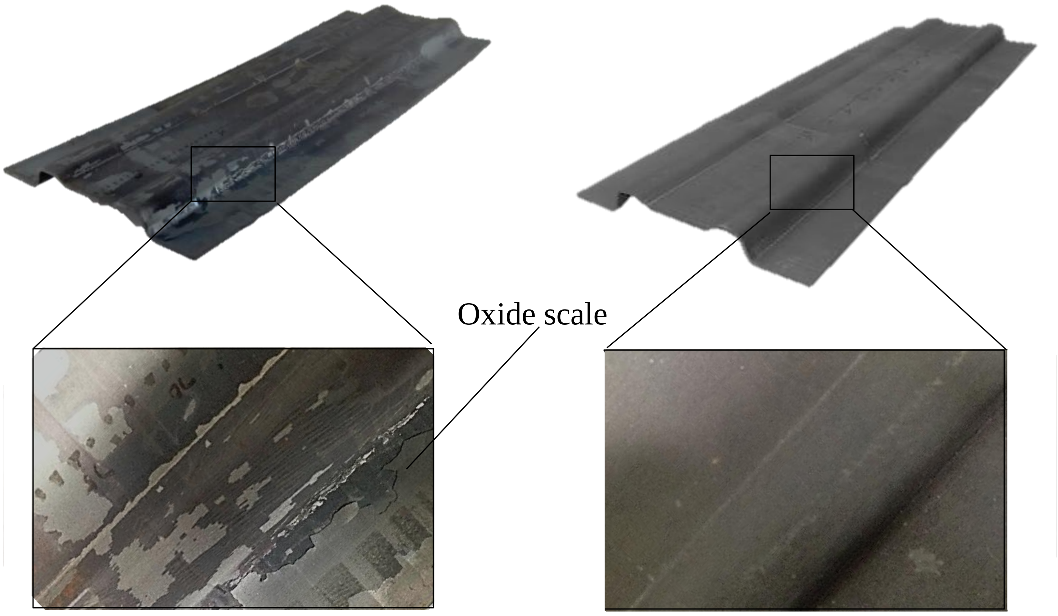


Fig. 4.11 Feeding control for 22MnB5 tailored blank having two thicknesses.

The surface of miniatures of roof rail from 22MnB5 and Al-Si coated quenchable steel are given in Fig. 4.12. Remarkable oxide scales were observed on the surface of the 22MnB5. However the protective layer of Al-Si prevented the formation of oxide scale and hence a good surface was obtained.



(a) Non-coated quenchable steel (b) Al-Si coated quenchable steel

Fig. 4.12 Surface of miniatures of roof rail from different materials.

4.4.2 Bending test

A three-point bending test was conducted to analyse the mechanical properties of the miniatures of roof rail. The roof rails were located on two supports and was subjected to load at the centre. The relationship between bending load and stroke for 22MnB5 roof rail miniatures of tailored blank and uniform thickness blank is given in Fig. 4.13. The maximum load before failure for the tailored blank is smaller than that of the uniform one due to the smaller thickness at the centre portion. The weight of the miniature of roof rail from the tailored blank reduces almost up to 30%.

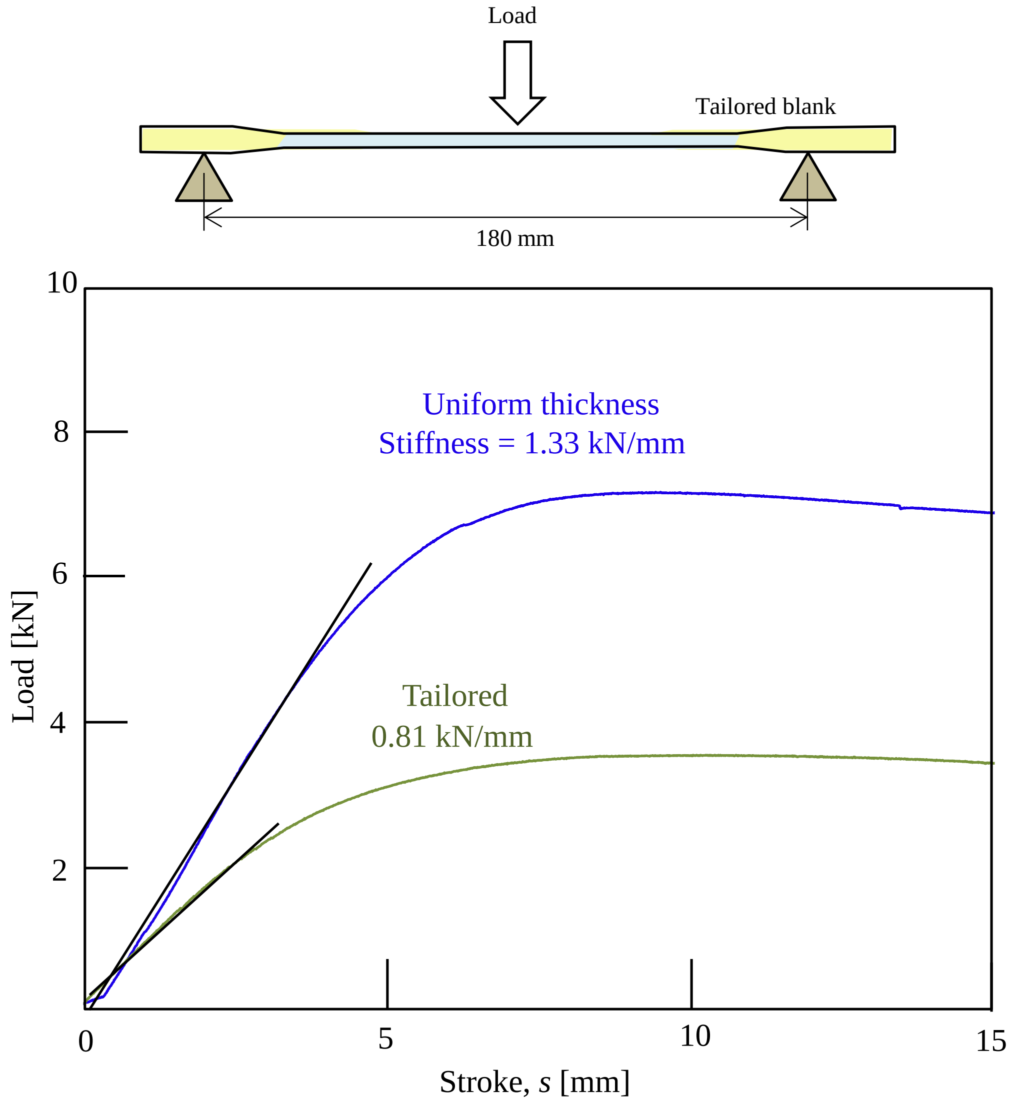


Fig. 4.13 Relationship between bending load and stroke for 22MnB5 roof rail miniatures of tailored blank and uniform thickness blank.

4.5. Conclusions

Hot stamping is effective in forming high strength steel. By heating the blank, not only the load is reduced but the formability is improved and springback is minimised. Generally whole body of the stamped part are heated and die-quenched with dies, hence the entire body is high strength. Tailoring in hot stamping is useful in controlling the strength distribution of a hot-stamped part. Although parts having combination of ductility and strength are produced by local heating and cooling, the weight is not optimised. Therefore hot-stamping of tailored blanks is important in producing stamped parts having a strength distribution with controlled thickness distribution to increase the weight saving.

Tailored blank having a thickness distribution was hot-stamped into a miniature of roof rail. The thickness of the tailored blank was controlled by adjusting the amount of feeding in a successive forging process. Although the strength of the thin area increases by work hardening, the strength of the thick and thin areas increases significantly after hot stamping, eliminating the contrary strength distribution. The Al-Si coating are preserved during successive forging and hence formation of oxide scale is prevented during hot stamping. With the tailored blank having an optimum thickness distribution, the weight of the part is reduced without decreasing the strength.

Chapter 5
Local thickening of aluminium and SPCC sheets by beading and compression

5.1. Introduction

The use of tailored blanks having different thicknesses and materials increases in the automotive industry for the construction of body in white components of a car due to the reduction in weight. Tailored blanks locate the right material at the right place to ensure optimum performance of the stamped part. Parts having local thickening are produced to increase the strength, compensate thinning and prevent rupture during stamping [33-35, 75, 76]. Patchwork blanks for example are produced by overlapping smaller blanks on the main blank before stamping [21]. The blanks are joined by laser welding. The addition of thickness at a desired area increases the strength locally. However the sudden change in thickness increases the stress concentration. Forming patchwork blank having multi thicknesses is difficult as compared to a uniform thickness blank.

Although tailored blanks are mainly produced by joining sheets of different thicknesses, tailored blanks having a thickness distribution are also produced by a rolling process. In this process, the thickness is reduced by changing the rolls gap [27, 28, 32]. Although tailor-rolled blanks reduce the stress concentration by eliminating the sudden change in thickness, the portion of large reduction in thickness is work-hardened [31, 77]. However, the strength required for the thin portion is small, whereas the strength is increased by work-hardening.

In the present chapter, forging of sheet having local thickening by beading and compression was proposed. In this two stage thickening process, the portion requiring high strength is beaded and compressed to form a local increase in thickness. Since the compressed region is work hardened, the strength increases. The produced tailored blank has high and low strengths for the thick and thin portions, respectively.

5.2. Approach of local thickening by bending and compression

A sheet forging process consists of beading and compression shown in Fig. 5.1 was developed. The centre portion of the sheet was beaded and compressed to form local thickening. In the 1st stage, the width of the sheet was reduced from the beading process. The beading die heights were varied to control the amount of local thickening. During the 2nd stage, the width of the blank was confined while the beaded portion are compressed to obtain a local thickening at the centre portion of the blank. The thick part possess higher strength as compared to the thin part due to the work hardening during compression.

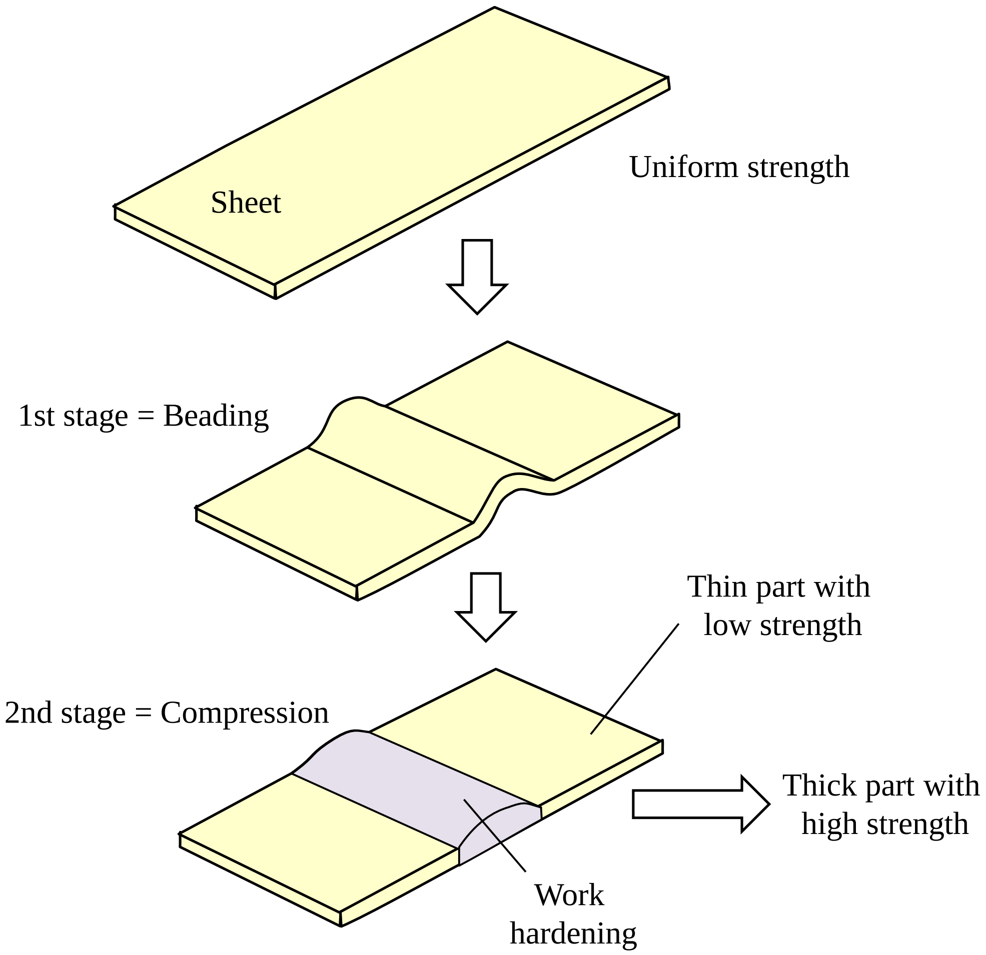
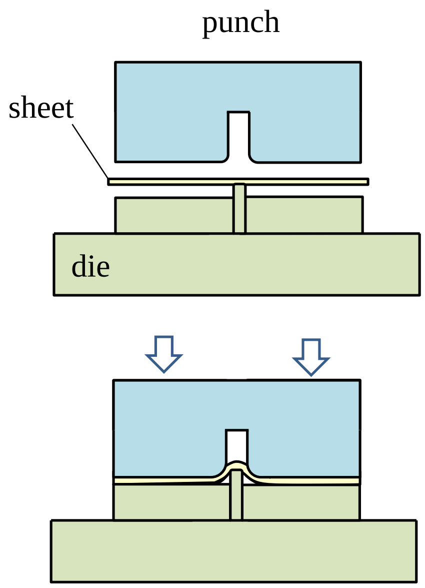
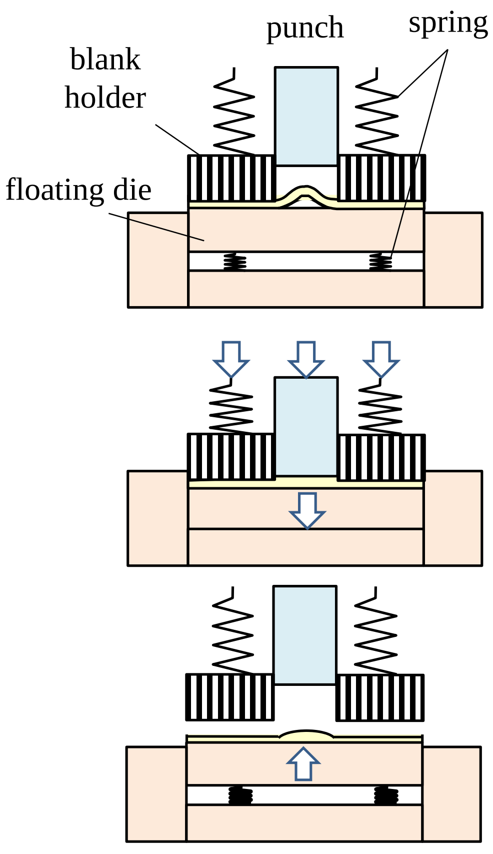


Fig. 5.1 Sheet having local thickening by beading and compression.

The experimental setup for sheet having local thickening by beading and compression is illustrated in Fig. 5.2. In the beading stage, the blank having a uniform thickness was beaded freely by a punch. The sheet width decreased during the beading process. In the compression stage (see Fig. 5.2(b)), the flanges of the blank were restricted with the die. Springs were attached onto the blank holders. The blank holders clamped both the flanges of the sheet to prevent wrinkling. The punch then compressed the beaded area to obtain thickening. The floating die was supported by two springs. These springs pushed the floating die up after compression to ease the sheet removal. No change in the sheet width occurred during compression.



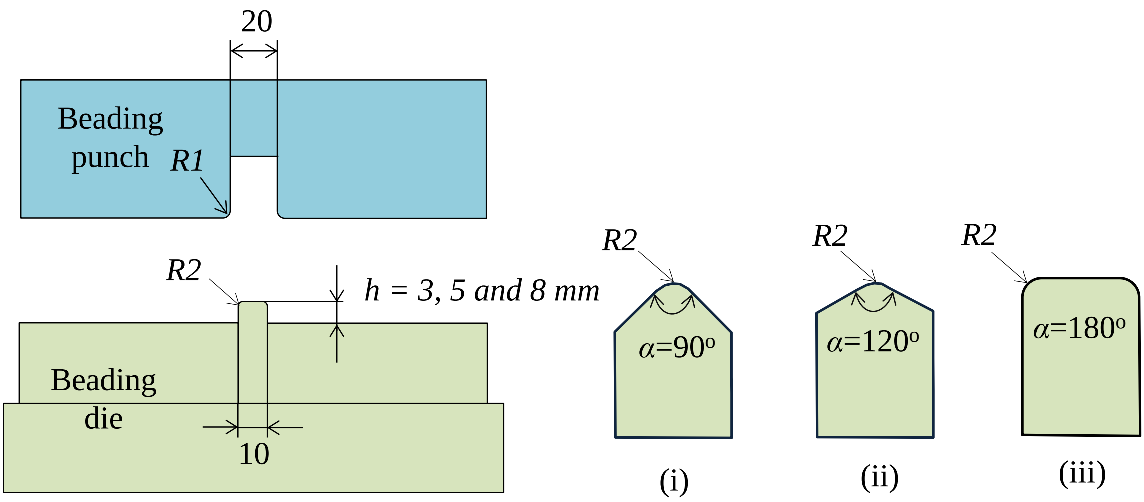
(a) 1st stage for beading



(b) 2nd stage for compression

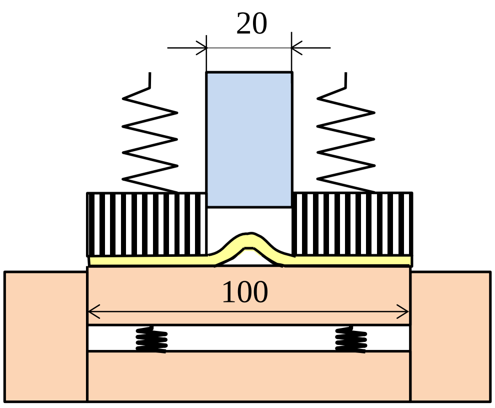
Fig. 5.2. Experimental setup for sheet having local thickening by beading and compression.

The beading and compression dies dimension is given in Fig. 5.3. The punches and dies were made of SKD11. The beading die height, *h* was varied between 3 and 8 mm to investigate the effect of the beaded height on the local thickening formed. Three types of beading die were used as shown in Fig. 5.3(b). The angles of the beading die, α were 90°, 120° and 180°. The corners of the beading die have a radius of 2 mm. The confined area of the compression die was 100 mm (see Fig. 5.3 (c)).



(a) Beading die

(b) Types of beading die



(c) Compression die

Fig. 5.3. Beading and compression dies dimension.

Conditions used for sheet forging of aluminium A1050 and SPCC sheets are given in Table 5.1. The thicknesses of the aluminium sheet were 0.5, 1.0 and 1.5 mm while SPCC sheet were 0.5 and 1.0 mm. Since the beading height was varies, the sheet widths were set to 101.0, 10.3.5 and 108.5 mm to obtain a constant sheet width of 100 mm after the beading process. The sheet length is the same for all condition which is 50 mm. No lubricant was applied in the thickening process.

Table 5.1 Conditions used for sheet forging of aluminium A1050 and SPCC sheets.

Material	Aluminium A1050	SPCC	
Tensile strength [MPa]	105	334	
Hardness [Hv]	31	95	
Sheet thickness *t* [mm]	0.5, 1.0, 1.5	0.5, 1.0	
Sheet length [mm]	50		
Sheet width [mm]	101.0	103.5	108.5
Beading die height *h* [mm]	3	5	8

5.3. Results of local thickening of aluminium sheet

5.3.1 Thickening behaviour

Fig. 5.4 shows the aluminium sheet deformation after beading and compression for different beading heights with a beading die α = 180^o. The thickness of the sheet was 1.0 mm. As the beading die height increases, the beaded portion increases. Local thickening was observed for beading height of 3 and 5 mm. However for beading height of 8 mm, folding of the sheet occur instead of thickening.

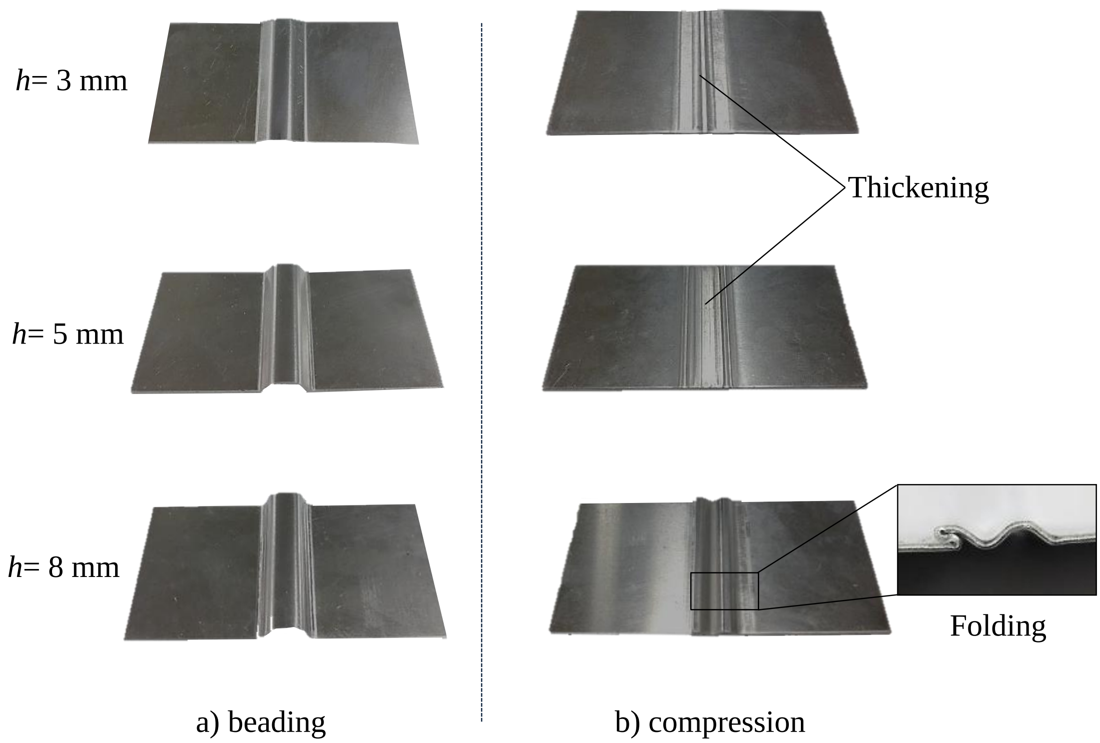


Fig. 5.4 Aluminium sheet deformation after beading and compression for different beading heights with beading die α = 180°.

The thickening behaviour of aluminium sheets was observed to investigate the formation of local thickening and folding during beading and compression. Fig. 5.5 shows the thickening behaviour for aluminium sheets having a thickness of 1.5 mm and beading heights of 5 and 8 mm. The beading die of α = 180° was utilised. The cross-sections of the sheet was taken at different punch strokes. For a beading height 5 mm, the sidewall was inclined and local thickening formed at the beaded portion. However as for beading height 8 mm, both sidewalls of the beaded portion were almost vertical as compared to the beading height 5 mm. Therefore folding was observed.

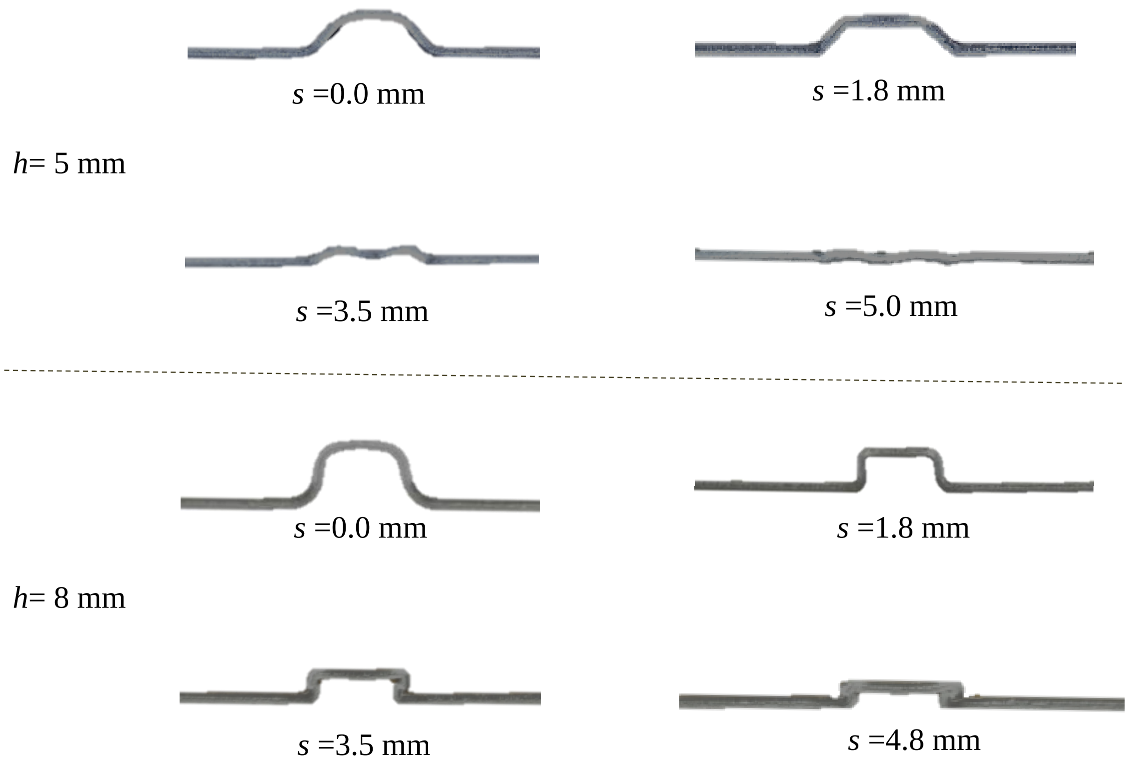


Fig. 5.5 Thickening behaviour for aluminium sheets having thickness of 1.5 mm and beading heights of 5 and 8 mm with beading die of α = 180^o.

5.3.2 Thickness distribution

The cross-sections of the local thickening area after beading and compression with beading die α = 180^o are given in Fig. 5.6. The thickness of the sheet was 0.5 and 1.0 mm. No crack was observed on the cross-section of the sheet for beading height 5 mm. The thickening region shows an increase in thickness as compared to the original thickness for beading height 5 mm. Since the beaded portion is restricted to 20 mm width, the formation of thickening has almost at the same width. The increase in thickness for beading height 3 mm and 5 mm for sheet thickness 1.0 mm were 9% and 25%. As for the beading height 8 mm, folding was observed.

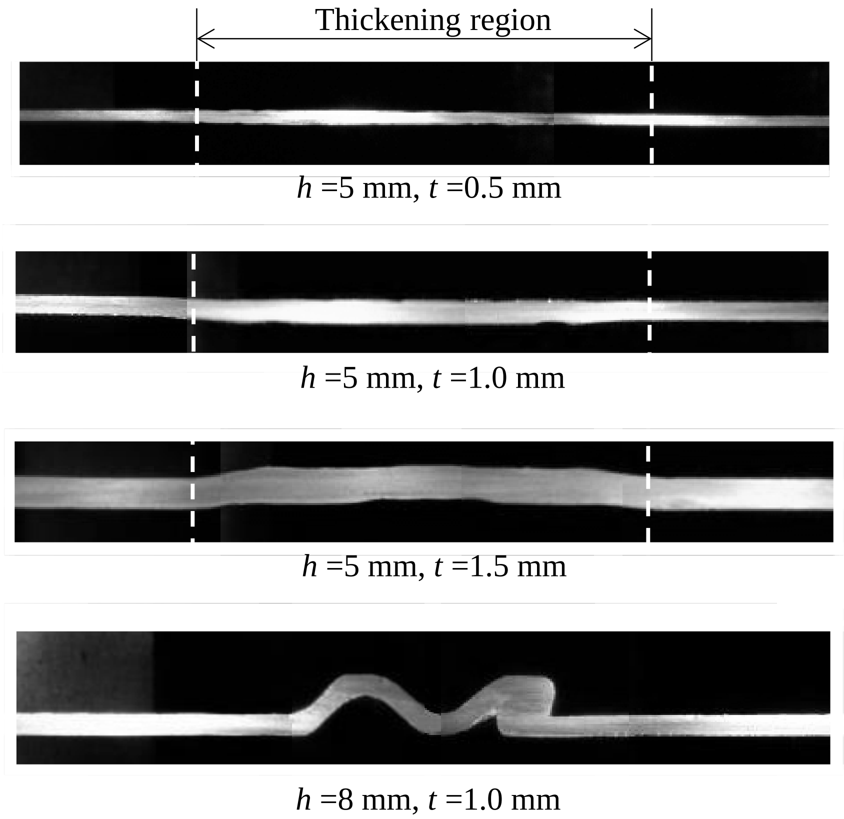


Fig. 5.6 Cross-sections of local thickening area after beading and compression with beading die α = 180^{o}.

The thickness distribution for aluminium sheets with beading height of 3 mm before and after the local thickening process is shown in Fig 5.7. The thicknesses of the sheet before beading, after beading and after compression are compared. The original sheet shows a uniform thickness distribution. Since the sheet was beaded freely without blank holder, the thickness distribution shows no thinning occur at the beaded portion after the beading process. After the compression, thickening was formed with a peak thickness at the centre of the sheet.

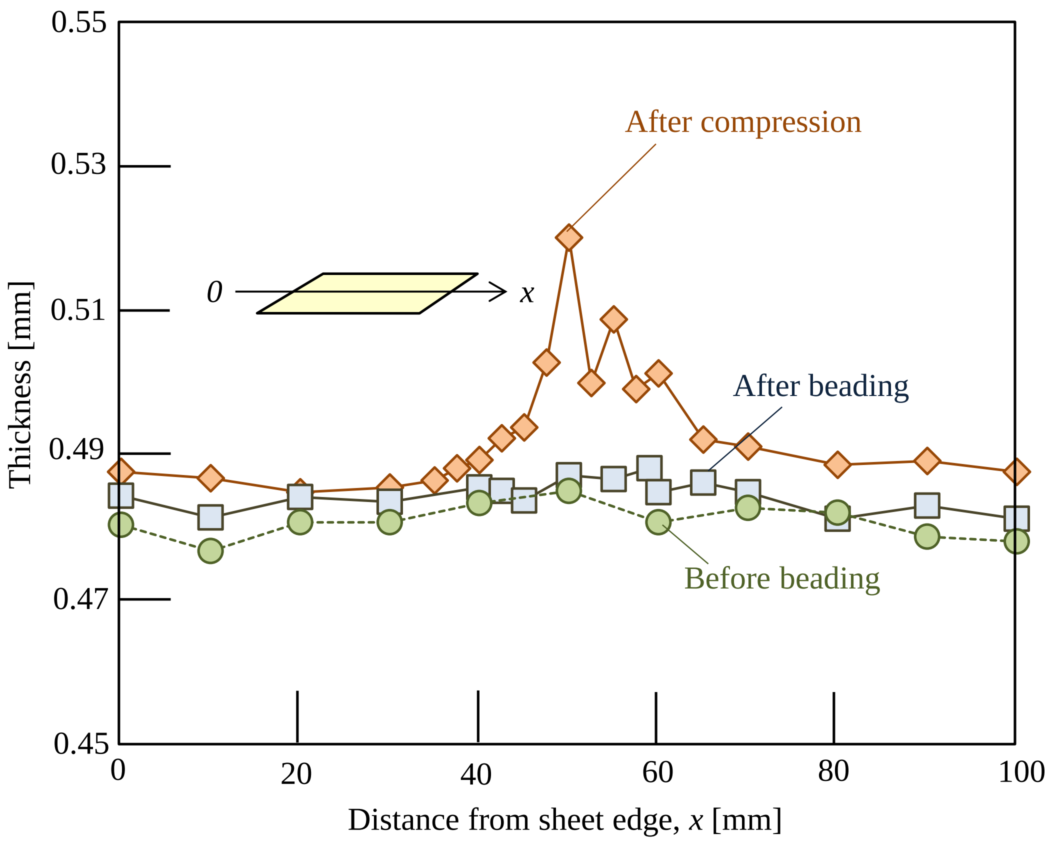
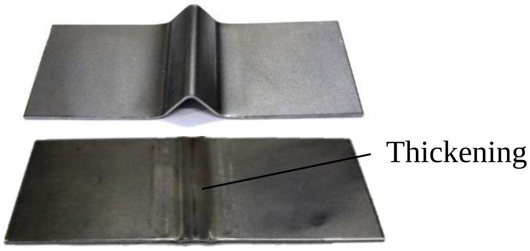


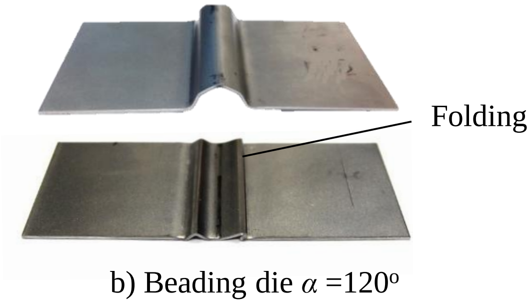
Fig. 5.7 Thickness distribution for aluminium sheet with beading height of 3 mm.

5.4 Effect of die angle on local thickening of SPCC sheets

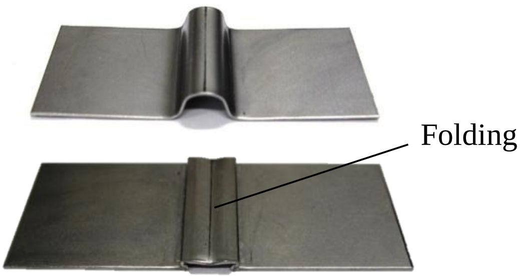
Since folding was formed instead of thickening for the beading height 8 mm, the beading die angle was analysed. From Fig. 5.5, the sidewalls of the beaded portion was almost vertical for a beading angle, α = 180°. To prevent right angle of sidewalls, the angle of the beaded die was reduced. The effect of beading die angle on the SPCC sheet deformation behaviour is shown in Fig. 5.8. For a large beading height of 8 mm, local thickening was achieved with the beading die angle, α = 90°. As the beading die angle increases, folding was formed.



a) Beading die α =90^{o}



b) Beading die α =120^{o}



c) Beading die α =180^{o}

Fig. 5.8 Effect of beading die angle on local thickening of SPCC sheet.

The thickening behaviour of SPCC sheets for beading die angle of 90^{o} and 120^{o} are shown in Fig 5.9. The thickness of the sheet was 1.0 mm and the beading height was 8 mm. The deformation of the sheets was observed at different punch strokes. For beading die angle of 90^{o}, inclined sidewalls was formed. The sidewalls decrease as the punch stroke increases, and hence local thickening was observed. As for beading die angle of 120^{o}, a dome-like shape beaded portion was observed. At punch stroke 3mm, sidewalls of the beaded area reduced and became almost vertical, producing fold of the sidewall.

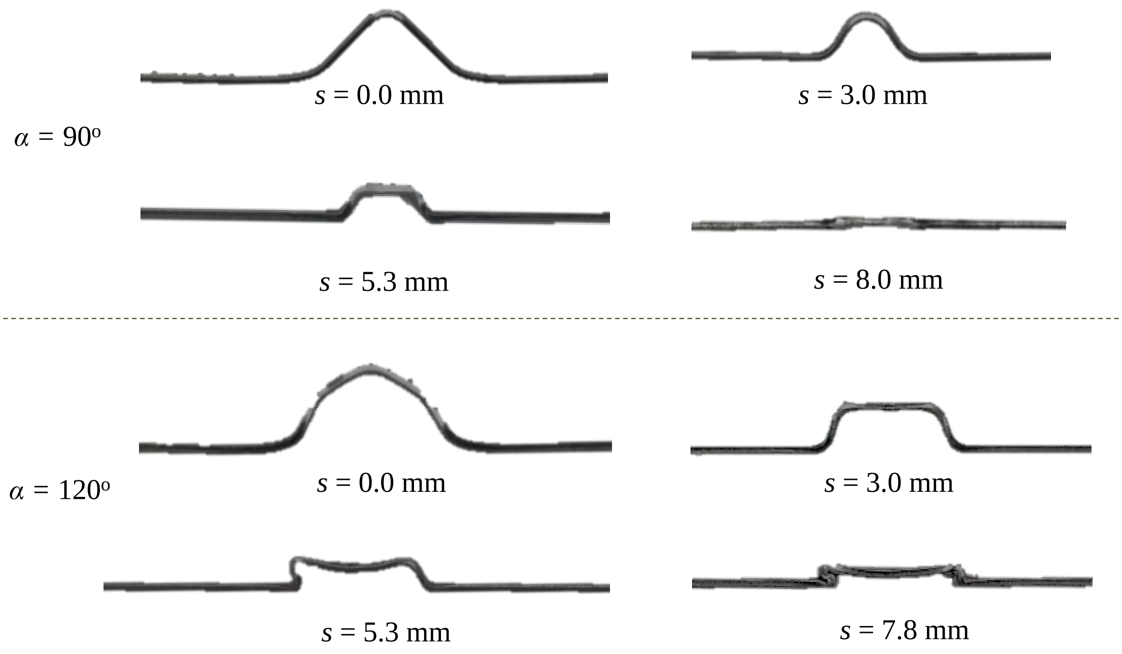


Fig. 5.9 Thickening behaviour of SPCC sheets for beading die angle of 120° and 180°.

Fig 5.10 shows the relationships between the thickness distribution and the distance from sheet edge, and between the strength distribution and the distance from sheet edge. The thickness of the sheet was 1.0 mm. The beading die was varied between 3 mm to 8 mm. The beaded portion was formed with a beading die of angle 90°. The estimated strength of the material was calculated from the hardness values obtained at the cross-section of the SPCC sheet. As the amount of local thickness increases, the hardness and strength of the sheet increase.

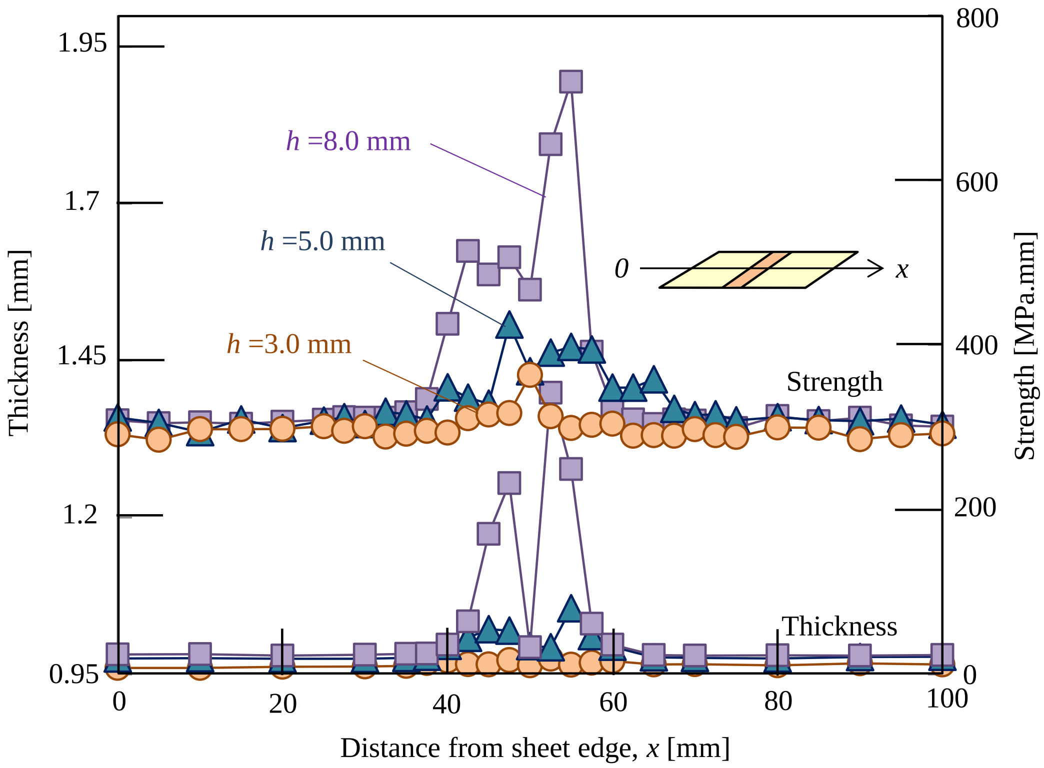


Fig. 5.10 Relationships between thickness distribution and distance from sheet edge, and between strength distribution and distance from sheet edge.

5.5 Comparison of local thickening between Aluminium and SPCC sheets

Fig. 5.11 shows the maximum change in thickness for aluminium and SPCC sheets. The forging of sheet having local thickening using beading and compression was conducted for sheet having thickness of 1 mm. Comparing between beading die angles, α = 180° produced the largest local thickening for beading heights 3 and 5 mm due to a large beading portion. However for a beading height 8 mm, local thickening could not be achieved with beading die angles 120° and 180°. A small angle beading die of 90° managed to produce local thickening with 45% increase in thickness for both aluminium and SPCC.

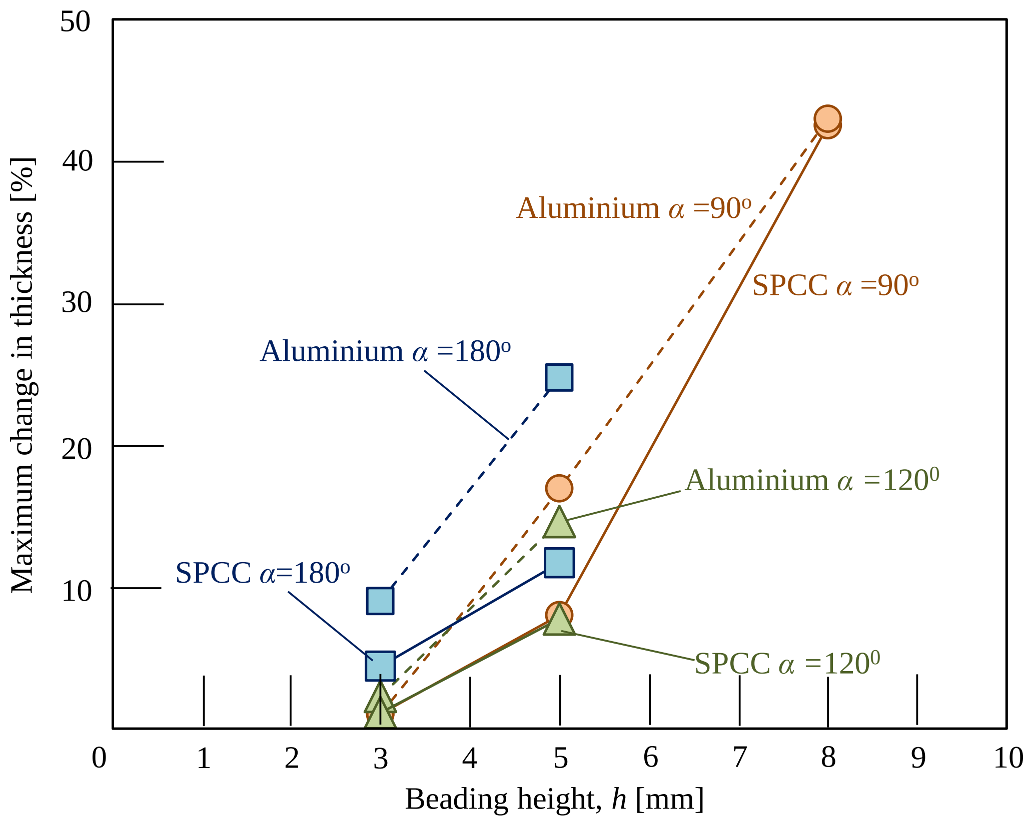


Fig. 5.11 Maximum change in thickness for aluminium and SPCC sheets by beading and compression.

5.6 Conclusions

Tailored blanks having an optimum thickness distribution are essential in producing lighter cars. Reinforcement is done only at the desired area where strength is needed without increasing the overall thickness of a part. Tailor blanks are generally produced by welding and rolling. Since welding involves joining of blanks, the process is difficult for parts requiring multi-thicknesses. Tailored blanks without joining are produced by rolling. Although tailor-rolled blanks have high thickness flexibility and formability, a large reduction in thickness during rolling increases the strength of the blank. The produced parts form tailor-rolled blanks have an opposite strength distribution.

Sheet forging having local thickening was successfully carried out by beading and compression. During beading, the beaded portion was formed without blank holders, hence thinning does not occur. In the compression stage, the width of the sheet was restricted to allow thickening to form at the beaded portion. The amount of the thickening increases with the beading height. For a small beading height, beading die 180^o produces larger local thickening as compared to beading die 90^o and 120^o. For a large beading height, beading die 90^o produces sheet having local thickening without folding. The local portion of large thickness have higher strength while the thin parts have lower strength.

Chapter 6
Successive forging of aluminium and stainless steel long sheets having inclined cross-section

6.1. Introduction

In electrical industry, blades for cleaning and regulating toners used in laser beam printers are made from long sheets having an inclined cross-section. Long sheets having an inclined cross-section are generally produced by cutting, however the material loss is problematic. Rolling process has been applied to produce long sheet having uniform cross-sections. For thin walled structures, the long sheets are subjected to buckling, wrinkling and flatness defect during rolling due to heterogeneous elongation along the strip [78-80]. Rolling non-uniform cross-section on the other hand produces parts having large curvature and wrinkling due to non-uniform reduction in thickness. It is desirable in electrical industry to develop a forming process of long sheets having an inclined cross-section with good accuracy and defect free to ensure optimum printing performance.

Extrusion process has been employed to produce long products having a complex cross-section. The metal bar is being forced into a die of a desired cross-section and parts having a new cross-section are produced. During direct extrusion, the slide between metals and container wall causes an increase in the friction, temperature and extrusion force [81-83]. Generally, aluminium alloy bar are extruded into various complicated cross-section. Stainless steel bars on the other hand are not extruded because of high heating temperatures.

Plate forging is widely used in metal forming industries to form plates having a thin cross-section into various shapes and thicknesses. Complex automobile components such as gear parts are being produced by plate forging. In this process, the forming load becomes high due to the large frictional restraint [37, 39]. For long parts, the forming load greatly increases for large deforming area.

In this study, a successive forging process of long sheets having an inclined cross-section was developed. Since the deforming area is small for a small forging interval, the forging load reduces. The effects of the punch shapes and forging intervals on the forging load, sheet waving and curvature were examined. The final publication of this study is available at Elsevier via http://dx.doi.org/ doi:10.1016/j.proeng.2014.10.334.

6.2. Approach of successive forging of aluminium and stainless steel long sheets

A successive forging process illustrated in Fig. 6.1 was developed to produce a long sheet having an inclined cross-section. The long sheet is move into the compression region with a feeder. The sheet is then compressed with a punch to form an inclined cross-section. The sheet is moved again for the next compression with the same forging interval. These steps are repeated until the desired compression length is achieved.

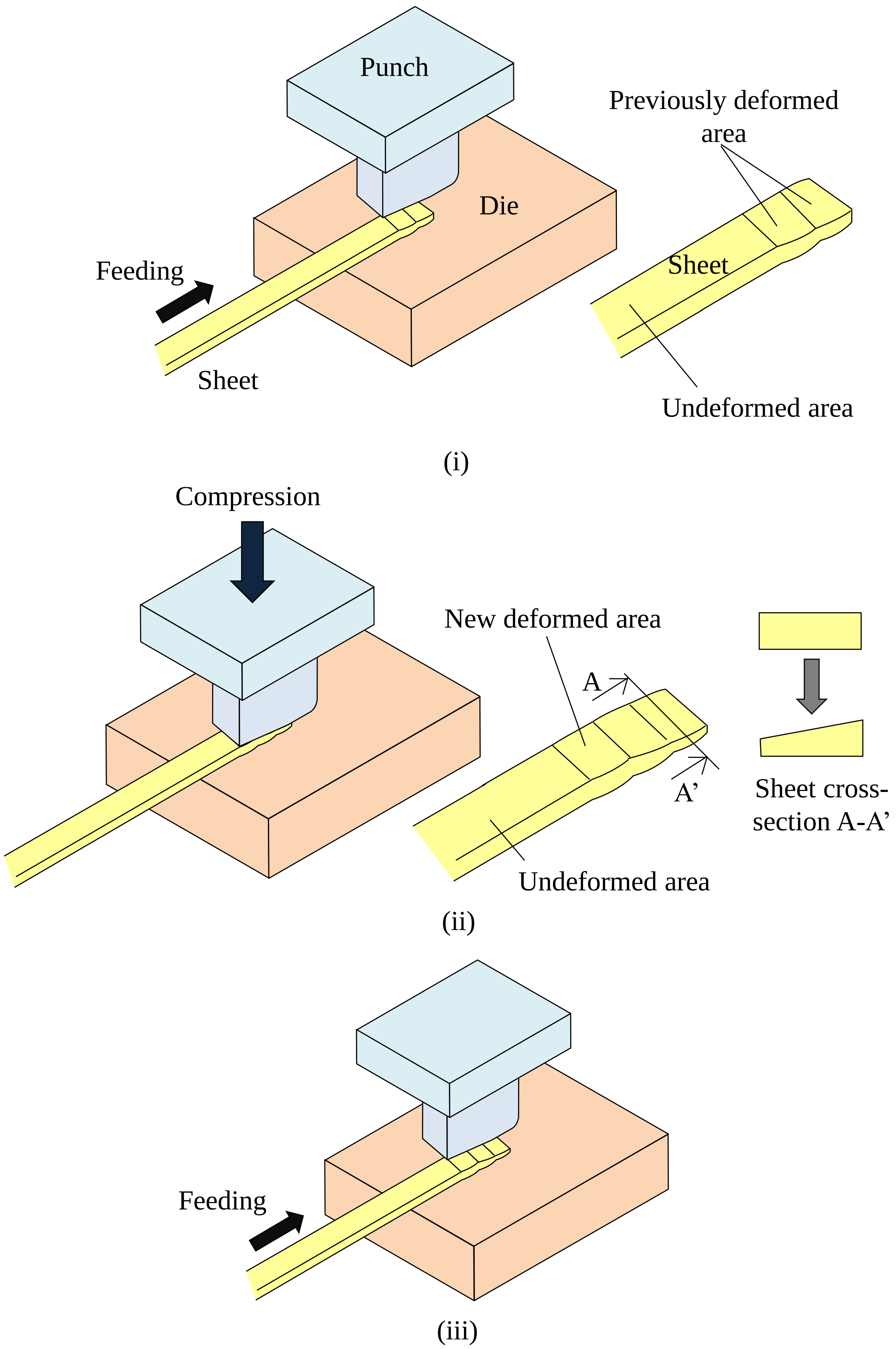


Fig. 6.1 Steps in successive forging of long sheet having inclined cross-section.

The experimental setup for successive forging of long sheet having an inclined cross-section is shown in Fig. 6.2. A 1500 kN mechanical servo press was employed. A feeder machine allows the feeding of the material with specific forging interval. An exit guide consist of an upper guide prevents the forged sheet form curving up while the side guide minimizes the curvature of the forged sheet. The entrance guide is used to align the sheet into the compression region.

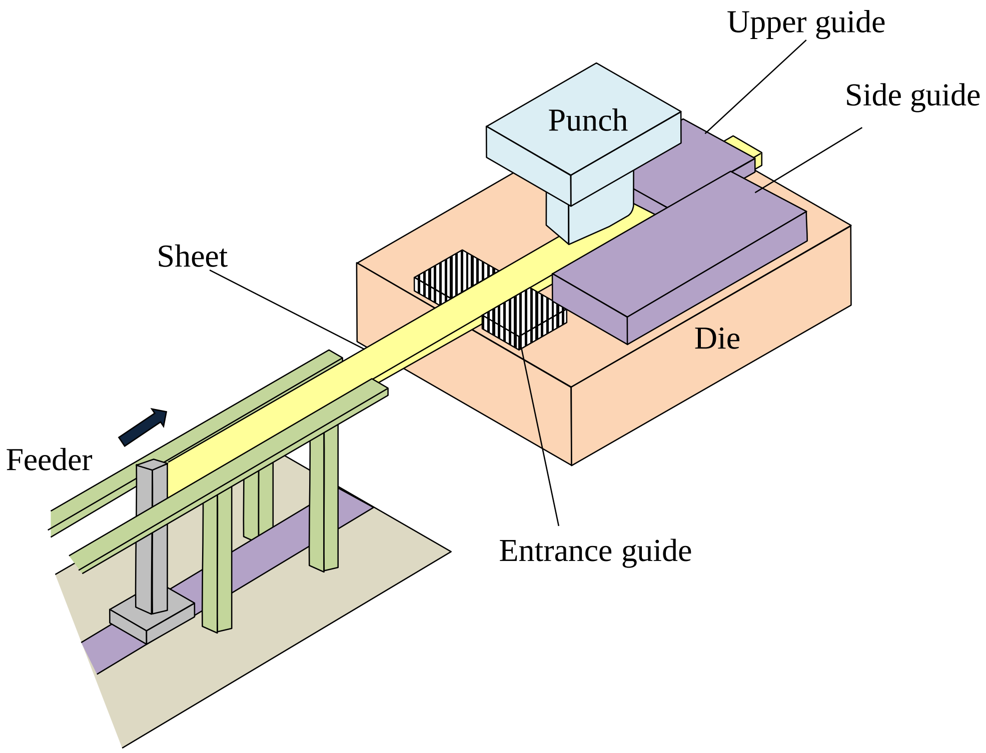
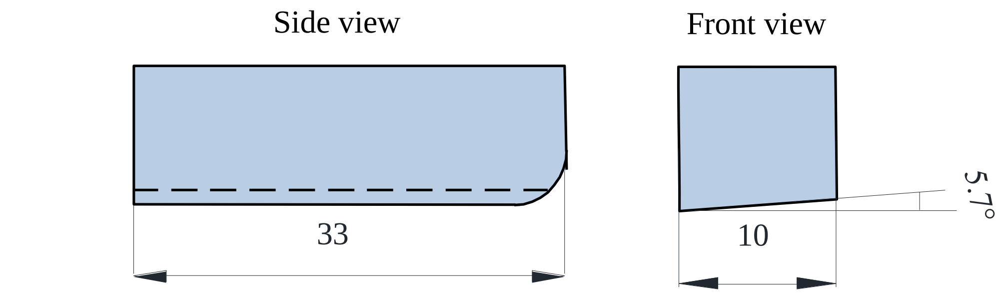
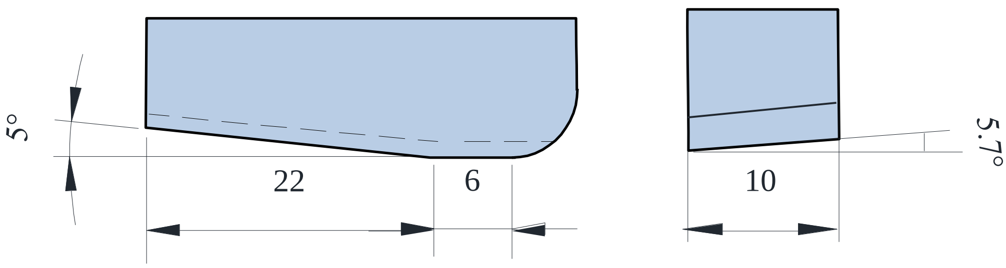


Fig. 6.2 Experimental setup for successive forging of long sheet having inclined cross-section.

Two types of inclined punch were used in this experiment to investigate the effect of the punch shapes on the sheet having an inclined cross-section. The flat and taper bottom punches are shown in Fig. 6.3 (a) and (b), respectively. Both of the punches have a surface inclination of 5.7^{o} that will give the sheet an inclined cross-section. The taper bottom punch has a 5^{o} inclination and a 6 mm of a straight horizontal surface while the flat bottom punch has a flat surface of 33 mm.



(a) Flat bottom punch



(b) Taper bottom punch

Fig. 6.3 Dimensions of flat and taper bottom inclined punches.

Two types of sheets were used in the experiment which are aluminium A1050 and stainless steel SUS430. The condition of sheets used for the experiment is shown in Table 6.1. The forging interval was varied to investigate its effect on the forging load and sheet deformation behaviour. The forging condition used for the experiment of successive forging is given in Table 6.2.

Table 6.1 Sheets used for experiment of successive forging.

Sheet	Hardness [HV 0.05]	Thickness *t* [mm]	width [mm]	length [mm]
Aluminium A1050	31.3	2.0, 3.0	8	500
Stainless steel SUS430	122	1.9	8	500

Table 6.2 Forging condition used for experiment of successive forging.

Conditions	Aluminium A1050	Stainless steel SUS430
Forging interval *f* [mm]	3, 5, 10, 20	1, 3, 5
Amount of feed [mm]	200	200
Average punch speed [mm/s]	20	20
Reduction in thickness at punch tip [mm]	1.2	1.1

6.3. Results of successive forging of long sheet

6.3.1 Aluminium sheet having inclined cross-section

The long sheet having an inclined cross-section was successively forged with the flat and taper bottom punches for t = 3 mm and f = 5mm (see Fig. 6.4). Without the exit guide, the curvature of the sheets is remarkable. For the flat bottom punch, waving on the sheet sides and depression on the sheet surface occurred. The waving and depression were prevented with the taper bottom punch.

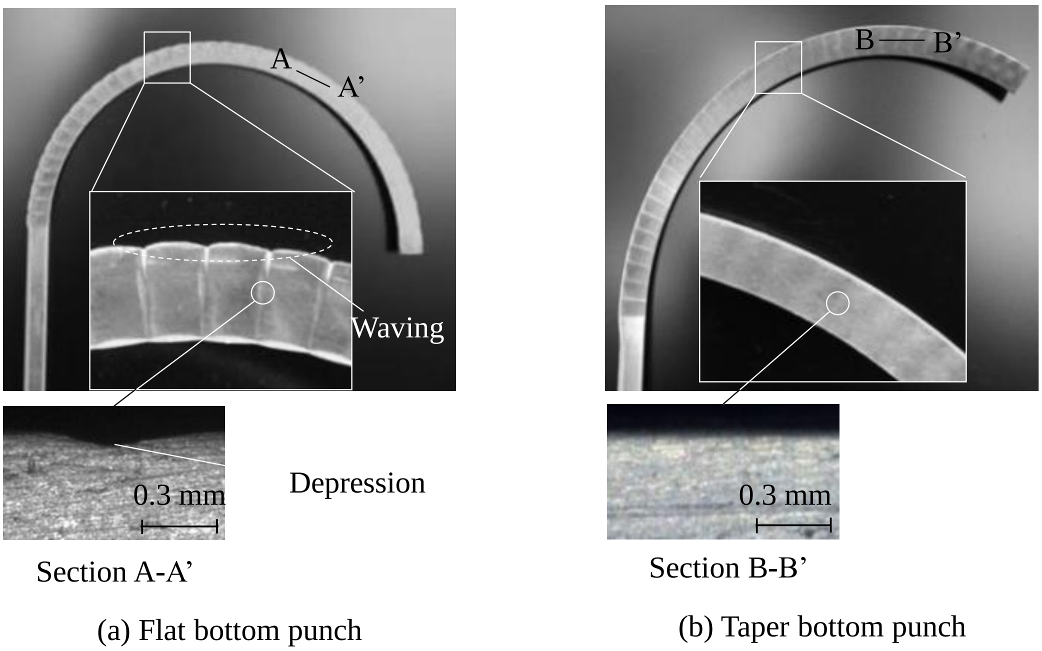


Fig. 6.4 Long sheet having inclined cross-section for t = 3 mm and f = 5mm.

The curvature of the forged sheet was large because of the different deformation rate of the sheet during compression. The relationship between forging interval and radius of curvature is shown in Fig. 6.5. The radius of curvature increases with the increase of forging interval.

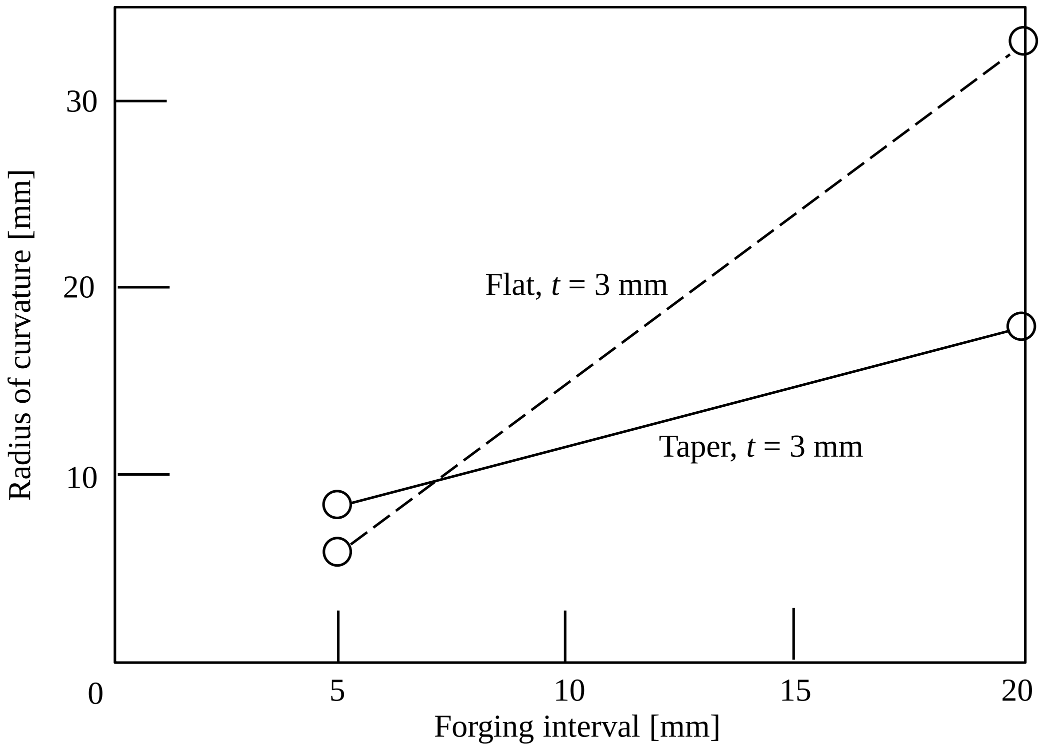
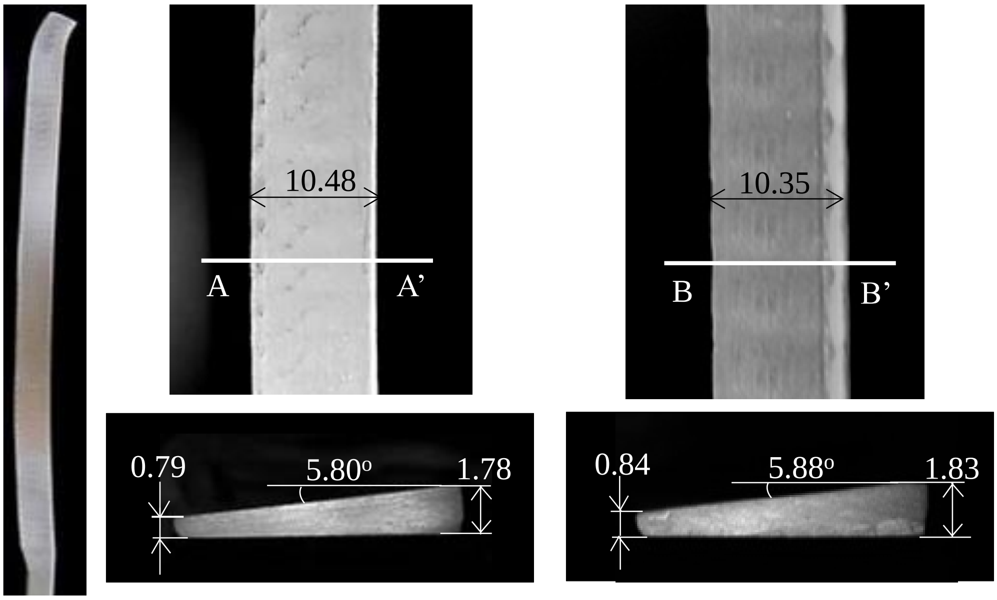


Fig. 6.5 Relationship between forging interval and radius of curvature.

A side guide was introduced to prevent the side curvature of the forged sheet. The distance between the sheet and the side guide was 3 mm. Fig. 6.6 shows the forged sheets having an inclined cross-section with the exit guide and taper bottom punch. The curvature of the forged sheet having an inclined cross-section was reduced. For a small forging interval of 3 mm, the reduction in thickness was larger than that of 5 mm.



(a) t= 2 mm, f= 3 mm (b) t= 2 mm, f= 5 mm

Fig. 6.6 Forged sheets having inclined cross-section with exit guide and tapered punch.

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 sheet. Fig. 6.7 shows the relationship between the average width difference and the forging interval for the two punches. The width difference was reduced with the tapered punch and the small forging interval. The waving defect was reduced.

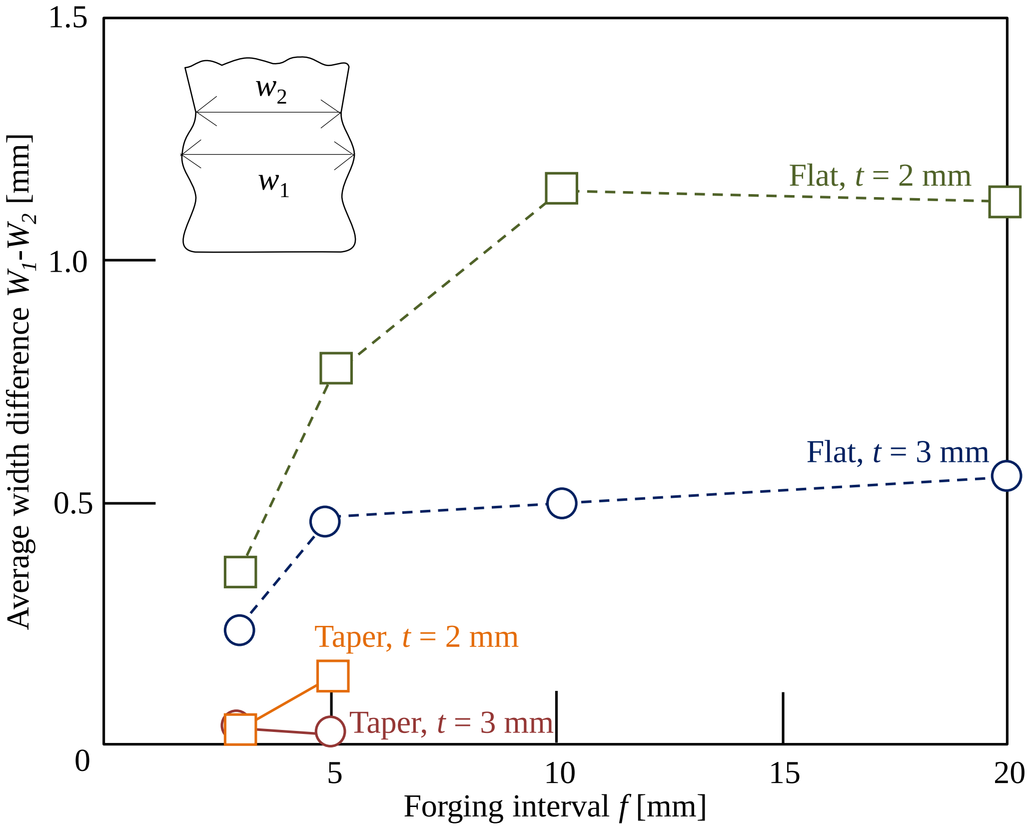


Fig. 6.7 Relationship between the average width difference and forging interval for two punches.

Fig. 6.8 shows the relationship between the elongation in the longitudinal direction and the forging interval for the two punches. As the forging interval decreases, the elongation of the compressed sheet increases. The change in the width is small as compared to the length due to the large width-to-length ratio of the punch.

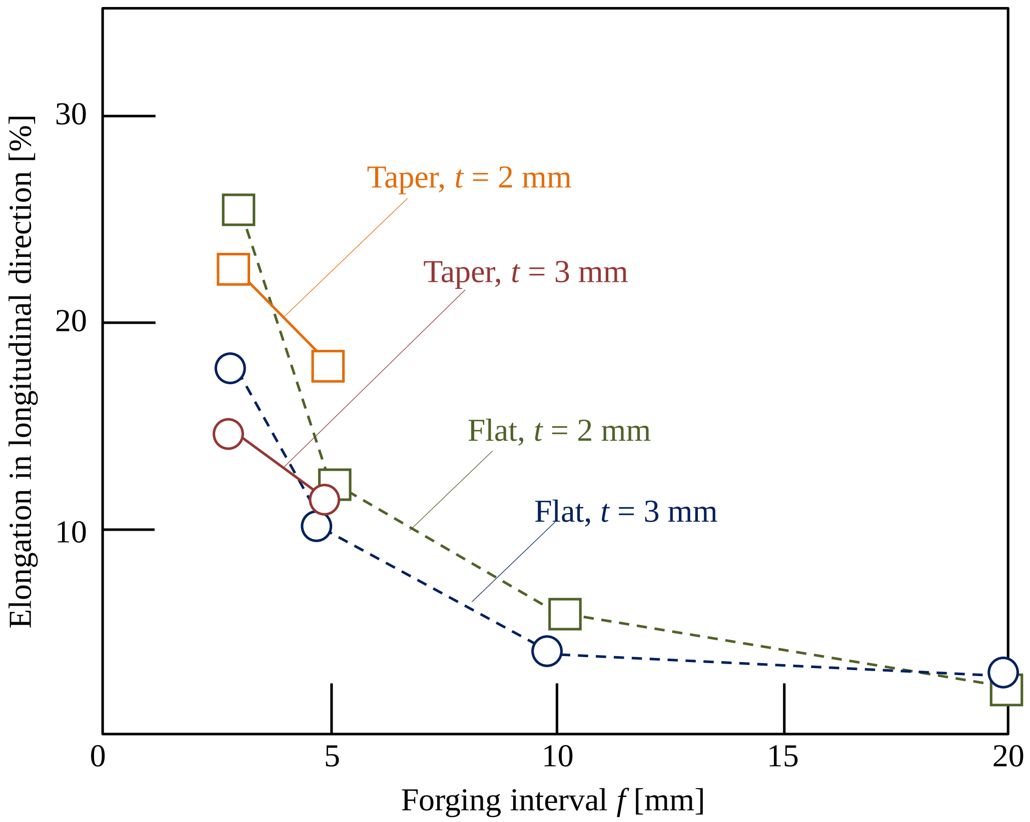


Fig. 6.8 Relationship between elongation in longitudinal direction and forging interval for two punches.

In successive forging, the forging load is comparatively small due to repeated local deformation of the sheet. The relationship between forging load and forging interval for two punches is given in Fig. 6.9. 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 straight punch. Since the forging load decreases with the decrease in forging interval, small mechanical presses conventionally used in forming industry can be used for a small forging interval.

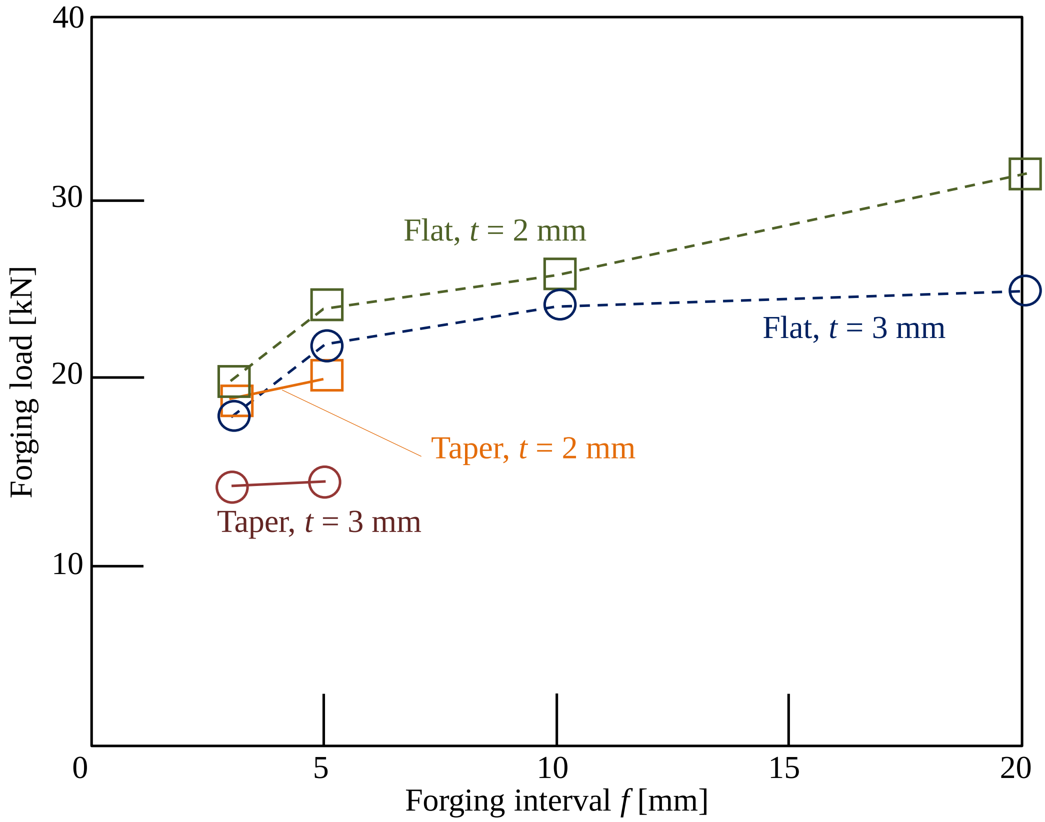


Fig. 6.9 Relationship between forging load and forging interval for two punches.

The relationship between reduction in thickness and forging interval is given in Fig. 6.10. The reduction in thickness of the sheet having an inclined cross-section increases with the decrease of forging interval. For a small forging interval, the load required is smaller as compared to a large forging interval. Therefore the elastic deformation of the press and tools is small and hence the reduction in thickness is large. For a large forging interval, the large load causes a large elastic deformation and hence the reduction in thickness is small.

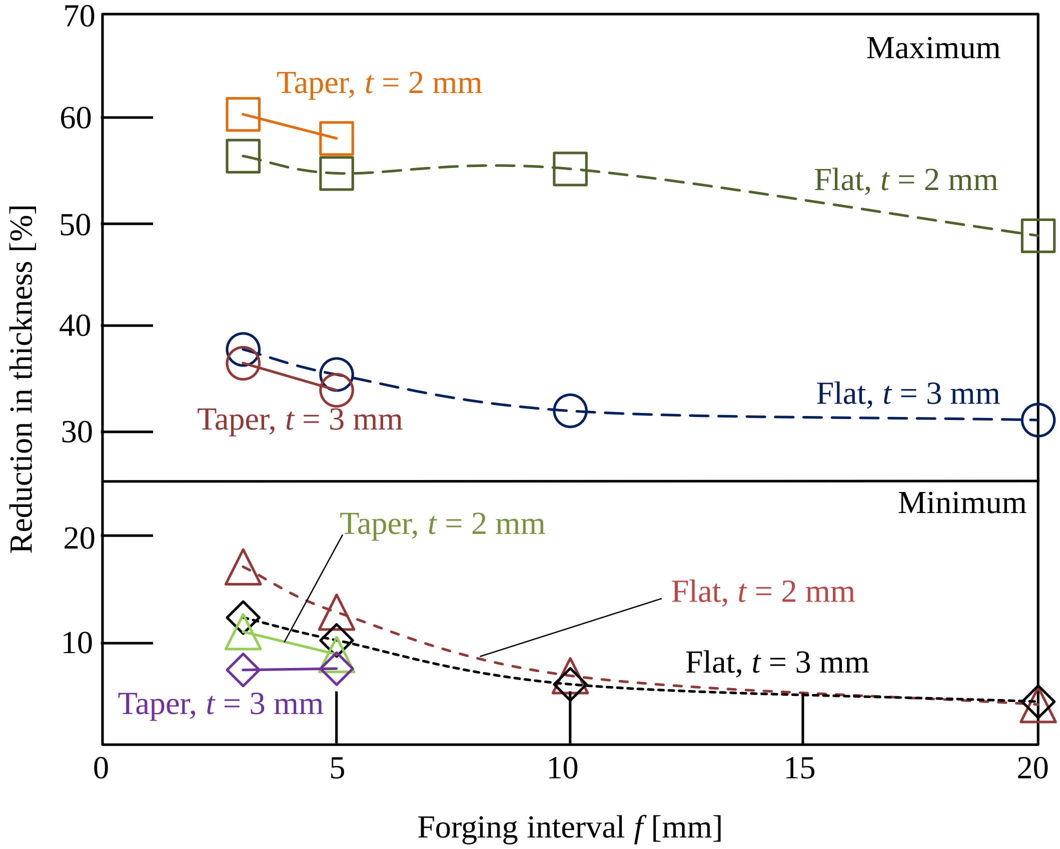
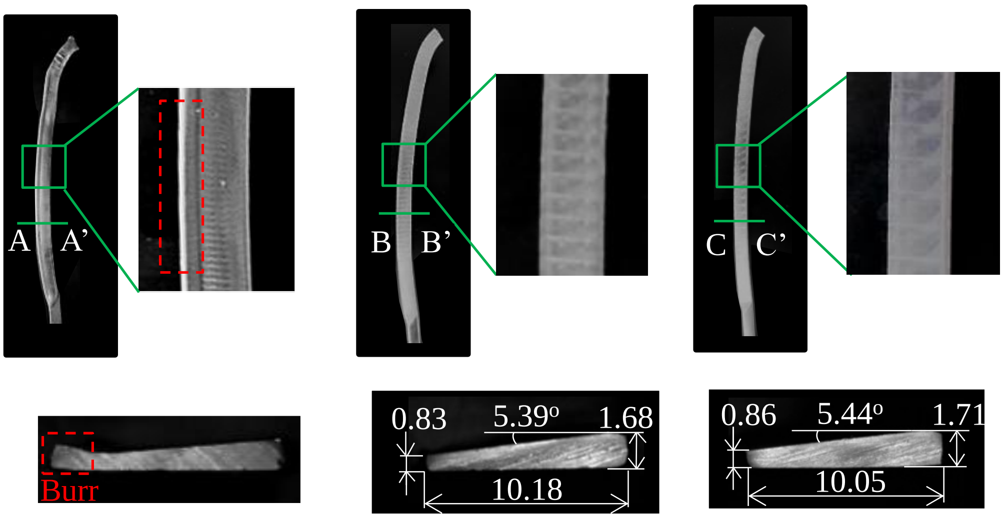


Fig. 6.10 Relationship between reduction in thickness and forging interval for two punches.

6.3.2 Stainless steel sheet having inclined cross-section

The successive forging process of stainless steel sheets with a taper bottom punch and an exit guide was carried out. The forging intervals were 1, 3 and 5 mm. Fig. 6.11 shows the stainless steel sheets having an inclined cross-section for different forging intervals. The sheets showed minimum waving and depression. However, a slight curvature formed on these sheets. For the stainless steel sheet with a forging interval of 1 mm, a burr formed on one side of the sheet as shown in Fig. 6.11(a).



Section A-A'
(a) f= 1 mm

Section B-B'
(b) f= 3 mm

Section C-C'
(c) f= 5 mm

Fig. 6.11 Stainless steel sheets having an inclined cross-section for (a) f = 1 mm, (b) f = 3 mm and (c) f = 5 mm.

Forging the sheet with a very small forging interval (f = 1 mm) will cause a large sheet curvature. The sheet curved towards the side guide and shifted away from the forging area. As the sheet shifted out, the burr was formed during the compression process. The burr formation on the side of stainless steel sheet having an inclined cross-section is illustrated in Fig. 6.12.

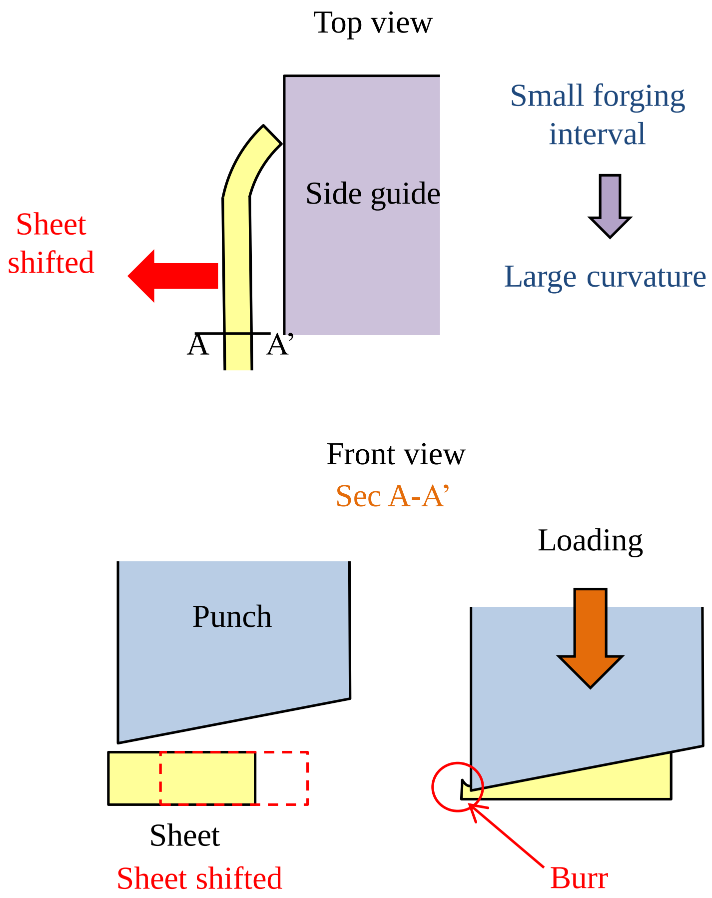
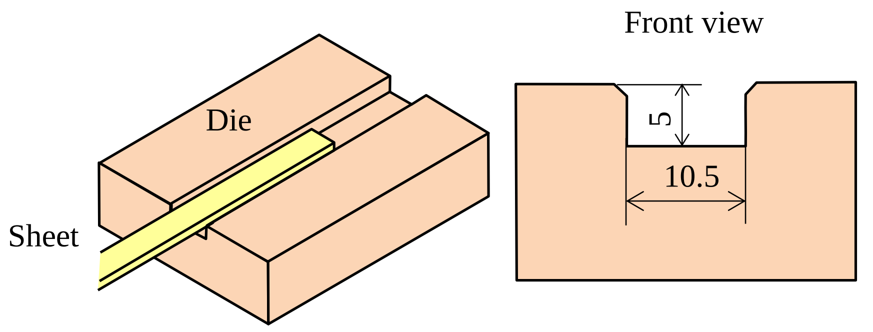


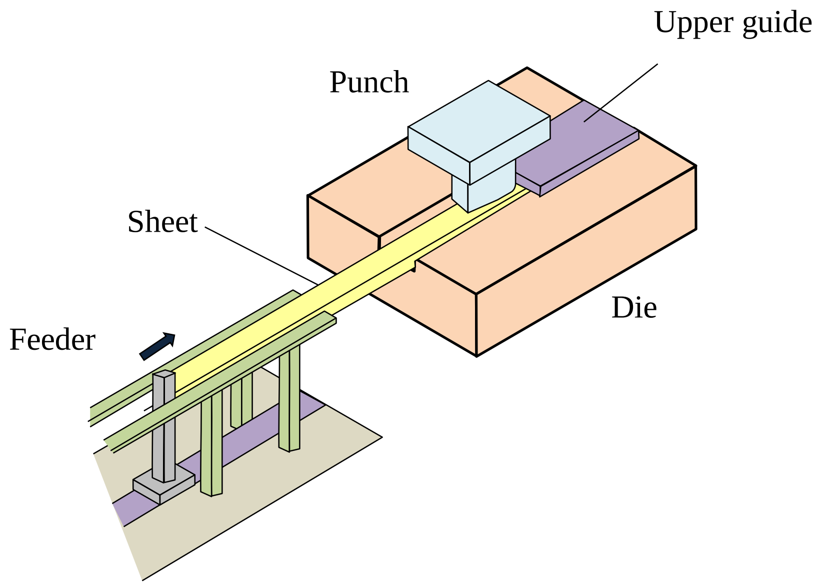
Fig. 6.12 Burr formation on side of stainless steel sheet having inclined cross-section.

6.4. Prevention of side curvature and burr by grooved die

The deformation behaviour of the aluminium and stainless steel sheets with the exit guide have been examined. Even though the side guide reduces the curvature of the forged sheet having an inclined cross-section, the sheets formed a burr for a forging interval of 1 mm and a slight curvature. To overcome these problems, a grooved die was introduced. The grooved die is shown in Fig. 6.13 (a). This die has a grooved width of 10.5 mm. The taper bottom punch and the upper guide were employed as shown in Fig. 6.13 (b).



(a)



(b)

Fig. 6.13 (a) Grooved die for preventing curvature of formed sheet and (b) experimental setup with grooved die.

The resulted stainless steel sheets having an inclined cross-section are shown in Fig. 6.14. For the forging intervals of 3 mm and 5 mm, the curvature of the sheets was further reduced. Since the taper bottom punch was utilised, wrinkling and depression were minimised. For a forging interval of 1 mm, burr was eliminated however waving on the sides of the sheets was observed.

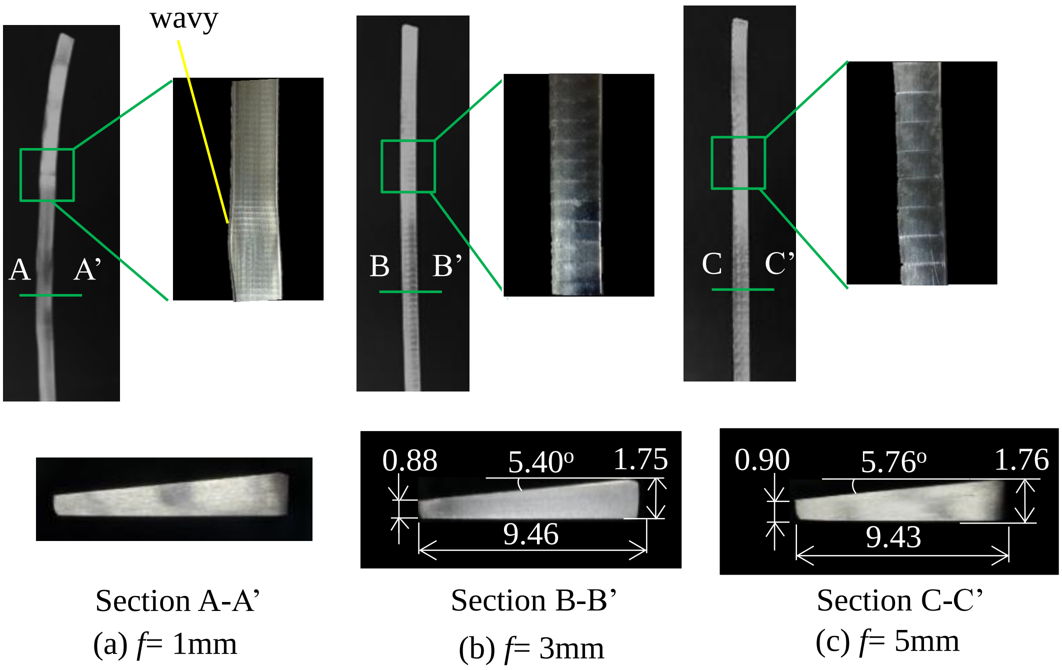


Fig. 6.14 Stainless steel sheets having inclined cross-section for (a) f = 1 mm, (b) f = 3 mm and (c) f = 5 mm.

The relationship between forging load of the stainless steel and aluminium sheets and the forging interval is shown in Fig. 6.15. The forging load for each material was almost the same for the forging intervals of 1, 3 and 5 mm using a taper bottom punch.

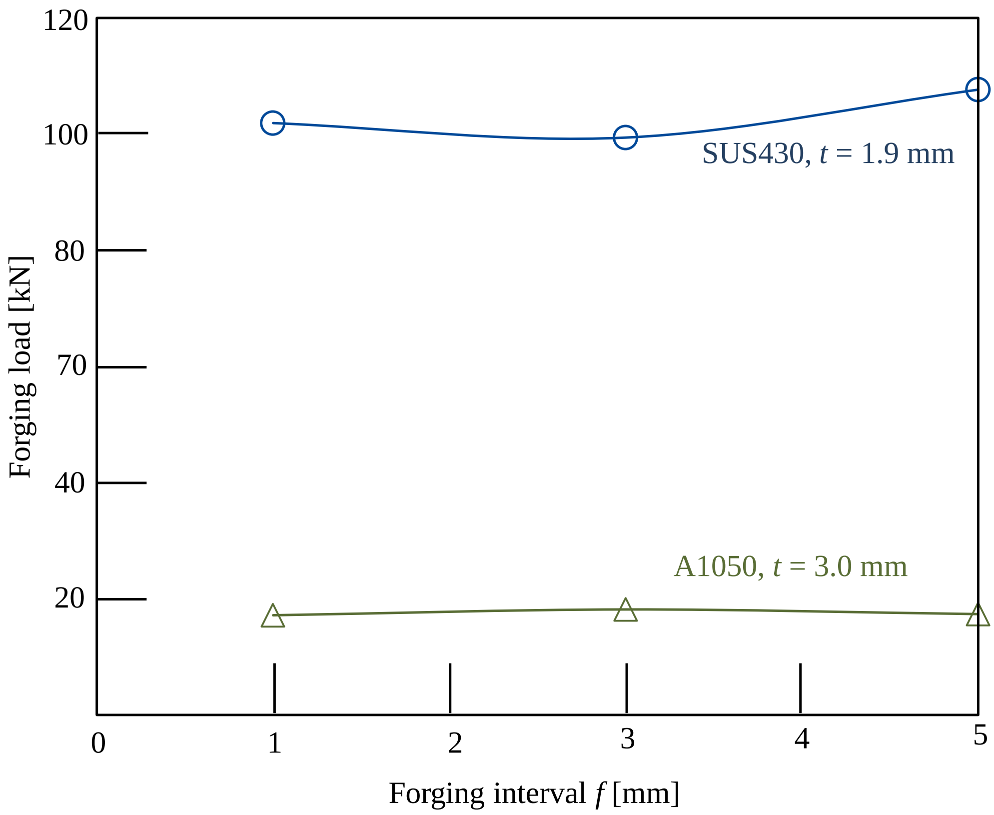


Fig. 6.15 Forging load for stainless steel and aluminium sheets.

The relationship between the average width difference and forging interval for aluminium and stainless steel sheets is shown in Fig. 6.16. The waving for both sheets were minimised by the taper bottom punch.

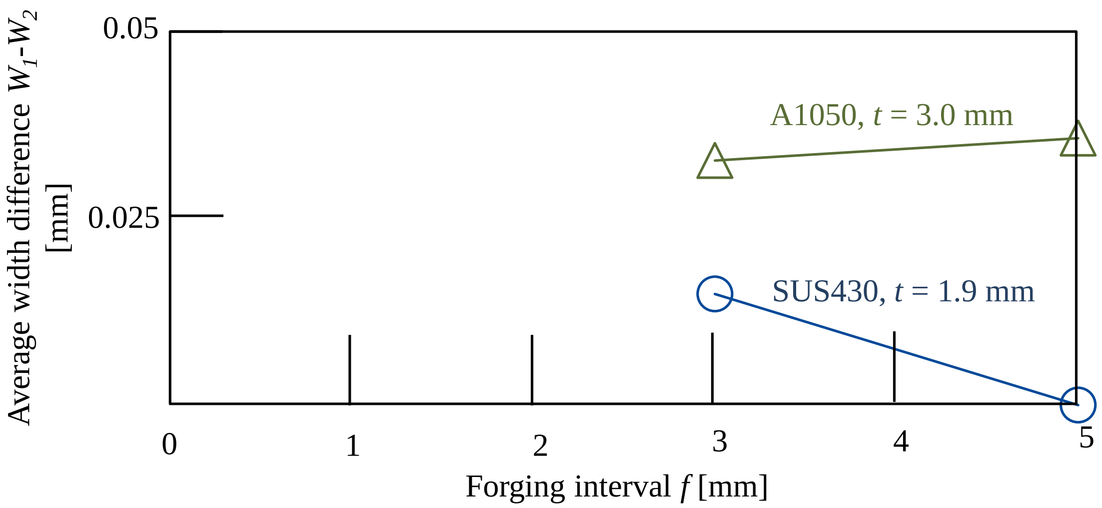


Fig. 6.16 Relationship between the average width difference and forging interval for aluminium and stainless steel sheets.

6.5. Conclusions

Long sheets having an inclined cross-section are found in printers to remove excess toners and regulate the inks for high quality printing. These sheets are generally produced by shearing however this process generates a large amount of scrap. Although rolling produces long sheets, the non-symmetrical cross-section caused wrinkling and curvature due to different deformation ratio. Sheet forging on the other hand is attractive to produce sheets having an inclined cross-section due to its flexibility. However a large load is required to forge a large workpiece.

The successive forging of long sheet having an inclined cross-section was developed to produce long sheets having an inclined cross-section. Due to the small feeding interval and forging load, successive forging is effective in forming a long sheet. A small mechanical press which is more common in the forming industry can be used since the forging load is greatly reduced. The inclined punch having a taper bottom has the advantage of minimizing waving and depression of the forged sheets. The curvature and burr of the forged sheet were minimised by the grooved die.

Chapter 7
Concluding remarks

7.1. Summary

7.1.1. Successive forging of tailored blank having thickness distribution

A successive forging of tailored blank having a thickness distribution was developed for hot stamping. Successively forged-tailored blanks offer an improvement in the strength and crash properties as well as reduction in weight. The thickness of the blanks was controlled by adjusting the amount of feeding under a constant punch stroke. A large reduction in thickness of the blank was obtained from a small feeding while a small reduction was obtained from a large feeding. A small feeding required a small forging load as compared to a large feeding. Hence elastic deformation of the tool and press was small. The steady-state reduction in thickness is almost linearly changed with the amount of constant feed. As the constant feed increases, the reduction in thickness decreases while the forging load increases. The transient region connecting the thick and thin portions was controlled to prevent excess weight and to produce symmetrical change in thickness. For the decrease in thickness, a large constant feeding produced a sharp change in thickness while a small feeding produced a gradual change in thickness. For the increase in thickness of the transient region, a small increment of the variable feeding produces a gradual change in thickness.

7.1.2. Improvement of surface quality of tailor-forged blank produced by successive forging by optimisation of punch shape

Improvement of surface quality of tailor-forged blank produced by successive forging by optimisation of punch shape was conducted. The upper punch inclination due to C-frame press deflection caused tool marks on the surface of the tailor-forged blanks. Optimisation by finite element simulation was conducted to obtain the optimised punch shape to prevent tool marks. The corner punch radius showed a minimised tool marks depth as compared to the sharp edge punch. Although a corner radius punch was utilised during successive forging, tool marks are still large. Therefore concave and convex plates were introduced to prevent the upper punch inclination. With the corner radius punch and the concave and convex plates, the tool marks formed were minimised.

7.1.3. Hot stamping of roof rail from tailored blank having thickness distribution

A tailor-forged blank having two thicknesses was hot-stamped into a miniature of roof rail. The tailored blanks were heated to the austenitising temperature and quenched within dies. Although the tailored blank curved after the successive forging process, the curvature was prevented after hot stamping. After the successive forging, the Al-Si coating remained on the surface of the tailored blank and protected the blank from oxidation. For roof rails of 22MnB5 without coating, remarkable oxide scale was observed. The strength of the roof rails greatly increased after the hot stamping process. The produced hot-stamped tailored roof rail miniatures possessed great hardness and strength with a reduction in weight.

7.1.4. Local thickening of aluminium and SPCC sheets by beading and compression

A sheet forging process was developed to produce sheets having local thickening. The uniform thickness sheet was beaded freely without blank holders and thinning was prevented. The beaded portion was compressed while the width of the sheet was restricted and the strength increased locally from work hardening. The degree of local thickening increases with the increase in beading height. For a small beading height, local thickening was obtained using a flat beading die. However for a large beading height, folding occurred. A large beading height caused a vertical sidewall during compression. For a large feeding, local thickening was successfully produced with a beading die having an inclined surface. An inclined sidewall of the beaded portion improved the thickening behaviour and prevented the folding defect.

7.1.5. Successive forging of aluminium and stainless steel long sheets having inclined cross-sections

Successive forging of long sheet having an inclined cross-section was carried out. The sheet was forged sequentially and repeatedly by an inclined punch. Although a long sheet was being forged, only a small load is required due to a small compression area. Waving and depression were observed on the forged sheet with a flat bottom inclined punch. These defects were minimised by the use of a tapered bottom inclined punch. Due to different deformation rate, the sheet remarkably curved after the successive forging process. The reduction in thickness of the forged sheet decreases with the increase in the amount of feeding due to the elastic deformation of the press and tools. A side punch was introduced to prevent the curvature. The curvature was reduced however for a small feeding, burr was formed on the side of the sheet. To further minimize the curvature of the forged sheet having an inclined cross-section, a groove die was developed. Since a small load is required in the successive forging process, small mechanical presses conventionally used in forming industry can be used for a small forging interval.

7.2. Future perspectives

Rising demand of lightweight vehicles increases the use of light metals and improves the process of producing parts with an optimum thickness distribution. Although lightweight vehicles reduces the fuel consumption and CO_2 emission, the strength and safety of the vehicles are not to be compromised. Tailored blanks joined with different materials and thicknesses offer substantial weight reduction and strength improvement. Tailored blanks locate local reinforcement at crucial area for example, area requiring high strength, the thickness is made larger as compared to the low strength area. This combination increases the strength and improve the safety of the passenger as well as reducing the weight of the vehicle. Tailored blanks are generally made by joining two or more sheets by welding. Although tailored blanks are advantages, the stress concentration due to the sharp change in thickness reduces the formability. Another type of tailored blanks is the tailor-rolled blank which is produced without joining. The thickness of the sheet is controlled by adjusting the gap between the rollers. The sharp change of thickness is overcome by the smooth transient region and hence formability is improves. However the supply of tailor-rolled blank is limited.

The development of successive forging process produces tailor-forged blank having a thickness distribution without joining similar to tailor-rolled blanks. Since local deformation is small, the forging load is also small. Therefore small mechanical presses commonly used in forming industry can be applied to produce tailored blanks by successive forging. In the present study, the thickness of the tailor-forged blank was successfully controlled. An automatic feeding history involving control of transient regions and thickness and length distribution as shown in Fig 7.1 is required for application in industry. With the comprehensive analysis of thickness and length distribution as well as the transient region, an accurate parts having a thickness distribution can be produced.

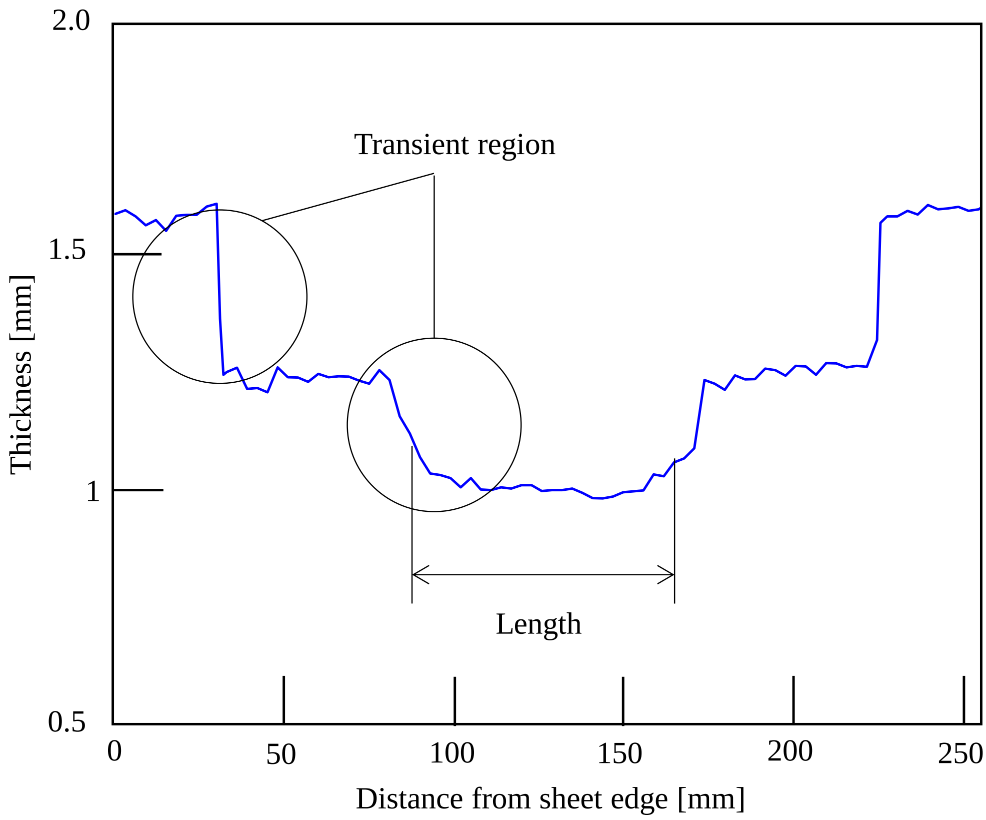


Figure 7.1. Control of transient regions and length distribution.

Currently the tailor-forged blank having longitudinal thickness transition was produced by successive forging. Although the productivity of successive forging process is lower than that of rolling, the successive forging process is suitable for producing prototype and preliminary tailored blanks having thickness distributions. To increase the flexibility of the tailor-forged blank, new punch shape and movement are required. Fig 7.2 shows the punch shapes and movements to produce a 2D profile tailor-forged blank having both longitudinal and lateral thickness distributions. With the combination of longitudinal and lateral thickness distribution, a more precise control of thickness distribution will be achieved.

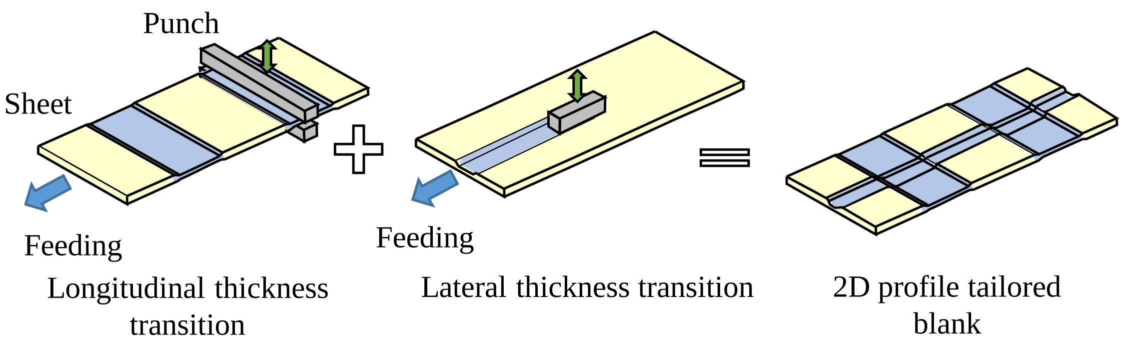


Figure 7.2. Punch shapes and movements for producing 2D profile tailor-forged blank.

Tailored blanks having a thickness distribution locate the right material and thickness at the right place to increase the strength and reduced the weight. Parts having local thickening increases the strength to prevent thinning at the critical area that causes fracture during stamping. Currently, the tailored blank having local thickening produced by beading and compression is conducted separately. To increase the production rate and reduce the forming stage, successive forging of tailored blanks having local thickening by beading and compression shown in Fig. 7.3 is proposed. In the successive forging, a small portion of the sheet is beaded and compressed. A feeder is utilised to feed the sheet into the beading and compression areas. As the feeding progresses, the beaded portion is compressed. The beading and compression processes are conducted simultaneously.

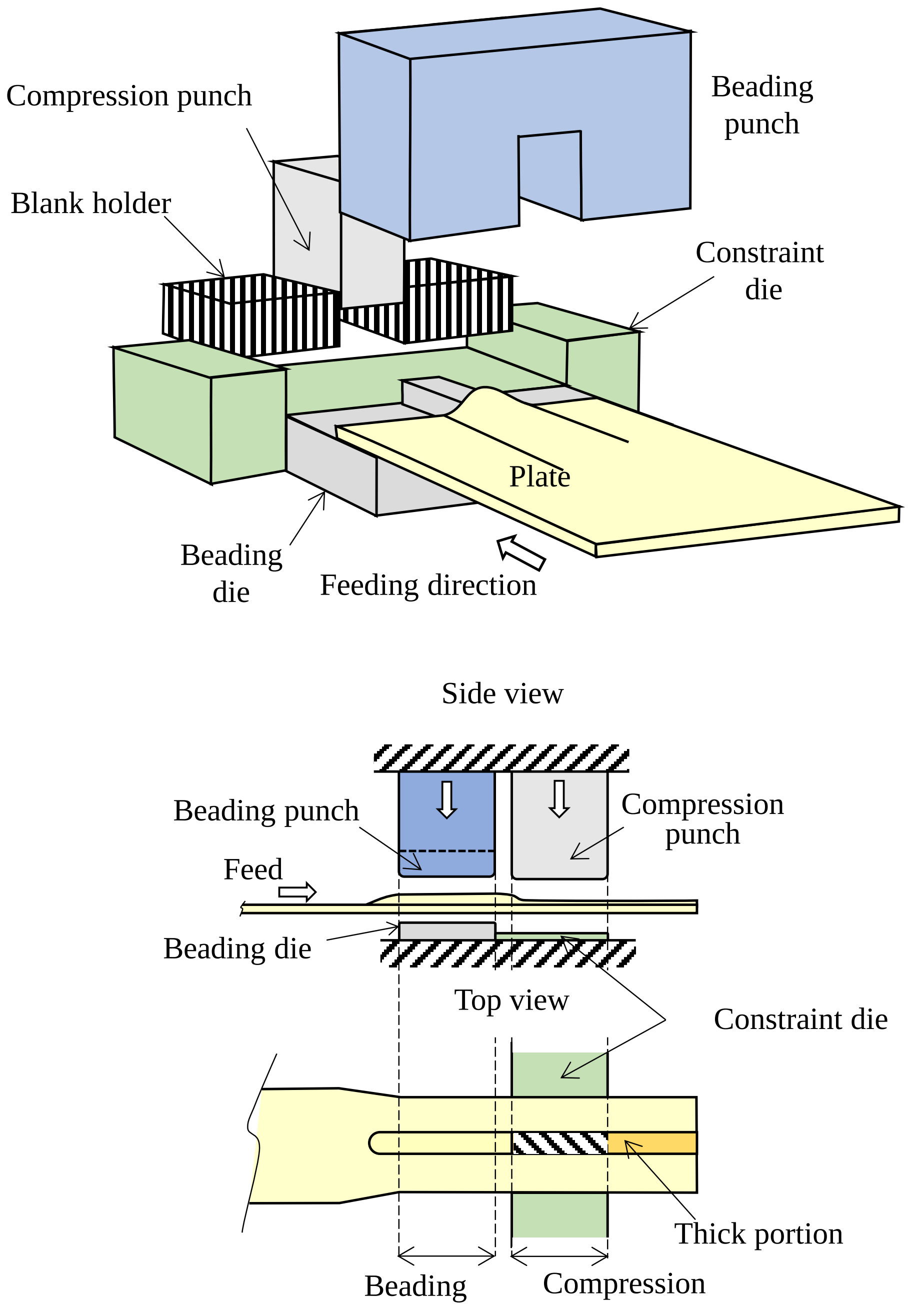


Fig. 7.3 Successive forging of tailored blanks having local thickening by beading and compression.

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List of publications

1. **Liyana Tajul**, Tomoyoshi Maeno, Ken-ichiro Mori, Incremental forging of long plates having inclined cross-section and local thickening, International Journal of Mechanical & Mechatronics Engineering, 16 (3) (2016), pp. 34-52.
2. **Liyana Tajul**, Tomoyoshi Maeno, Takaya Kinoshita, Ken-ichiro Mori, Successive forging of tailored blank having thickness distribution for hot stamping, International Journal of Advanced Manufacturing Technology, (2016), doi:10.1007/s00170-016-9356-z.

List of conferences

International

1. **Liyana Tajul**, Tomoyoshi Maeno, Ken-ichiro Mori, Successive forging of long plate having inclined cross-section, Procedia Engineering, 81 (2014), pp. 2361 – 2366.
2. **Liyana Tajul**, Tomoyoshi Maeno, Takaya Kinoshita, Ken-ichiro Mori, Successive forging of tailored blank having thickness distribution for hot stamping, *JSTP 7th International Seminar on Precision Forging*, Nagoya, Japan, 9-12 March 2015.

Local

1. **Liyana Tajul**, Tomoyoshi Maeno, Ken-ichiro Mori, Takaya Kinoshita, Successive forging of long plate having inclined cross-section, *The 64th Japanese Joint Conference for the Technology of Plasticity,* Osaka, Japan, 1-3 November 2013.
2. **Liyana Tajul**, Tomoyoshi Maeno, Ken-ichiro Mori, Takaya Kinoshita, Forging of plate having local thickening using beading and compression, *The 2014 Japanese Spring Conference for the Technology of Plasticity,* Tsukuba, Japan, 6-8 June 2014.
3. **Liyana Tajul**, Tomoyoshi Maeno, Takaya Kinoshita, Ken-ichiro Mori, Control of thickness distribution in successive forging of tailored blank for hot stamping, *The 65th Japanese Joint Conference for the Technology of Plasticity,* Okayama, Japan, 11-13 October 2014.
4. **Liyana Tajul**, Tomoyoshi Maeno, Takaya Kinoshita, Ken-ichiro Mori, Improvement of surface quality of tailor forged blank produced by successive forging for hot stamping by incline correcting die, *The 2015 Japanese Spring Conference for the Technology of Plasticity*, Yokohama, Japan, 29-31 May 2015.

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