Punching and Trimming of Die-Quenched Steel and Ultra-High Strength Steel Sheets

（ダイクエンチ鋼板と超高張力鋼板のトリミングおよび穴抜き加工）

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Abstract

In the introduction, an overview of reduction in weight of automobiles for a less CO_2 emission is presented. The use of lightweight materials such as aluminium, magnesium and titanium alloys is attractive for the reduction. However the high cost of the alloys is disadvantageous, and thus the steel is preferable. Hot stamping processes of ultra-high strength steel sheets are attractive as a key technique for the reduction in weight of automobiles parts having a tensile strength of 1.5 GPa can be formed by die-quenching. However, finishing operations such as hole-making become difficult, and the application of laser cutting having high investment cost and low productivity is a bottleneck. The conventional punching process is desirable for mass production.

In Chapter 2, a cold small clearance punching process of die-quenched steel sheets by punch having a small round edge was developed to improve the quality of the sheared edge. The sharp edge of the punch leads to the concentration of stress at the punch edge, and thus initiates the early onset of cracks. Therefore the rough fracture surface on the sheared edge becomes large. For a small clearance and small round edge of the punch, the concentration of deformation around the edge of the punch was relieved, and thus the onset of a crack from the edge of the punch was prevented. The burnished surfaces became considerably large.

In Chapter 3, an automatic centring process using a moving die was developed to correct the eccentricity between the punch and die in the small clearance punching process.Although small clearance was effective for a high quality sheared edge in punching of die-quenched steel sheets, setting of tool becomes difficult due to the less space and complex structure of the die. For a small clearance the punch and die tend to be eccentric. By setting a gap between the moving die and holder, the die is shifted by imbalanced force, and the punch and die become concentric after several strikes.

In Chapter 4, since the small clearance punching is effective, a repeated small clearance punching process of die-quenched steel and ultra-high strength steel sheet were carried out. In the real industry application, car parts usually consist of multiple holes for joining, attaching, painting, etc. For repeated small clearance punching with fixed die, the punch was broken by an eccentricity between the punch and die after several strikes. The combination of small clearance and automatic centring using a moving die is effective for a high number of strikes in repeated punching of die-quenched steel and ultra-high strength steel sheets. However the high strength of the sheet deteriorates the punch life. By lubricating the surface of the punch, galling is reduced and tool life is increased.

In chapter 5, an attempt to reduce the fall velocity of the scrap and noise level during trimming of ultra-high strength steel parts using the bevel punch was developed. Since the use of the ultra-high strength steel sheets for automobile body-in-white parts is increased, trimming is required to remove the scrap portions. In trimming of ultra-high strength steel sheets, the flying speed is large due to the high strength, and thus the scraps jump out from a disposal box. The trimming operation also becomes noisy due to high trimming load. The deformation and shearing behaviours of the sheet during trimming with the flat punch were investigated and the level of noise during trimming was measured. By the bevel punch, only a local zone of the sheet is in contact with the punch during trimming, and thus the trimming load and the flying speed of the scrap are reduced.

In chapter 6, an approach to prevent chipping and fracture on the trimmed edge of the ultra-high strength steel parts having curved shape was developed. Trimming of ultra-high strength steel parts having curved shapes with the flat punch has possibilities of defect such as chipping, edge fracture, and bent which deteriorates the surface quality and dimensional accuracy of the part. In trimming of an L-shape ultra-high strength steel sheet having curved shapes, the scrap at the curved zone is bent and results in chipping and fracture of the sheet edge. The L-shaped punch having an inclined angle was introduced to prevent chipping and fracture at the trimmed edge, and at the same time reduces trimming load and energy.

The conclusion emphasises the importance of small clearance punching by punch having small round edge to produce high quality of the sheared edge surface and prevent the delayed fracture. The application of automatic centring eases the small clearance punching process especially for repeated punching. By gradually trimming ultra-high strength steel sheets with the bevel punch, the flying speed of scraps and noise level are reduced. Moreover the problem of chipping and edge fracture was prevented.

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Chapter 1
Introduction

1.1 Lightweight automobiles - An overview

1.1.1. Reduction of CO2 emission

In recent years, global warming, the greenhouse effect and climate change are among global issues which demand great attention and collective action. The transportation sector contributes almost 14% of global CO_2 emissions with emissions from road vehicles, in particular, being almost three times larger than the emissions from the aviation and shipping sectors combined [1-2]. In 2009, in Japan, more than 20% of the CO_2 emissions come from the transportation sector for year 2009 as shown in Fig 1.1. In particular, more than 84% of the CO_2 emissions from the transportation sector in Japan were derived from road vehicles including passenger cars and commercial vehicles such as trucks, buses, etc. [3]. Since the increment in vehicle ownership worldwide is unavoidable, these levels are expected to grow in the future. A transformation in modern transportation engineering is required to overcome the global greenhouse issue. Since reduction of CO_2 emissions are vital, various technologies have been developed and implemented in the automobile industry, including hybrid-electric, plug-in hybrid-electric and hydrogen vehicles. Although hybrid-electric, plug-in hybrid-electric and hydrogen vehicles have the potential for lower carbon emissions, the issues including the initial high cost for the vehicle, the limited range of travel of on-board fuel storage, high fuelling costs compared to gasoline, and limited numbers of alternative fuel stations represent challenges for global implementation [4-7].

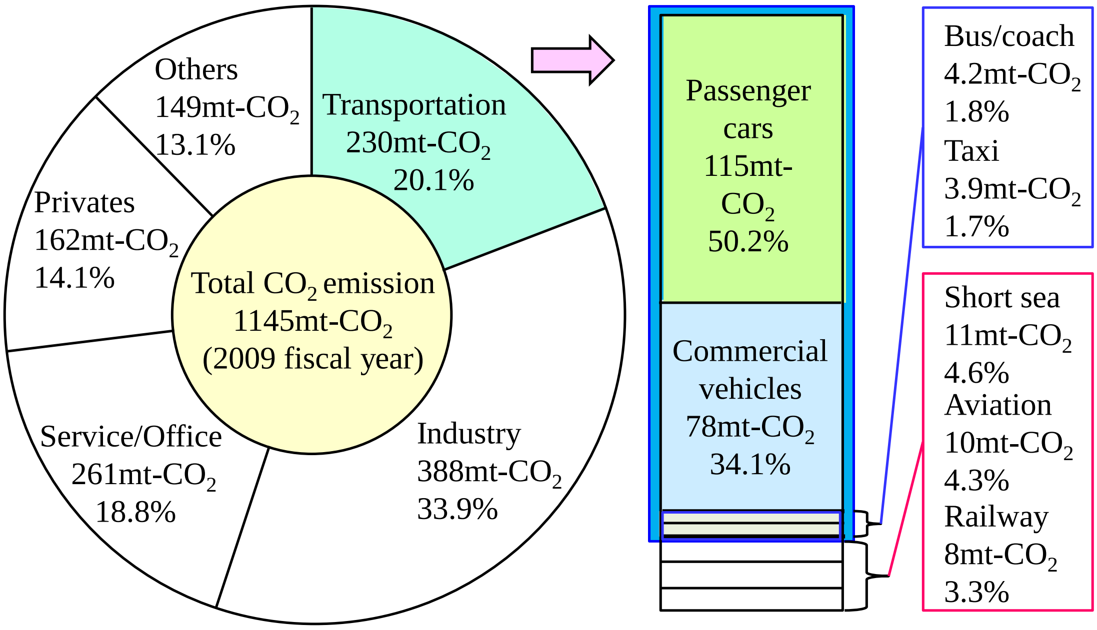


Fig. 1.1. CO_2 emission in Japan 2009 – by Ministry of Land, Infrastructure, Transport and Tourism [3].

The reduction of fuel consumption and lowering of CO_2 emissions is one of the most important challenges facing the automotive industry. A vehicles body mass has a strong influence on fuel consumption and CO_2 emission. Therefore the key to improving a vehicle's fuel consumption and CO_2 emission rate is weight reduction. The body-in-white contributes more than 30% of the overall weight of the car (see Fig. 1.2). Although the body-in-white accounts for only about one-third of the total weight of an automobile, reducing the weight of this section is paramount for improvement in fuel economy and lower CO_2 emissions [8-10]. In previous decades, conventional mild steel has been the primary material for manufacture of the car body. The emergence of forming technology for strong and lightweight materials stands a good chance of eventually being adopted by industry in general and especially the automotive industry. Replacing cast iron and traditional steel components with lightweight materials can directly reduce the weight of a vehicle's body, and thus additional safety devices and advanced emission control systems can be added without increasing the overall weight of the vehicle [10-13].

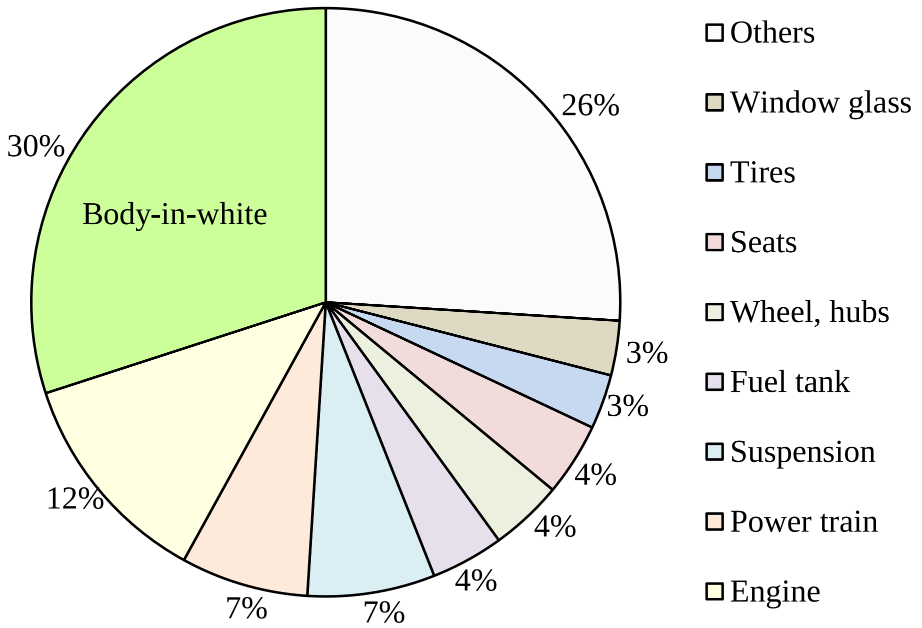


Fig. 1.2. Car component part weight ratio [10].

1.1.1. Lightweight materials: Aluminium, magnesium, and titanium alloys

The usage of lighter materials in vehicle manufacturing has progressively increased over time. Aluminum (Al) alloys, magnesium (Mg) alloys, high-strength steel, carbon fiber, and polymer composites are among the lightweight materials which have been widely applied to the vehicles body in order to reduce weight. A 10% weight reduction from the total vehicle weight can improve fuel economy by 4–8%, depending on the performance of the car engine. Aluminum alloy has gradually replaced cast iron as the material for engine blocks, which is one of the heaviest parts in the car and as such results in significant weight reduction. Aluminum castings have been applied to various automobile parts to produce almost 100% of pistons, about 75% of cylinder heads, 85% of intake manifolds and transmission, 40% of wheels, and some other small parts such as brackets, brake components, suspension (control arms, supports), steering components and instrument panels [14-16]. Aluminum alloys, of the 5000 series, possess good formability and weldability, maintain high strength after forming, and have outstanding corrosion resistance. Al–Mg–Si alloy sheets of the 6000 series are targeted as materials for body panel because they are heat-treatable and achieve required strength when undergoing the bake hardening process [17-19]. Ford has actively applied lightweight materials in their products to reduce weight without compromising strength. The latest body frame of the Ford F-150 truck was made from the 5,000 and 6,000 series of aluminum alloys (see Fig. 1.3).

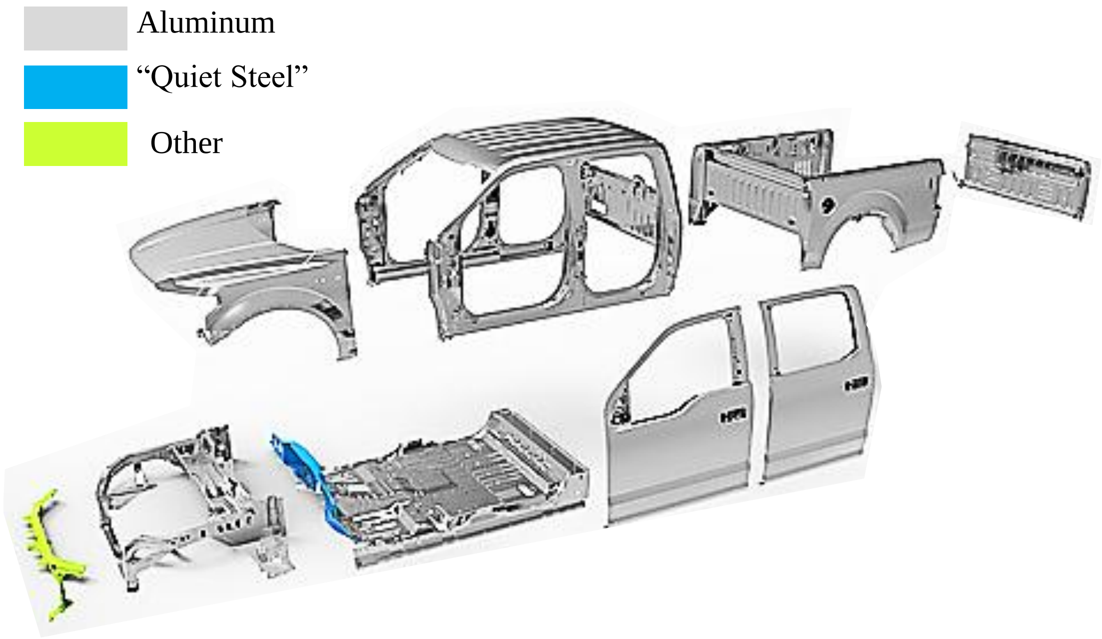


Fig. 1.3. Body frame of truck made of aluminium alloys [20].

Magnesium alloys have a density of 1/4 of mild steel, whereas the specific strength is 2.5 times larger. The research and development of magnesium alloy has significantly grown as the demand by automobile makers and other large-scale potential users of magnesium has increased [21-22]. Some automotive makers use magnesium alloys replacing previously used steel stampings in such items as safety components, airbag container and housing, safety belt spool, instrument panels, steering wheels, steering column components, etc (see Fig. 1.4). GM and Ford are leaders in the application of magnesium alloys for making four-wheel-drive transfer cases in high-volume truck production; while Volkswagen is aggressively expanding the use of magnesium in manual transmission cases [24-26]. Since the forming technology of the magnesium alloys at an elevated temperature has been well developed, the applications of magnesium for engine blocks and power train components is possible, because the limitation of the formability for the magnesium alloys have been extended [27-30].

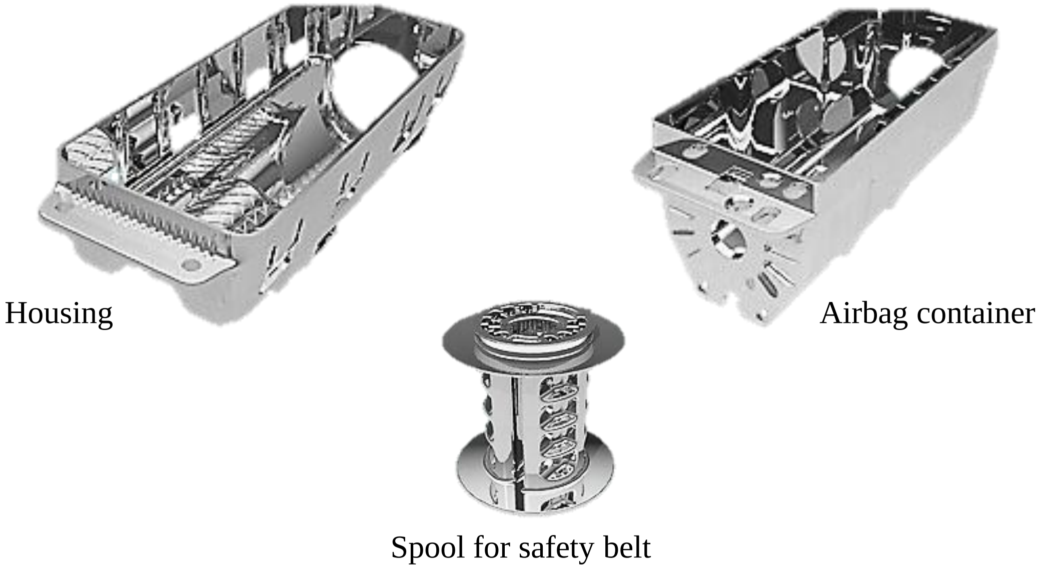


Fig. 1.4. Car components made of magnesium alloys [23].

Titanium alloy is an excellent lightweight material for weight reduction. Although titanium alloy sheets are widely used in aerospace and aviation for making aircraft bodies, the application of titanium alloy for commercial car and motorcycle parts has gradually increased (see Fig. 1.5). Titanium is alloyed with other elements (mainly aluminum, vanadium, molybdenum, silicon, chromium, iron, zirconium and niobium) to produce titanium-based alloy metals which have superior physical properties such as high strength, low density and a high resistance to corrosion [31-35]. Many car makers use titanium alloys for high performance vehicles in exhaust systems, mufflers, suspension springs, valves and connecting rods. For racing cars, since the high performance of the car is vital, the use of titanium alloys components is more common. As titanium alloy has half the density of steel and better dynamic properties than aluminum, the engine, valves, springs, torsion bars, fasteners, flywheels and clutch components are made from titanium alloy to enhance the overall performance of the car [36-37].

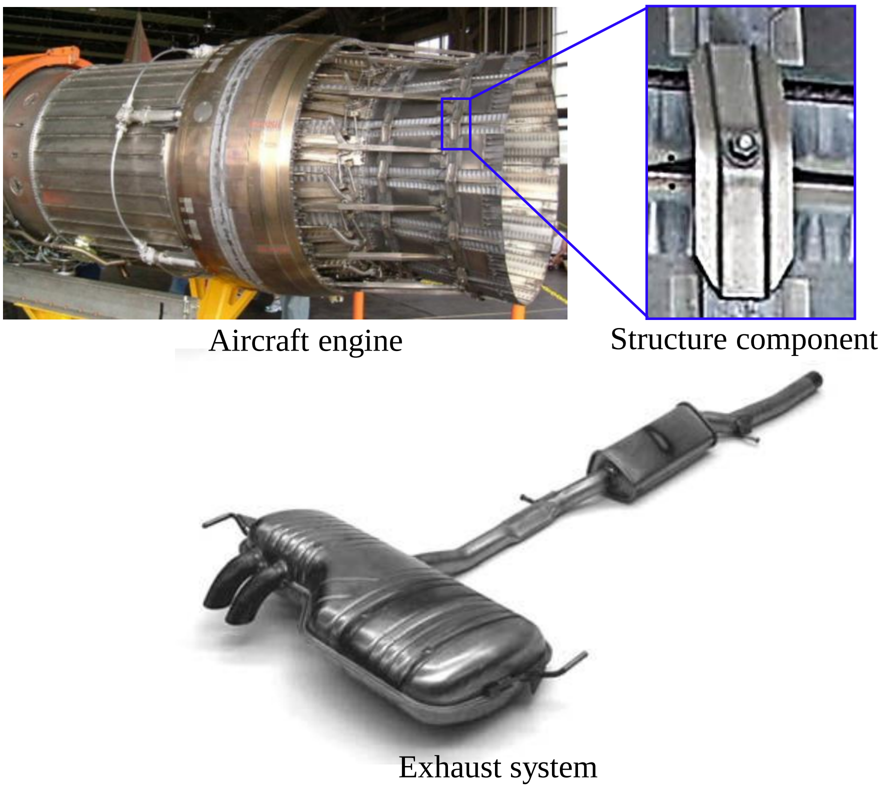


Fig. 1.5. Titanium alloys for aerospace and automobile components [31, 32].

Aluminium, magnesium, and titanium alloys offer a great reduction in weight and quality improvement for the automotive industry, with their superior mechanical properties of high strength, low density and high corrosion resistance. However, it is difficult to use these lightweight materials in large scale automotive production, unless the high cost of alloy materials and metalworking of the parts is lowered to an acceptable level. Moreover, the limitation of the formability at room temperature especially for magnesium and titanium alloys is problematic. Although forming at an elevated temperature is a solution, the equipment required for preheating and cooling systems are expensive and economically challenging for small companies [24, 38-39]. Therefore, due to these limitations and problems, the industry still has a significant interest in steel sheets due to their cost competitiveness.

1.1.2. High strength steel

High strength steel is the best choice for car makers when it comes to cost efficiency, environmental issues and overall value for money. High strength steel provides car body parts with lower mass, higher strength, and greater safety to the user. The areas of the body structure which are commonly constructed using high strength steel sheets, have replaced the thicker conventional reinforcement mild steel parts is shown in Fig. 1.6. Since material replacement is generally more effective in automobile light-weighting than structure modification, this approach is widely applied by car makers. Material thickness can be reduced without compromising the needed strength of the parts, thus reducing body mass [11-12, 40-41]. The much higher strength steel, so called ultra-high strength steel, is actively utilized for car body part production on a large scale. The tensile strength of the ultra-high strength steel sheets can reach above 1 GPa; a significant strength for a body part. While certainly harder than mild steel, the rapid improvement in the metal forming process allows the high strength and ultra-high strength steel sheets to be formed into advanced shapes [42-46].

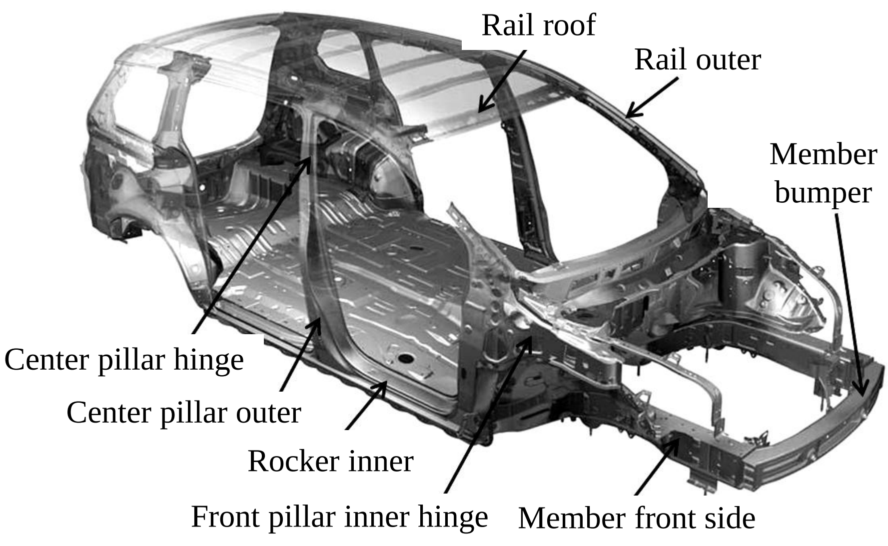


Fig. 1.6. Application of high strength steel sheets for automobile parts [40].

1.2 Cold stamping of high strength steel

For the reduction in weight and improvement of crash safety of automobiles, the use of high strength steel sheets having a high specific strength has remarkably increased. The high strength steel sheets are mainly employed in the body-in-white components to enhance passenger safety. As the strength of the high strength steel sheets rises, cold stamping of such sheets becomes difficult. A higher contact pressure at the die/sheet interface accelerates wear and galling of the tools, resulting in low surface quality of the products. The large springback deteriorates dimensional accuracy of formed products due to die deflection. For the complex shape of the body-in-white parts, even bending is more preferable for ultra-high strength steel sheets as the large strength and small ductility make the process difficult [47-50].

Even though using high strength steel sheet offers many advantages, the large springback, small formability, short tool life, etc. are significant problems for car makers. A new approach to assess the bending limits, based on optical strain measurement, was developed to identify the critical deformation and failure stages during bending of high strength steel sheets [51]. The finishing reduction in thickness direction was introduced to produce uniform stress distribution at the bending zone and reduce the springback [52]. In the flanging process of ultra-high strength steel sheet, the gradually contacting punch was introduced in order to improve formability of the sheets and a conical punch was found effective in smoothing the fracture surface of the sheared edge during the hole expansion of ultra-high strength steel sheets, thus minimizing the occurrence of cracks [53-54]. To expand the tools life used in the stamping of ultra-high strength steel sheets, the application of hard coatings significantly improved wear resistance and reduced galling of the tools [55-57].

1.3 Hot stamping of quenchable steel sheet

1.3.1. Different method of heating blank

Hot stamping of quenchable high strength steel sheets is an attractive process for producing ultra-high strength steel parts. The sheets are heated up to the austenization temperature for an austenitic microstructure, then hot-stamped and finally rapidly cooled down and die-quenched by holding at the bottom dead centre of a press. This process produces high strength through the phase transformation from austenite to martensite, which induces the tensile strength of the formed parts up to 1.5 GPa. In hot stamping, the forming load is remarkably reduced, springback is prevented and the formability is greatly improved. As the sheets are soft during forming, the stamping operation becomes easy due to the decrease in flow stress and the increase in ductility [58-61].

Since a homogenous temperature of the sheet and a short heating time are important for hot stamping, the heating procedures are important. Heating procedure of has a great influence on the part properties, the process time, and the cost-efficiency of hot stamping [62-63]. The most applicable method for heating the sheet is the furnace heating where the blank is heated by radiation in the furnace (see Fig. 1.7). Furnace heating is suitable to produce a homogeneous temperature for a part having a large surface area. However the heating time is comparatively long. For the smaller size part, the drop in temperature is large during transferring the part into the die from the furnace.

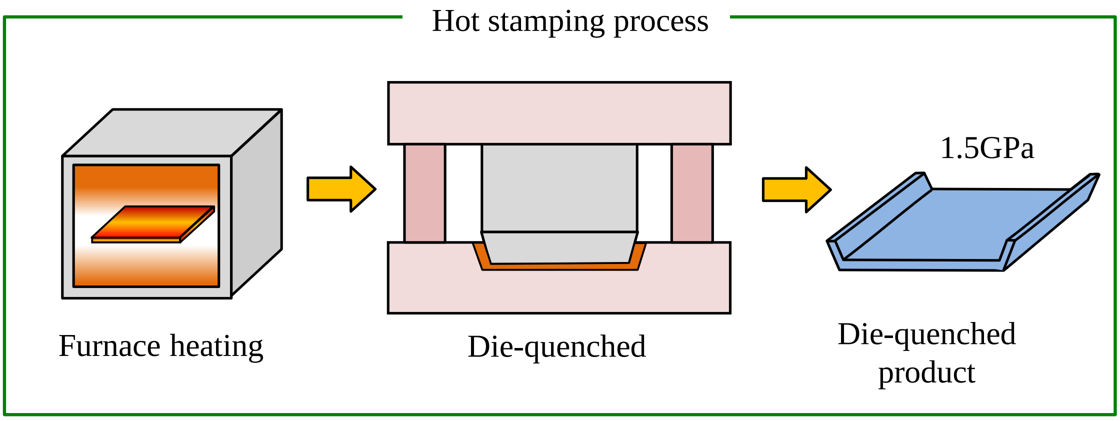


Fig. 1.7. Furnace heating, hot stamping, and die quenching process of quenchable steel sheet.

Since the conventional hot stamping processes by furnace heating are limited to large size parts having small temperature drop, hot stamping of small size parts is quite different. Warm and hot stamping processes of ultra-high tensile strength steel sheets using resistance heating was developed to rapidly heating the small size part, avoids the temperature drop and improve springback and formability [64-65]. In hot stamping by resistance heating the sheet is clamped between the two pairs of electrodes and the current is forced to flow through the sheet metal part (see Fig. 1.8). The resistance of the material causes the rapid heating of the sheet. The rapid resistance heating was effective to heat the sheet up to 900ºC in 2 s. The resistance heating were used in the tailor die-quenching for producing parts having a strength distribution and in the spline forming of ultra-high strength steel gear drums [66]. Beside the ultra-high strength steel pats, the resistance heating was also applied to the hot stamping of the titanium alloy sheets [67-68].

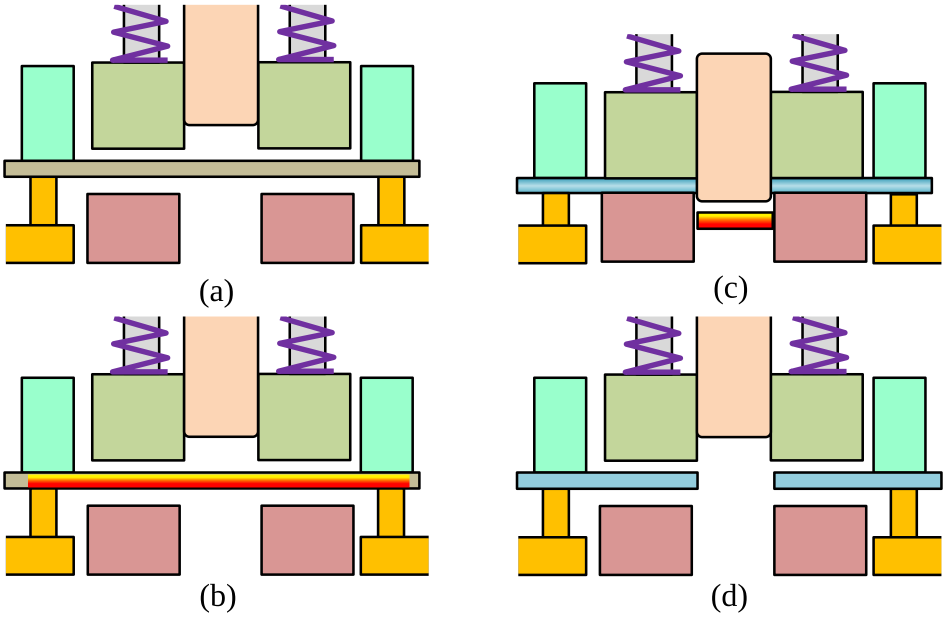


Fig. 1.8. Hot stamping of ultra-high strength steel sheet consisting of resistance heating, blanking and die quenching: (a) setting; (b) resistance heating; (c) blanking and die quenching and (d) release punch.

An induction heating device consists of two components; a high-frequency generator and an induction coil (see Fig. 1.9). In induction heating, the sheets are transferred into the heating zone (induction coil) by a conveyer. As the current passes through the induction coil, an eddy current is induced in the steel sheet [69]. Since the system is not limited to the connecting area, such as in rapid resistance heating, induction heating is suitable for both large and small size parts. The two-step induction heating system consists of the longitudinal field inductor and the face inductor that was developed to increase the uniform distribution of heat in the sheets. The only drawback of this system is that the conveyer system must be designed from non-electro conducting materials for handling the transfer of the sheets in the heating process. This is because all ferromagnetic materials that enter the magnetic field of the induction coil will be heated.

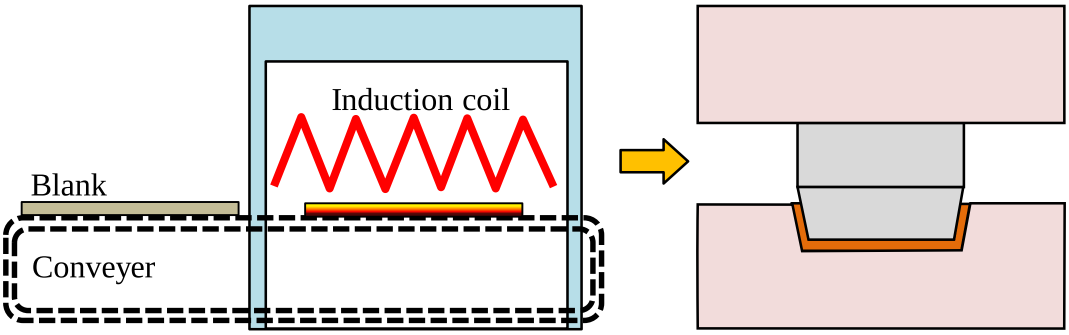


Fig. 1.9. Hot stamping by induction heating.

The surface of the quenchable steel sheets undergoes oxide scale formation at the austenitization temperature. The oxidation becomes severe during the transfer of the heated sheet from the furnace into the die due to contact with air. To avoid surface oxidation and scale formation during the direct hot stamping operation, the sheet is pre-coated with a metallic coating, commonly the Al-Si or Zn layer [58-59]. Another approach to prevent the scale formation is by applying the oxidation preventive oil at the sheet. A solid film is generated on the surface and during heating in the furnace the film changes into a liquefied film having an oxidation barrier [70].

Since forming of the sheet must be completed before the beginning of the martensite transformation and therefore, a fast cooling closing process is important for die-quenching. Hence, designing of the die with a high cooling rate significantly influences the final properties of the sheet and the process time. An addition of a cooling duct inside the die is effective in increasing the cooling rate of the sheet during die-quenching [71-72].

1.3.2. Blank development of hot stamped product

To reduce the waste of the material, production cost and finishing operation, the net shape and near net-shape forming is important [73]. The blank development is the method to form a part having a specific size and complex shape near to its accurate dimension. The blank is made slightly bigger in size as than that of the real dimension; heated and form during soft according to the die shape. Since the shape of blanks for hot stamping is roughly determined by developing that of products, the dimensional accuracy of edges of the stamped parts is not very high (see Fig. 1.10). Although the near net-shape is achieved by blank development, the hot formed part need to be trimmed to remove the unnecessary portion, especially for the complex zones which can only be remove either by trimming or punching

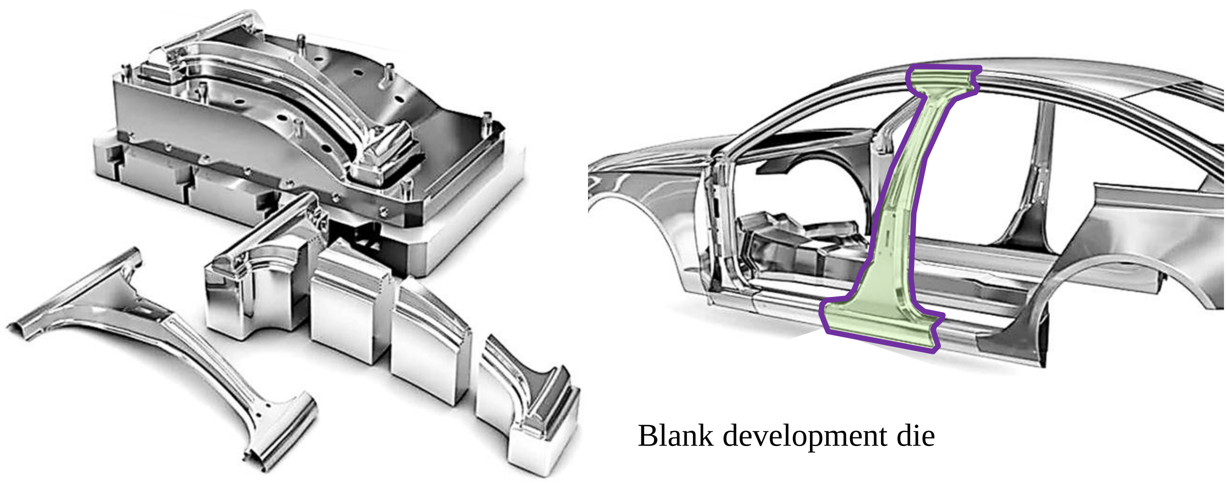


Fig. 1.10. Blank development die for hot stamping of centre pillar [74].

1.3.3. Punching during hot

Although hot stamping of quenchable steel sheets is a useful process for producing ultra-high strength steel parts having a tensile strength of approximately 1.5 GPa are obtained under a low forming load, the finishing process such as punching and trimming after hot stamping is difficult [58]. Another approach to eliminate this problem is by punching or shearing during hot. By heating the shearing zone, the flow stress is reduced and formability is increased, and thus the part can be cut for low shearing load [75-77]. Since deformation in the punching or shearing is limited to the shearing zone of the hole, only this zone is uniformly heated by passing electric current thru the electrode pins as shown in Fig. 1.11. The quality of the sheared edge was greatly improved and the punch life is prolonged. However for shearing during hot, the structure of die sets becomes complicated, because hot punching including die quenching is generally a one-shot process, and thus increases the production cost. Moreover, the hole after hot punching is shrink during cooling, and thus the dimension is change.

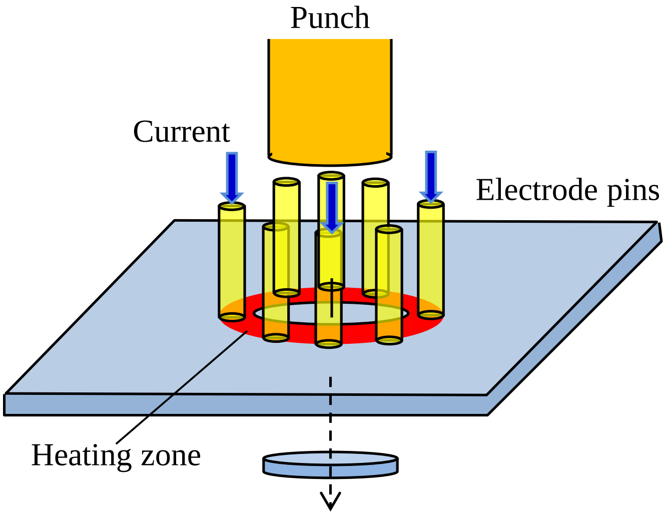


Fig. 1.11. Punching process of small hole using local resistance heating.

1.3.4. Laser cutting of die-quenched part

Although blank are hot stamped to make automobile body panels, it is not easy to punch or trim ultra-high strength steel parts that have been formed by hot stamping. Moreover, since the shape of blanks for the hot stamping parts are roughly determined by developing that of products, the dimensional accuracy of the edges of the stamped parts is not very high. Therefore, laser cutting and laser trimming are the most common, but expensive methods, used to make multiple holes on the body panel and to trim the excess and unnecessary areas of the quenched part [58-59]. Laser cutting is generally employed for the die-quenched parts to trim or cut the unnecessary portions or make holes on the blank. In the laser cutting process, the material is heated to its melting or vaporisation temperature by concentrating the beam energy in a very small spot. For laser cutting, the quality of the cut surface, including kerf width, the heat affected zone, and surface roughness of the blank are dependent on the various parameters such as cutting speed, power of the beam emitted by the generator, type of gas, the amount of pressure of the gas, laser pulse rate, laser pulse energy, etc. For parts having thicknesses of less than 1 mm, a good quality cut surface can be obtained by a high cutting speed of up to 7000 mm/s and a lower range of power of the beam between 200 W and 300 W. However, for parts thicker than 1 mm, a higher beam power of more than 300 W and a lower cutting speed of not more than 3000 mm/s are required to completely cut the part and produce a high quality cut surface. A high pulse rate, medium pulse energy and argon gas at high pressure assist with obtaining a high quality cut surface of the blank. [78-83]. In spite of its reliability for cutting high strength parts, the high energy consumption owing to the extensive production time in mass manufacturing, low productivity and high installation costs represent disadvantages in the use of laser cutting [84].

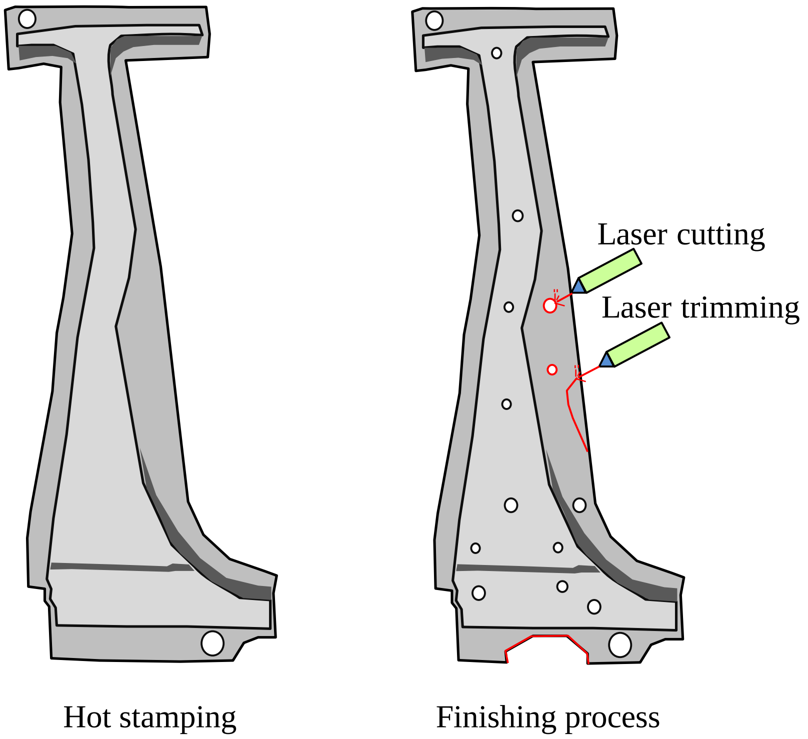


Fig. 1.12. Laser cutting and laser trimming on die-quenched centre pillar after hot stamping.

1.4 Cold punching of die-quenched steel sheet

Punching during hot is attractive to make hole on the hot stamped part. However the structure of die sets becomes complicated, because hot punching including die quenching is generally a one-shot process, and thus increase the production cost. In addition, it is not easy to design additional cooling channels for a fast cooling system. For mass production, the conventional punching process is more preferable for making multiple holes on hot stamped parts since it is fast and low in cost. A 5 to 10% of punch-die clearance is normally applied in the industry to ensure a good compromise between part edge quality and maximum blanking force. In the punching of die-quenched parts, it is important to optimize a punch-die clearance ratio of less than 20% of the thickness of the sheet to produce a good shear edge quality and minimize the formation of burr [85]. The chamfer angle of the punch has significant effects on the cutting force, tool stress and sheared edge quality in the trimming of die-quenched steel sheets [86-87]. In another approach, a quenchable steel sheet is semi-punched without the separation of punching scraps during hot stamping, and subsequently, the scraps are removed from the hot-stamped part at room temperature by means of conventional punching [88]. The same approach was applied to a half-trimmed sheet during hot stamping, and subsequently complete trimming was performed at room temperature to improve tool performance [89]. The combination of finish blanking and press shaving was found to be effective for producing high quality sheared edges in the blanking of the die-quenched part [90].

During punching of die-quenched steel parts, tool life is remarkably reduced by a large punching load. The worn tool brings about the deterioration, not only in the dimensional accuracy of the punched hole, but also in the quality of the sheared edge.

Studies on the development of new tool materials, tool surface treatments, and tool design have also been undertaken in order to enhance tool life. However the high cost of tool manufacturing and tool maintenance is still a barrier for its application. In addition, a delayed fracture is a risk for the cold punching of die-quenched parts [91-92]. The pre-existent cracks and defects generated at the cut edges due to laser cutting and shearing has a significant effect on the fatigue behaviour of die-quenched steel and ultra-high strength steel sheets [93-94].

1.5 Trimming of high strength steel sheet

Trimming of ultra-high strength steel parts is a process undertaken to separate the product and scrap portions. In the automotive industry, the part to trim is usually a car body panel which is drawn into a desired shape from a flat sheet. The body is held firmly between a die and a blank holder and then trimmed by a punch to remove the excess and unnecessary scrap portions (see Fig. 1.12). Trimming differs from blanking as the scrap-side of the body panel has little or almost a constraint-free condition during trimming. A significant bending occurs on the scrap-side, hence the deformation behaviour of the trimming part, and a stress concentration around the die edge are not the same as in blanking [95-96]. The quality of the trimmed edge, especially the formation of the burr, is important in the trimming process to minimize the tendency for edge fracture and varies for different materials [97-100].

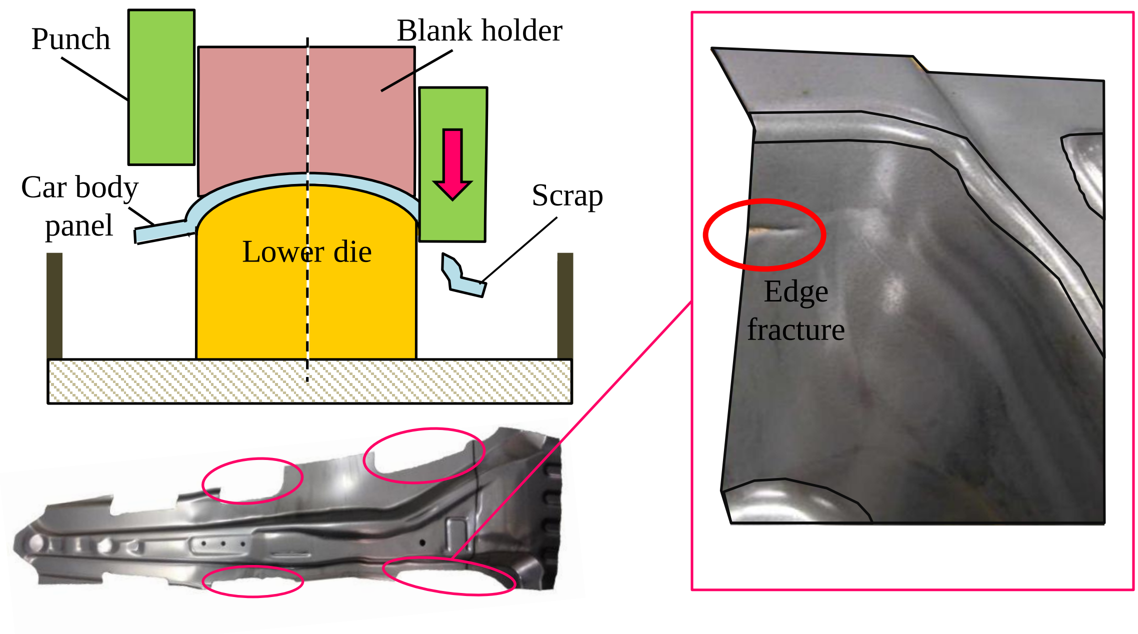


Fig. 1.13. Trimming of ultra-high strength steel panel and occurrence of edge fracture.

During the removal of the scrap portion, the noise generated during the trimming process is a problem especially with the trimming of hard material such as high strength steel sheets. An excessive exposure to noise, mainly on the shop floor, may affect the health of workers over the long-term. Not only the machine, but the process itself contributes to unsafe working conditions with its high level of noise. A 0olerable noise level in industrial plants is usually not more than 100 dB and a noise level of above 135 dB might result in hearing loss [101]. Although ear protection devices are compulsory, the level of sensitivity to dangers around the workplace is reduced in a high level noise pressure working area. For the workers, the noisy working area is very troubling and disturbing which, in turn, affects their job performance [101].

The use of a mechanical servo press having variable punch speed motion ability can reduce the noise level during the shearing of high strength steel sheet [102]. The flexible slide movement of the servo press has not only advantages in improving the forming limits and dimensional accuracy of the product in the bending, shearing, drawing, ironing and stamping of the steel sheets, but also in the reduction of noise because it does not produce strong vibration and impact noise [103]. In the blanking process using a conventional mechanical press, the sound pressure level during breakthrough is increased with an increase in the thickness of sheet metal and the blanking speed. However, the sound pressure level is decreased by 11% when blanking with a mechanical servo press when compared to a conventional mechanical press [104]. The hydraulic inertia damper and Magneto-rheological dampers are utilized in the press machine to reduce noise and vibration, and to withstand the break through shock generated during blanking operations [105-106].

1.6. Research objectives

1.6.1. Improvement of quality of sheared edge in punching of die-quenched steel sheets

The aim of this study is to develop a small clearance punching process for die-quenched steel sheet using a punch having a small round edge in order to improve the quality of the sheared edge surface. The tensile stress in the shearing region during punching is reduced by a small clearance. The small round edge of the punch has a function to relieve the concentration of deformation around the edge of the punch, and thus the onset of the crack from the edge of the punch is prevented. Since the small clearance is a problem for the concentric condition of the die to the punch during punching, an automatic centring punching process using a moving die was developed to automatically correct the eccentricity of the die to the punch. By setting a gap between the moving die and holder, the die shifts by an imbalanced force, and the punch and die become concentric after several strikes.

1.6.2. Reduction of noise and flying speed and prevention of edge fracture and chipping in trimming of ultra-high steel sheets

The ultra-high strength steel sheet parts usually require a post finishing process such as trimming to remove the scrap portions and it is not easy to cut the ultra-high strength steel sheet parts. In trimming of ultra-high strength steel sheets, the flying speed is large due to the high strength, and thus the scraps jump out from a disposal box. The trimming operation also becomes noisy due to high trimming load. In this study, an attempt to reduce the fall velocity of the scrap and noise level using a gradient trim punches was developed. In addition, the edge fracture and chipping on the trimmed edge of the sheet were also investigated and the method of prevention is introduced.

1.7. Outline of dissertation

This dissertation discusses about the small clearance punching process of die-quenched steel sheets, followed by the automatic centring in small clearance punching process and continues with repeated small clearance punching with automatic centring. The reductions of flying speed of scrap and noise in trimming of ultra-high strength steel sheets is discussed in the following chapter. Finally, the prevention of chipping and edge fracture in trimming of ultra-high strength steel sheets is presented. This dissertation consists of seven chapters:

Chapter 1 presents the general introduction of the contents of the thesis.

Chapter 2 presents the small clearance punching process of the die-quenched steel sheets using a punch having a small round edge to improve the quality of the sheared edge surface. By small clearance, the tensile stress in the shearing region during punching is reduced. In addition, the concentration of deformation around the edge of the punch was relieved by the punch having small round edge, and thus the onset of cracks is delayed for die-quenched steel sheets having small ductility.

Chapter 3 presents an automatic centring with moving die for cold small clearance punching of die-quenched steel sheets. A moving die was utilised to automatically correct the eccentricity of the die to the punch. By setting a gap between the moving die and holder, the die shifts by imbalanced force, and the punch and die become concentric after several strikes. The effect of punching without centring and with automatic centring thickening on the fatigue strength and delayed fracture is examined.

Chapter 4 presents the repeated punching of die-quenched and ultra-high strength steel sheets by automatic centring. The comparison of the quality of sheared edge for punching without centring and with automatic centring is shown. The performance of the punch in the repeated punching process of die-quenched steel sheet is investigated and the method to increase the punch life is also introduced.

Chapter 5 presents the investigation on the shearing and flying behaviour and the noise level in trimming of ultra-high strength steel. The effects of clearance, trimming speed and strength of the sheet were also examined. The new punch shapes are introduced to reduce the flying speed of the scrap and the noise level.

Chapter 6 presents the investigation of chipping and edge fracture in trimming of ultra-high strength steel sheets having curved shape. The coil spring and punch with an inclined angle are used to prevent the occurrence of chipping and edge fracture of trimmed edge of the sheet.

Finally, concluding remarks and future prospective are given in Chapter 7.

Chapter 2
Small clearance punching of die-quenched steel sheets by punch having small round edge

2.1. Introduction

Vehicle ownership has rapidly increased year after year; leading to an increase in demand for much more fuel efficient and higher safety standard cars [1-9]. The requirement for reduction in vehicle weight and higher safety standards has increased the use of lightweight material in car body manufacturing. New forming processes and the optimization of design for lightweight materials have been actively developed over the last two decades in order to reduce overall production costs [10-13]. Aluminium, magnesium and titanium alloy sheets are attractive lightweight materials offering a significant reduction in vehicle weight and overall quality improvement for the automobile, however high costs and small formability present problems [14-39] and consequently industry still has a great interest in steel sheets.

Body-in-white parts, made of ultra-high strength steel sheet, are generally punched to make holes for joining, paint removal, attachment, etc. With cold punching of ultra-high strength steel sheets, having a tensile strength of above 1 GPa, tools tend to wear and chip due to the large punching load, and thus tool life is short [44-52]. Accordingly, the quality of the sheared edge in the punching of ultra-high strength steel sheet deteriorates. Since the onset of cracks in the shearing is early due to the small ductility, the rough fracture surface increases [85-94].

Hot stamping of quenchable steel sheets is effective in solving the problems of cold forming of ultra-high strength steel sheet. Heated steel sheets are hot-stamped and then the stamped sheets are die-quenched by holding at the bottom dead centre of a press, to produce parts that have a tensile strength of above 1.5 GPa [58-59]. Although hot stamped parts are punched and trimmed for finishing, it is difficult to shear hot-stamped parts at room temperature due to their high tensile strength. The decrease in tool life and the occurrence of delayed fractures are particular problems. Therefore, laser cutting is generally used for hot stamping parts [78-83]. In spite of being reliable for shearing high strength parts, high energy consumption due to lengthy production time in mass manufacturing, low productivity and high installation costs present disadvantages with laser cutting [84] and thus, shearing processes are desired.

In the present study, a cold small clearance punching process of die-quenched steel sheets by punch having small round edge was developed to improve the quality of the sheared edge. The effects of the clearance, punching speed and corner radius of the punch on the quality of the sheared edge were investigated.

2.2. Small clearance punching with punch having small round edge

2.2.1. Effects of small clearance and small round edge

To improve the quality of sheared edges in cold punching of ultra-high strength steel sheets, a small clearance punching process using a punch having a small round edge was developed. The effects of small clearance and small round edge of the punch are shown in Fig. 2.1. By the small clearance, the tensile stress in the shearing region during punching is reduced (see Fig. 2.1(a)), and thus the onset of cracks is delayed for ultra-high strength steel sheets having small ductility. For the small round edge of the punch, the concentration of deformation around the edge of the punch was relieved, and thus the onset of the crack from the edge of the punch is prevented (see Fig. 1(b)).In addition, the small round edge has the functions of avoiding chipping of the tools in small clearance punching without direct contact between the punch and die.

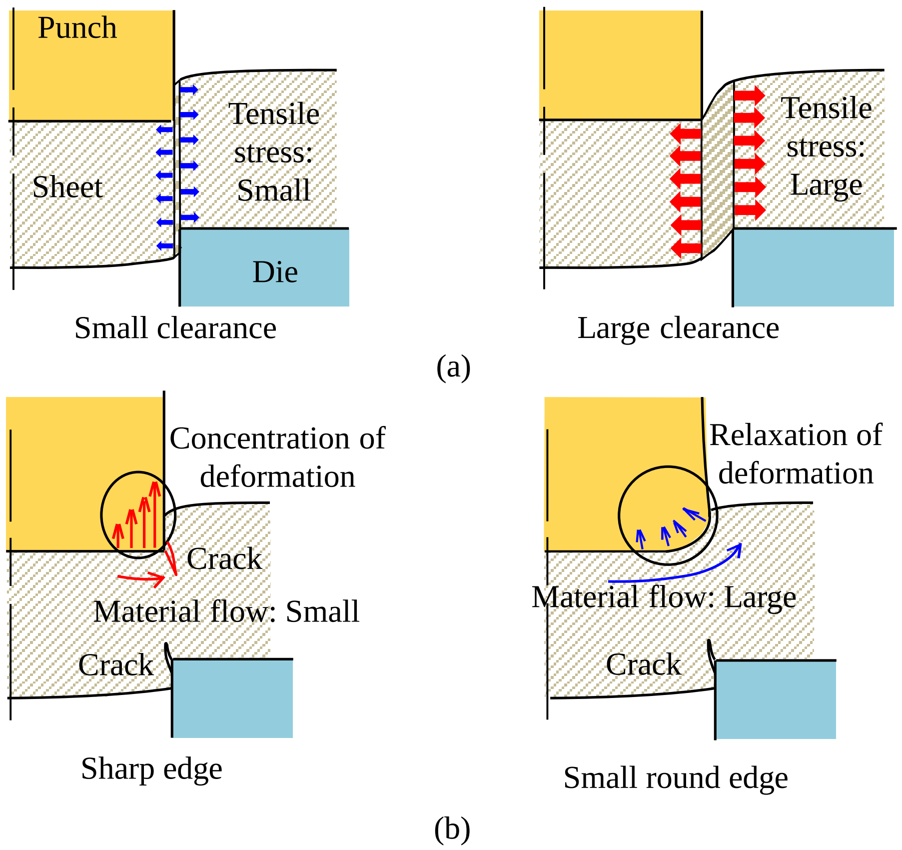


Fig. 2.1. Effects of (a) clearance and (b) round edge of punch.

2.2.2. Experimental procedure

The tool used for small clearance punching of die-quenched steel sheets using a punch having a small round edge is given in Fig. 2.2. The punch is attached to the punch holder and the die was held by the die holder. The die-quenched steel sheet was manually fed into the punching zone.

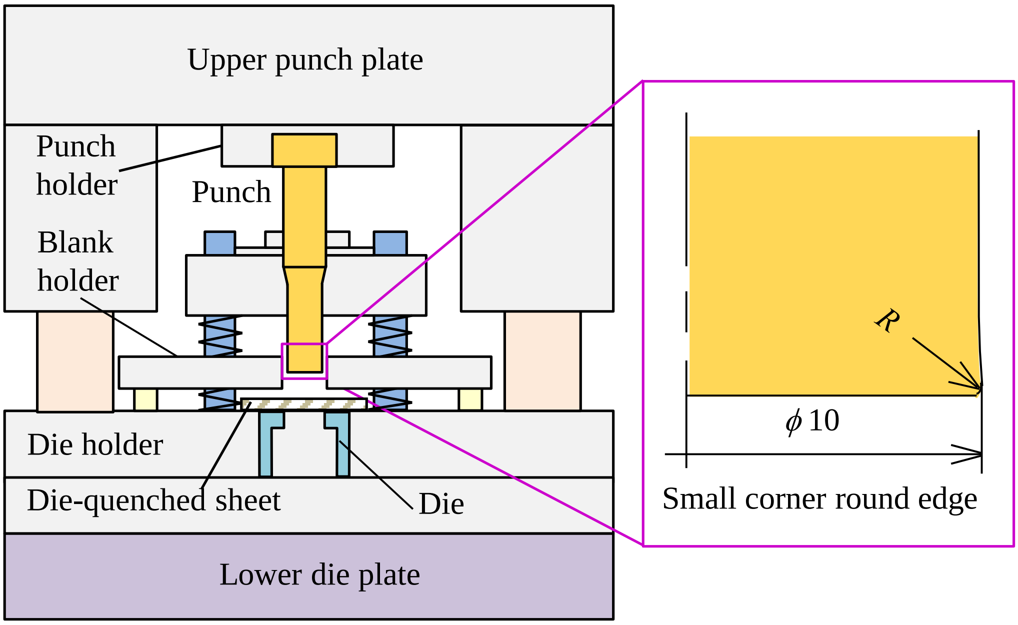


Fig. 2.2. Tools for small clearance punching of die-quenched steel sheets.

The four punches having a different round edge radius are shown in Fig. 2.3. The radius of the punch, *R* used for the experiment were 0, 0.15, 0.3, and 0.5 mm. The different radii of the small round edge of the punch were used to investigate the effects of the radii size on the quality of the sheared edge of the sheet.

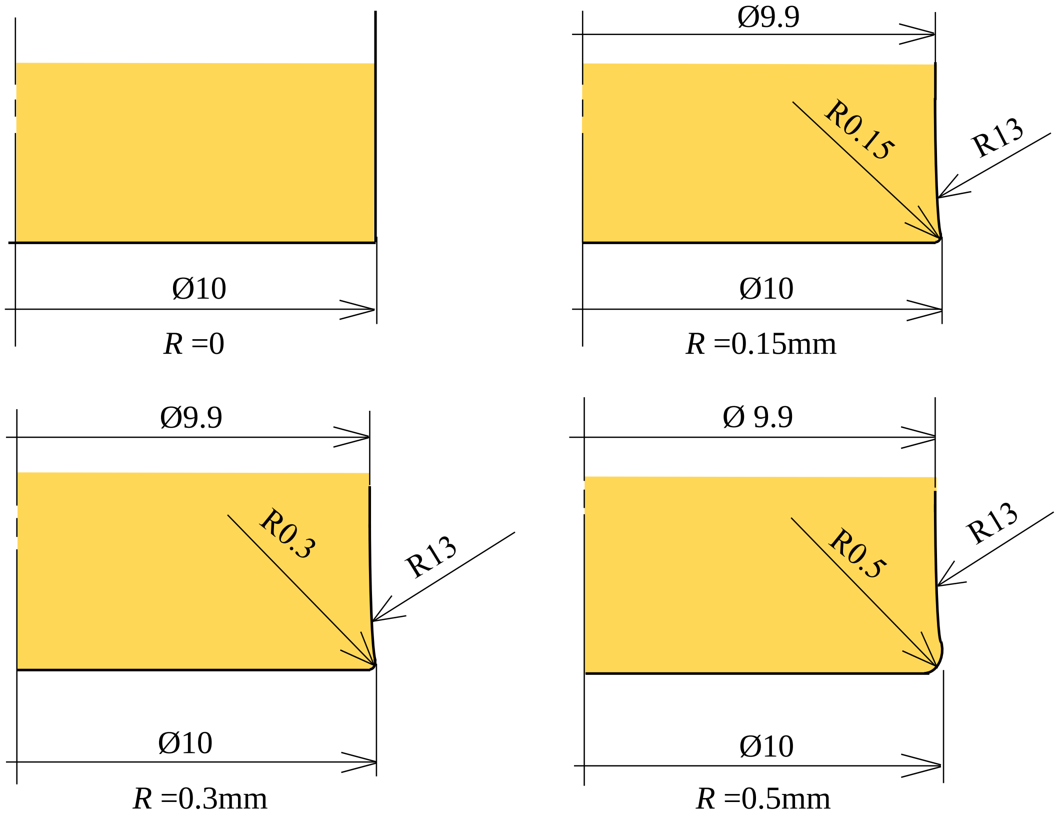


Fig. 2.3. Punches used in small clearance punching of die-quenched steel sheet.

The mechanical properties of the die-quenched steel sheet used for the experiment are given in Table 5.1. The tensile strength and hardness of the die-quenched steel sheet as received were 1504 MPa and 504HV20, respectively. The length, width, and thickness of the sheet were 60, 40, and 1.2 mm, respectively as shown in Fig. 2.4.

Table 2.1.

Mechanical properties die-quenched steel sheet used for small clearance punching.

Material	Thickness [mm]	Tensile strength [MPa]	Elongation [%]	Hardness [HV20]
Die-quenched steel sheet	1.2	1504	5.0	504

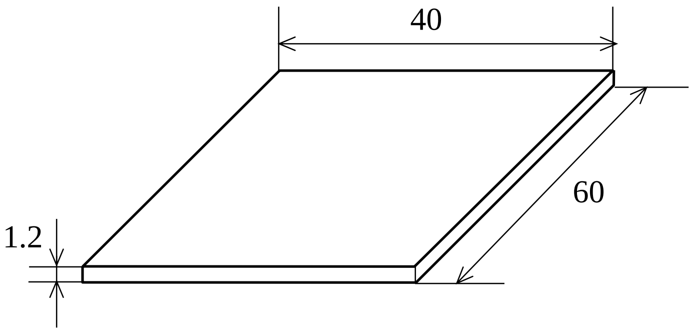


Fig. 2.4. Dimension of die-quenched steel sheets for small clearance punching.

The conditions of small clearance punching of the die-quenched steel sheet are given in Table 2.2. The sheets were punched with a TiAlN-coated punch using an 800 kN CNC servo press. The Vickers hardness of the TiAlN-coated punch was 3500 HV. The clearance of the small punching process was set for 0.8% of the sheet thickness (10 μm) and the clearance ratio of 10 % (120 μm) was employed for the comparison. The punching speed was varied from 0.03 until 75 mm/s.

Table 2.2.

Conditions of punching of die-quenched steel sheets.

Punch material	TiAlN-coated SKH51
Die material	SKD11
Clearance to thickness ratio, c [%]	0.8, 10
Punching speed [mm/s]	0.03-75

2.3. Results of small clearance punching of die-quenched steel sheets

2.3.1. Shearing behaviour for different punch radius

The effects of the edge radius of the punch on the deformation and shearing behaviour of the die-quenched steel sheet during punching are given in Fig. 2.5, where *s* is the punch stroke. For punch having *R* = 0 and 0.13mm, the cracks were caused from both of the punch and die edges, observed for *s* = 0.5 and 1.0 mm, respectively. The crack was only initiated from the edge of the die for the punches of *R* = 0.3 and 0.5 mm. The small round edge of the punch relieved the concentration of deformation around the edge of the punch, and thus the onset of the crack from the edge of the punch was prevented. However too small round edge i.e. *R* = 0.15 mm was not enough to prevent the initiation of crack from the edge of the punch.

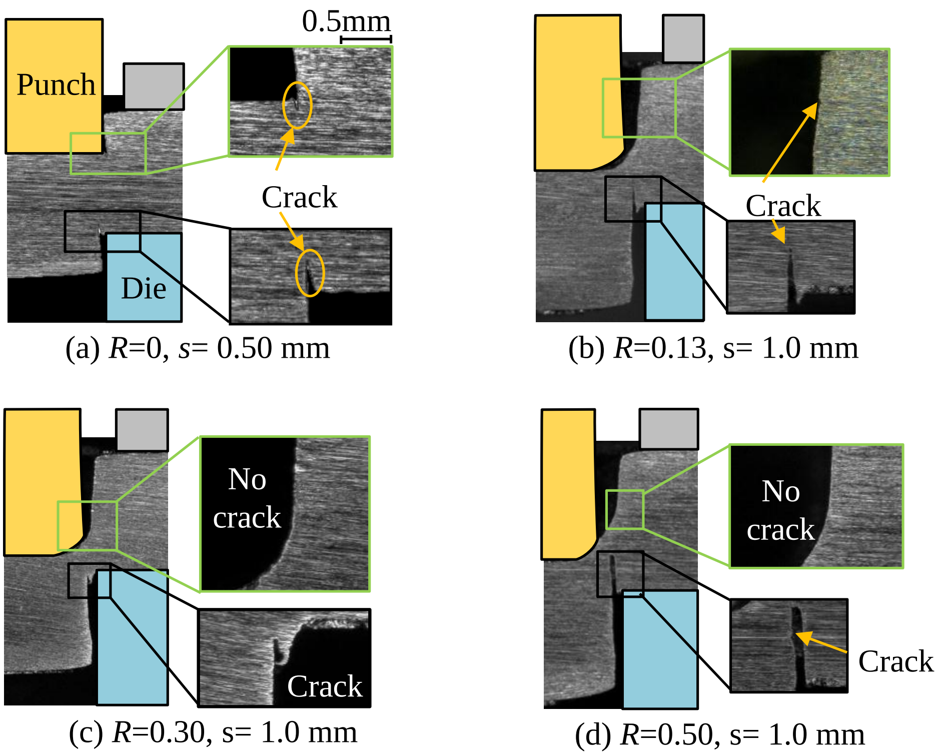


Fig. 2.5. Deformation and shearing behaviour of die-quenched steel sheet for different punch edge radius.

The punching load-stroke curves for the different radius of the punch are shown in Fig. 2.6. The maximum punching load all punches were almost the same and occurred around 0.7 mm of the punch stroke. However for the larger punch radius R = 0.5 mm, the maximum punching load was larger.

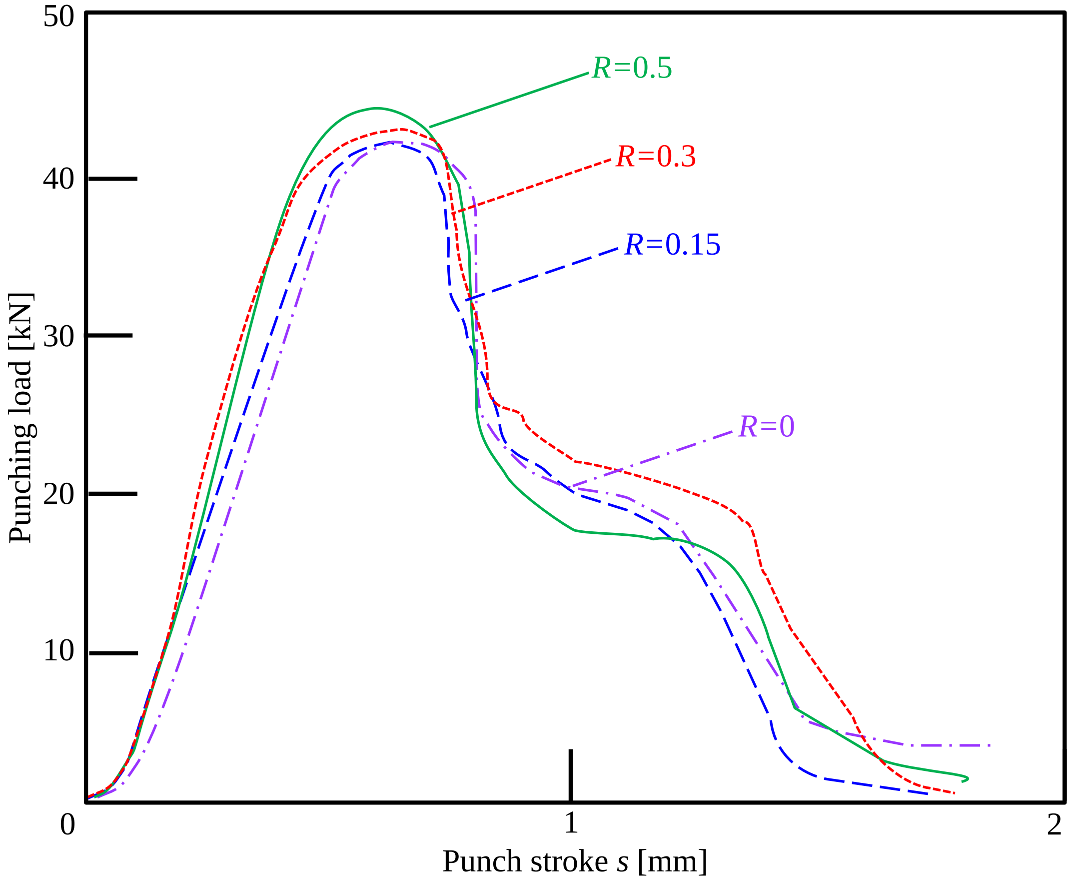


Fig. 2.6. Punching load-stroke curves for different radius of punch.

2.3.2. Effects of clearance

The surface and cross-section of sheared edge of the die-quenched steel sheets punching for clearance c = 10 and 0.8 % are given in Fig. 2.7 and 2.8, respectively. The punching speed chosen was 0.03 mm/s for both punching conditions. The fracture surface of punching c = 10 % was larger than that of c = 0.8 % for all punch radii.

However for R = 0.15 mm, since the linkage of the cracks initiated from both edges of the punch and die, the secondary burnished and fracture surfaces were caused, and the boundary with the fracture surface has a difference in level. For R = 0.13 and 0.33 mm as the crack only from the edge of the die, the secondary burnished surface does not appear, and however, the burnished surface larger was larger for c = 0.8 %. It was found that the small clearance is effective to generate a large shiny burnished surface on the sheared edge.

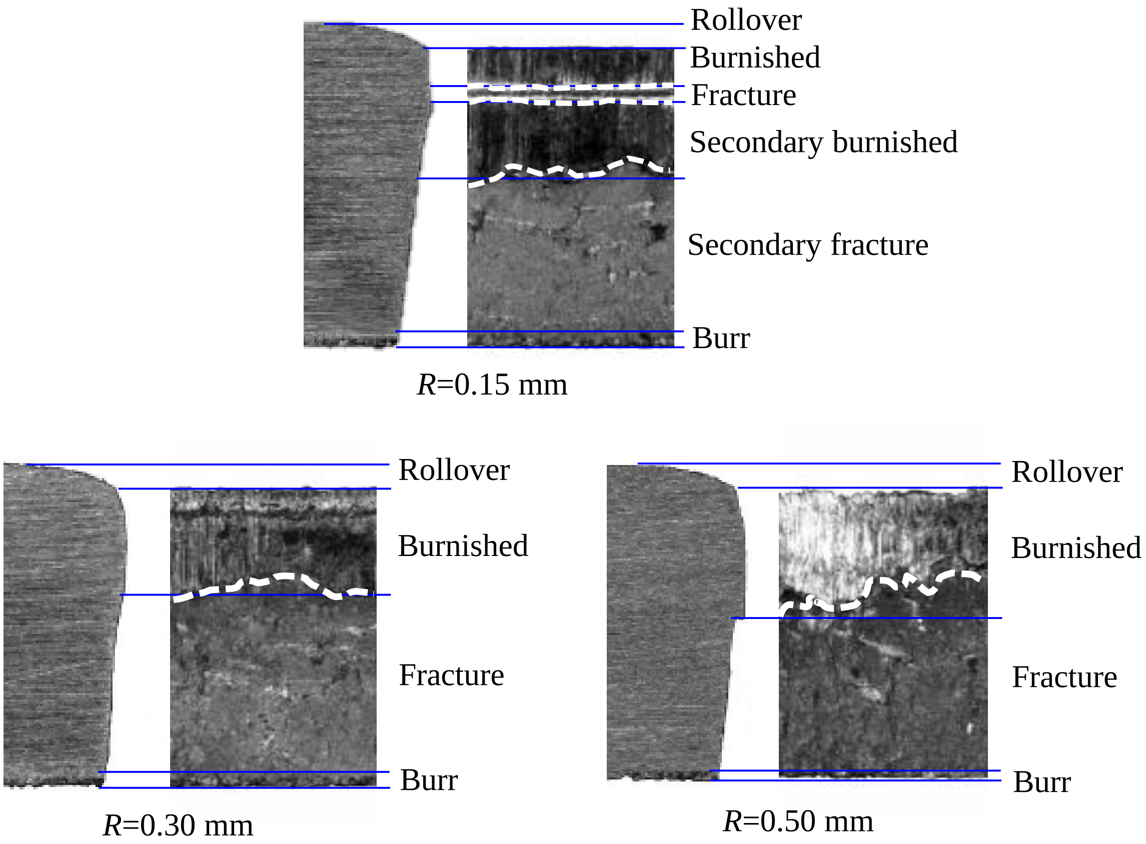
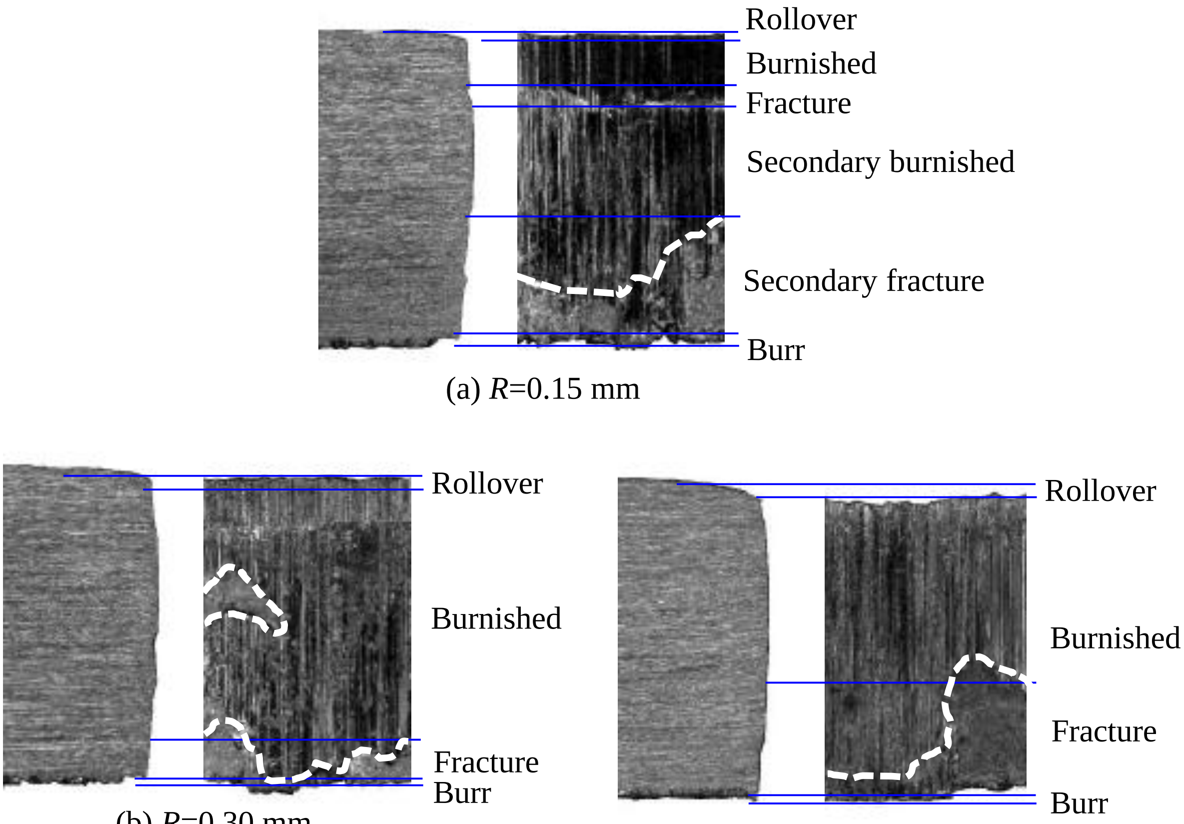


Fig. 2.7. Surface and cross-section of sheared edge of die-quenched steel sheets punching for c = 10% and v = 0.03 mm/s.



(a) *R*=0.15 mm

(b) *R*=0.30 mm

(b) *R*=0.30 mm

Fig. 2.8. Surface and cross-section of sheared edge of die-quenched steel sheets punching for *c* = 0.8 % and *v* = 0.03 mm/s.

2.3.3. Effects of punching speed

The effects of the punching speed on the deformation and shearing behaviour of the die-quenched steel sheet for R = 0.15 mm are shown in Fig. 2.9. For a slow punching speed, the cracks were initiated from both of edges of the punch and die for v = 0.03 and 1 mm/s. In the industrial operation, the punching speed is much higher for a higher production rate and therefore, a realistic punching speed of v = 75 mm/s was chosen. For v = 75 mm/s, no crack initiated from the edge of the punch and thus produced a much higher quality of sheared edge in small clearance punching of die-quenched steel sheet.

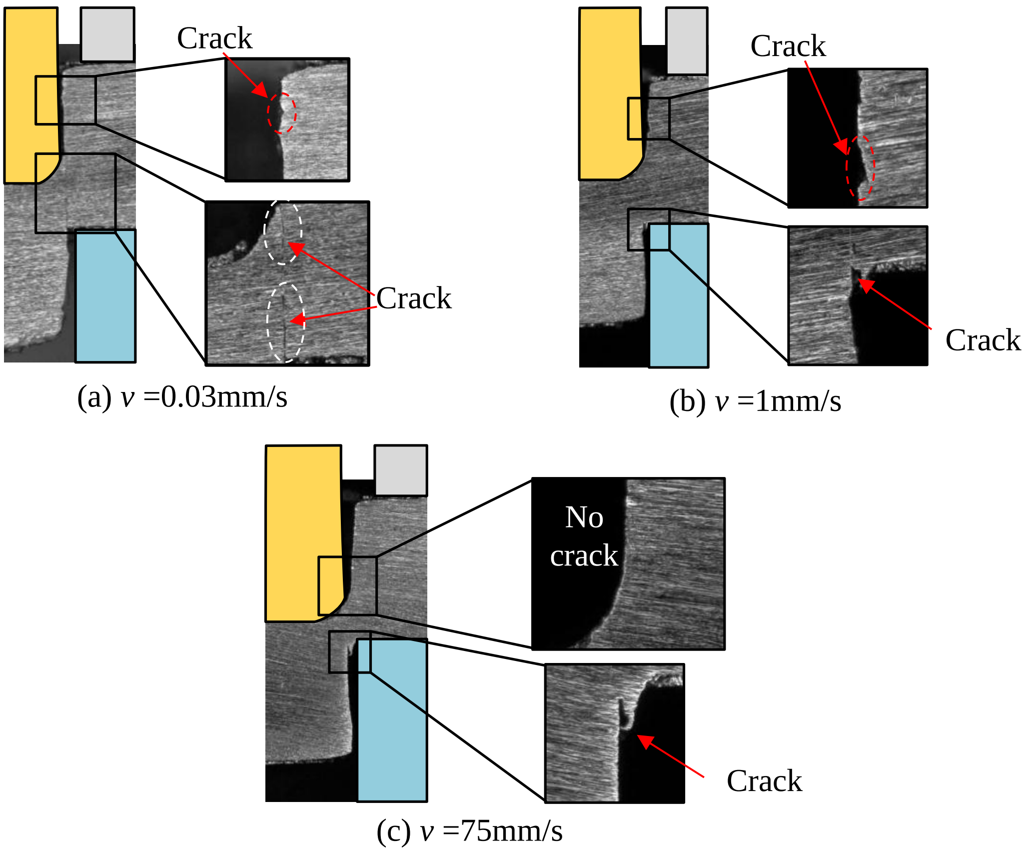


Fig. 2.9. Effect of the punching speed on deformation and shearing behaviour of die-quenched steel sheet for R = 0.15 mm.

The percentages of rollover, burnished and fracture depths and burr height on sheared edge of the die-quenched steel sheet for different radii and v = 75 mm/s are illustrated in Fig. 2.10. For punch having R = 0.15 mm, the sheared edge consisted of both secondary burnished and fracture surfaces, which was undesirable characteristic for a good sheared edge. For punching with R = 0.3 and 0.5 mm, a large burnished and small fracture surfaces were produced. The extent of the deformation zone is depends on the punching speed. The high punching speed make the heat generation by plastic deformation confined to a smaller zone. Thus, the sheared zone is narrower, and the sheared edge surface becomes smoother.

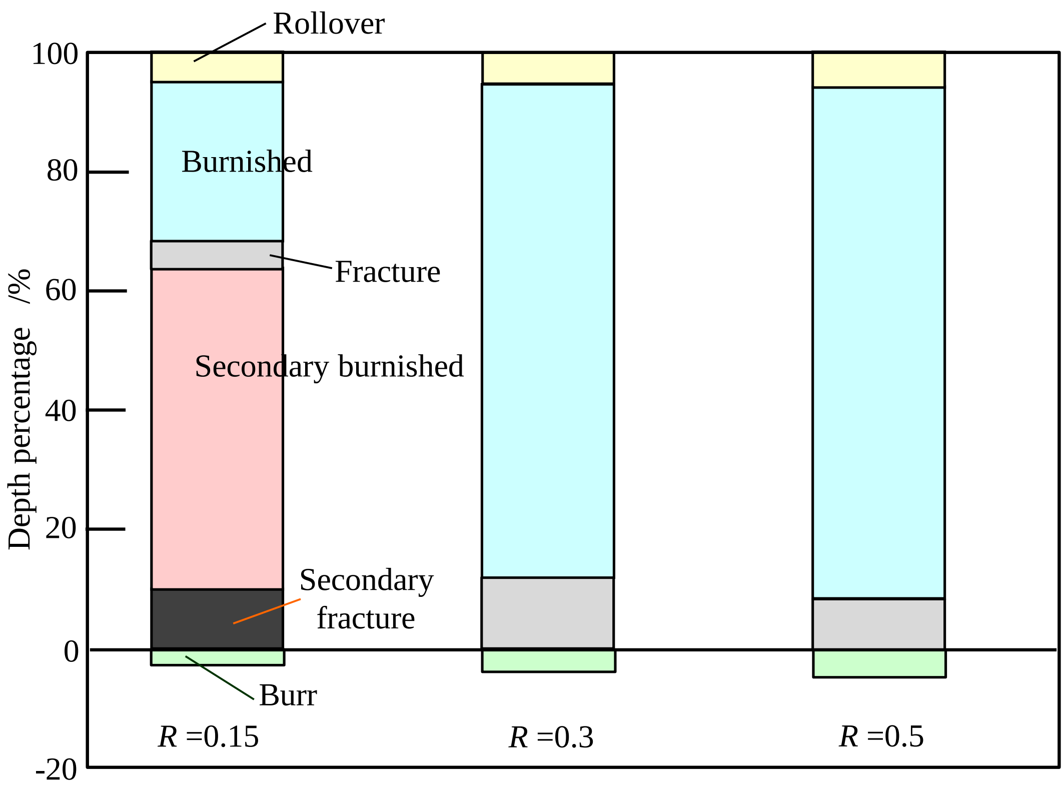


Fig. 2.10. Percentages of rollover, burnished and fracture depths and burr height on sheared edge of die-quenched steel sheet for different radii and v = 75 mm/s.

The relationship between depth percentages of the sheared edge surface and punching speed for R=0.3 mm is shown in Fig. 2.11. The punch with R = 0.3 mm was chosen as it produced lowest punching load among the four radii and large burnished surface. The fracture surface was decreased with the increase of the punching speed. However for v range from 0.03 until 10 mm/s, the fracture surface unevenly distributed on the circumference direction of the sheared edge.

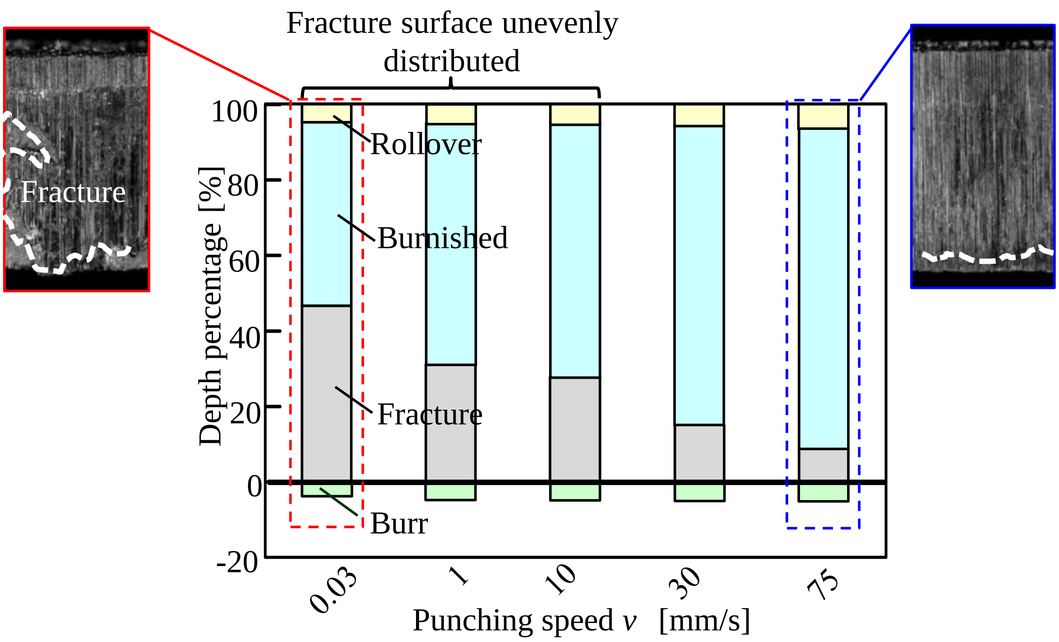


Fig. 2.11. Relationship between depth percentages of sheared edge surface and punching speed for R=0.3 mm.

The relationship between the diameter of the punched hole and the punching speed for different punch radius are given in Fig. 2.12. The diameter of the punched hole is less than 10 mm i.e. the punch diameter due to elastic recovery of the hole after punching. However hole diameter was not much change for the increase of punching speed. For *R* = 0.5 mm, the larger corner radius of the punch make the punched hole smaller as compared to the other punches.

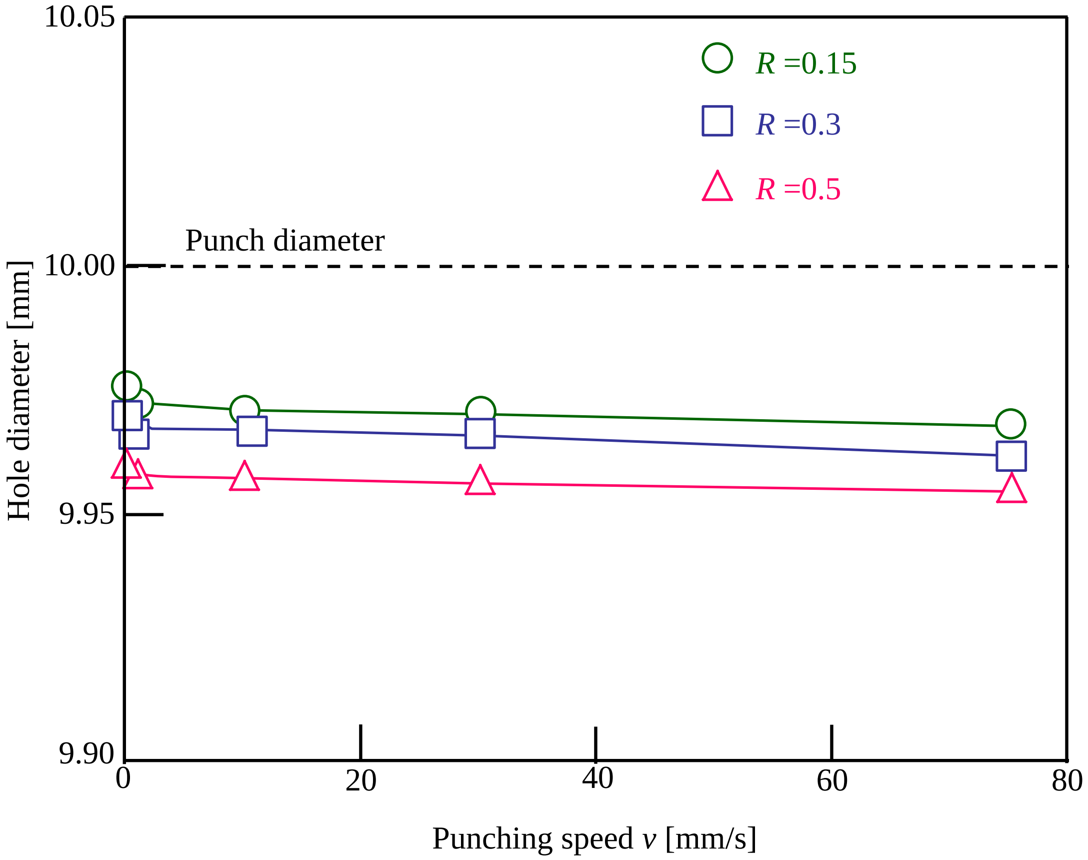


Fig. 2.12. Relationship between diameter of punched hole and punching speed for different punch radius.

2.4. Strength of punched sheet

2.4.1. Average Vickers hardness

The distributions of Vickers hardness in the thickness direction around the sheared edge for different punching speed and punch radius are shown in Fig. 2.13. The hardness was measured in the cross-section at 0.08 mm from the sheared edge and for every 0.1 mm from the surface in the thickness direction. The hardness around the sheared edge was increased as compared to the original hardness of the sheet due to the influence of ironing with the punch which caused work-hardening. The punching speed has less effect on the hardness of the shearing zone.

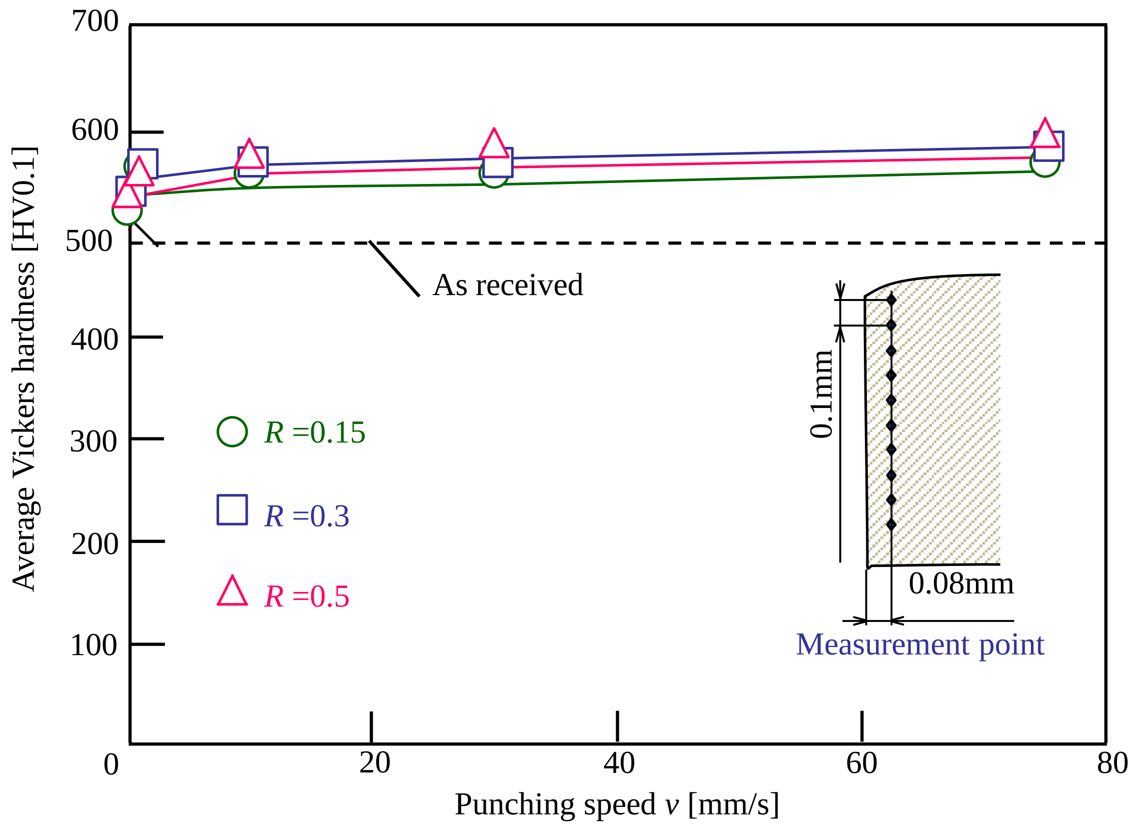


Fig. 2.13. Distributions of Vickers hardness in thickness direction around sheared edge for different punching speed and punch radius.

2.4.2. Delayed fracture

Punched high strength steel sheets have the risk of delayed fracture, particularly for die-quenched steel sheet. The effect of clearance on the delayed fracture was examined by immersing the punched sheets in 35% concentration hydrochloric acid at room temperature, where the delayed fracture time is the time from the soak of the sheet in the 35 % concentration hydrochloric acid to the visual observation of cracks. The occurrence of cracks was visually observed and time for the crack to appear was taken. The procedure for delayed fracture test is shown in Fig. 2.14. The occurrence of delayed fracture was accelerated with the high concentration of the acid.

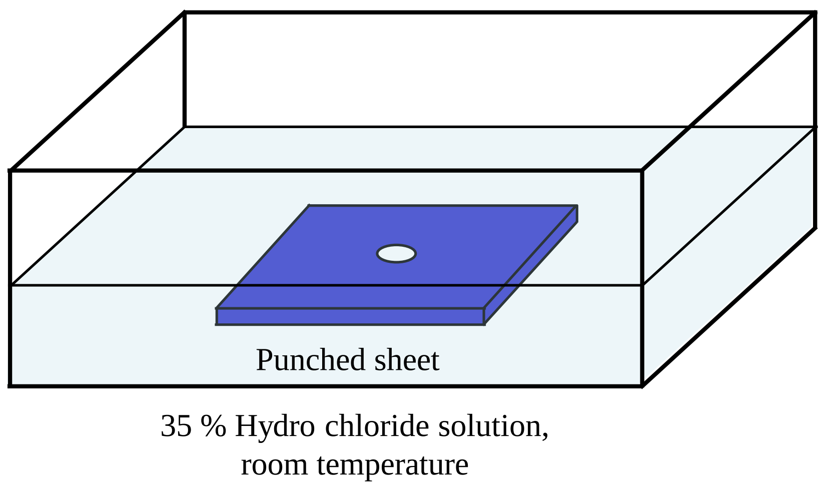


Fig. 2.14. Procedure for delayed fracture test by 35% concentration of hydrochloric acid.

The delayed fracture times for punching die-quenched steel sheets with different punch radius and c = 0.8 and 10% are given in Fig. 2.15. For c = 10 %, the cracks were observed just after 2.5 and 4 hours after immersion. Since the rough fracture surface in the sheared edge for c = 10 % was large, the containing microcracks becomes large, and thus the hydrogen tends to diffuse. For c = 0.8 % the delayed fracture was prevented for all punch radii. The large burnished surface increases the compressive stress and thus prevent delayed fracture.

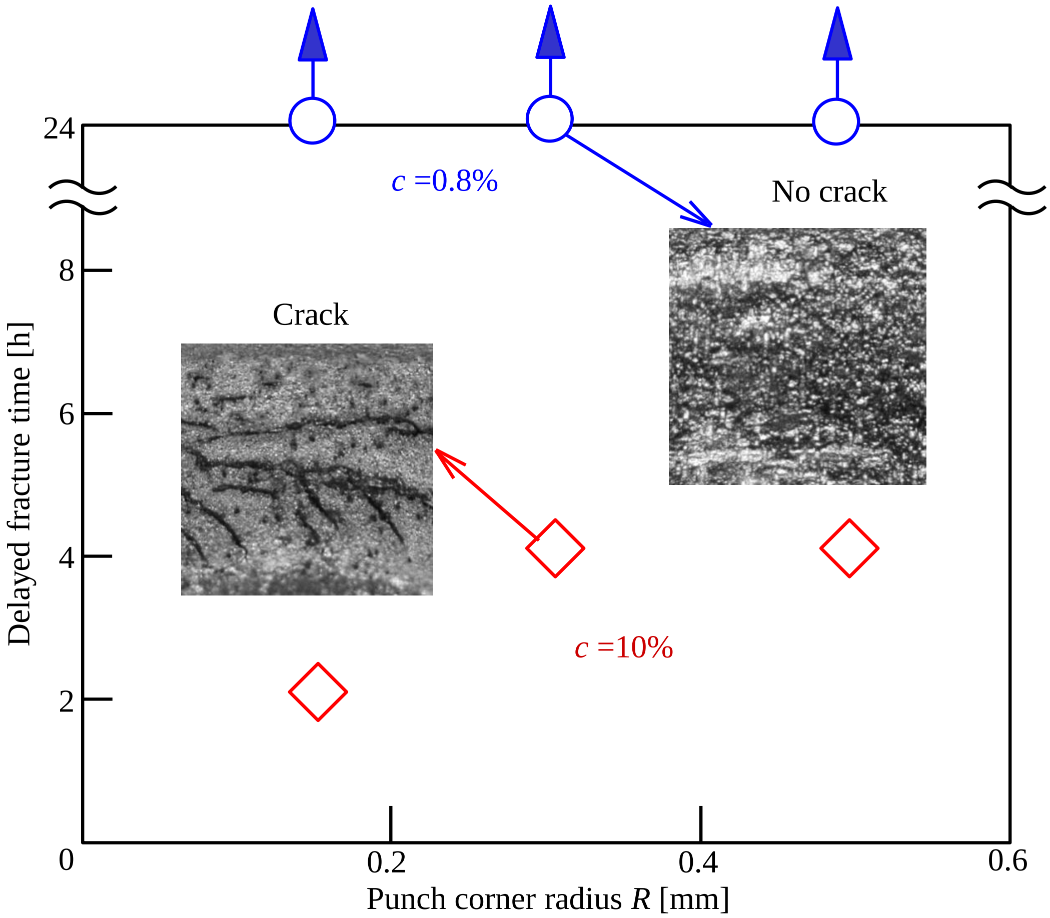


Fig. 2.15. Delayed fracture times around sheared edge for punching with different clearance.

2.5. Conclusions

In this study, a small clearance punching process of die quenched steel sheets using punch having a small corner radius was developed to improve the quality of the sheared edge. The influence of the shape of the punch and head on the quality of the sheared edge was investigated. In addition, effects of the clearance, punching speed and corner radius of the punch on the quality of the sheared edge were investigated. The results are summarized as follows:

1) The concentration of deformation around the edge of the punch was relaxed by the small round edge, the onset of a crack from the edge of the punch was prevented, and thus the burnished surfaces became considerably large.
2) The too small corner radius of punch of R = 0.15 mm caused occurrence of secondary burnished and secondary fracture surface at the sheared edge.
3) The quality of the surface of sheared edge is improved surface for punching with punch having corner radius of at least 0.3mm where no secondary burnished and secondary fracture surface was observed at the sheared edge.
4) The large burnished surface for punching with R=0.3 mm was limited to the small clearance between the punch and die and high punching speed of above above 30 mm/s.
5) The large burnished surface at the sheared edge for punching with a small clearance increases the compressive stress and thus prevents delayed fracture.

Chapter 3
Automatic centring in small clearance punching of die-quenched steel sheets

3.1. Introduction

The use of steel sheet having a tensile strength of more than 1 GPa for car bodies have increased remarkably [40-43]. Although parts made of ultra-high strength steels have superior mechanical properties, the stamping operation becomes difficult with an increase in the strength of the sheet. The forming load and springback characteristic becomes very large, and formability is decreased considerably [47-52].

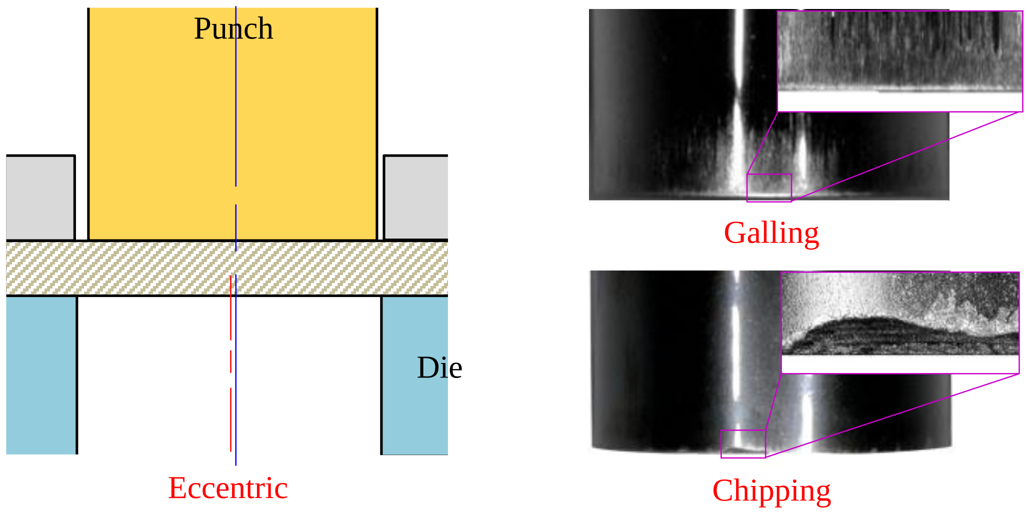
In cold punching of ultra-high strength steel sheets, a small clearance punching process using a punch having a small round edge [107] was developed to improve the quality of sheared edges. By the small clearance, the tensile stress in the shearing region during punching is reduced, and thus the onset of cracks is delayed for ultra-high strength steel sheets that have small ductility. The small round edge functions to avoid chipping of the tools in small clearance punching without direct contact between the punch and die. In addition, the concentration of deformation around the edge of the punch is relieved by the small round edge, and thus the onset of the crack from the edge of the punch is prevented.

Although ultra-high strength steel sheets below 1200 MPa in tensile strength were punched under a small clearance with the punch having a small round edge, the deformation behaviour for die-quenched parts of 1500 MPa is severer [85-94]. In small clearance punching, it is not easy to set the punch and die concentrically, and thus the punch tends to become eccentric to the die.

In the present study, an automatic centring process in small clearance punching of die-quenched steel sheets having high strength and low ductility was developed. The effectiveness of this method for improving the quality of the sheared edge of die-quenched steel sheets was investigated and compared against punching without centring.

3.2. Problem in small clearance punching

To punch die-quenched parts of 1500 MPa in tensile strength, a small clearance punching process using a punch having a small round edge was developed (Chapter 2) to improve the quality of the sheared edge. In punching of die-quenched steel sheet, although the sheets were punched under a small clearance with the punch having a small round edge, the deformation behaviour for die-quenched parts of 1500 MPa is severe. Since the clearance is small, it is not easy to set the punch and die concentrically, and thus the punch tends to get eccentric to the die as shown in Fig. 3.1. In addition, the punch is deflected by high punching load during punching. This brings about the tool failures such as galling and chipping and low quality of the sheared edge.



(a) Difficult tools setting: punch and die eccentric

(b) Tool failure: galling, chipping, etc.

Fig. 3.1. Problems in small clearance punching of die-quenched steel parts.

3.3. Automatic centring for small clearance punching

3.3.1. Approach of automatic centring

To punch die-quenched parts of 1500 MPa in tensile strength under a small clearance, a punching process having automatic centring with a moving die was developed (see Fig. 3.2). Initially the punch and moving die are eccentric, and thus the left and right clearances between the punch and die are different. When the left clearance is larger than the right one, the force acting to the right half of the die during punching is larger than that to the left half. The moving die slightly shifts right, because the slight gap is set between the moving die and die holder. As the die shifts, the imbalanced force expressed as a difference between the left and right forces decreases, and finally the punch and die become concentric

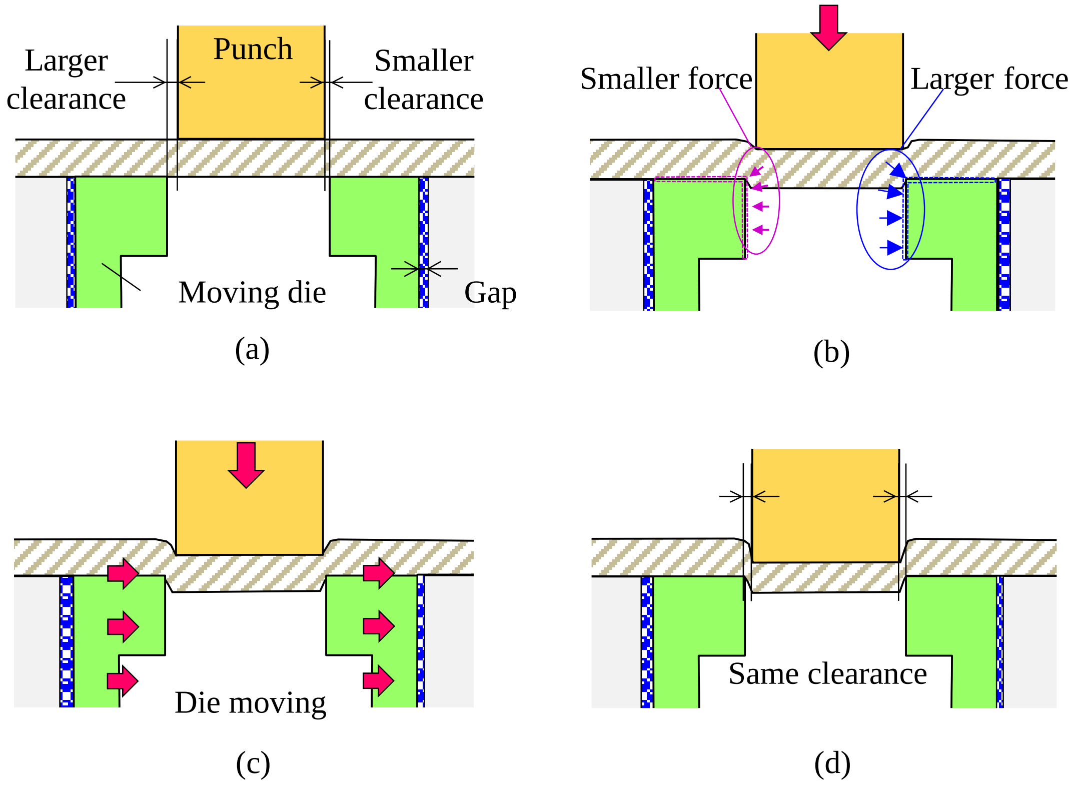
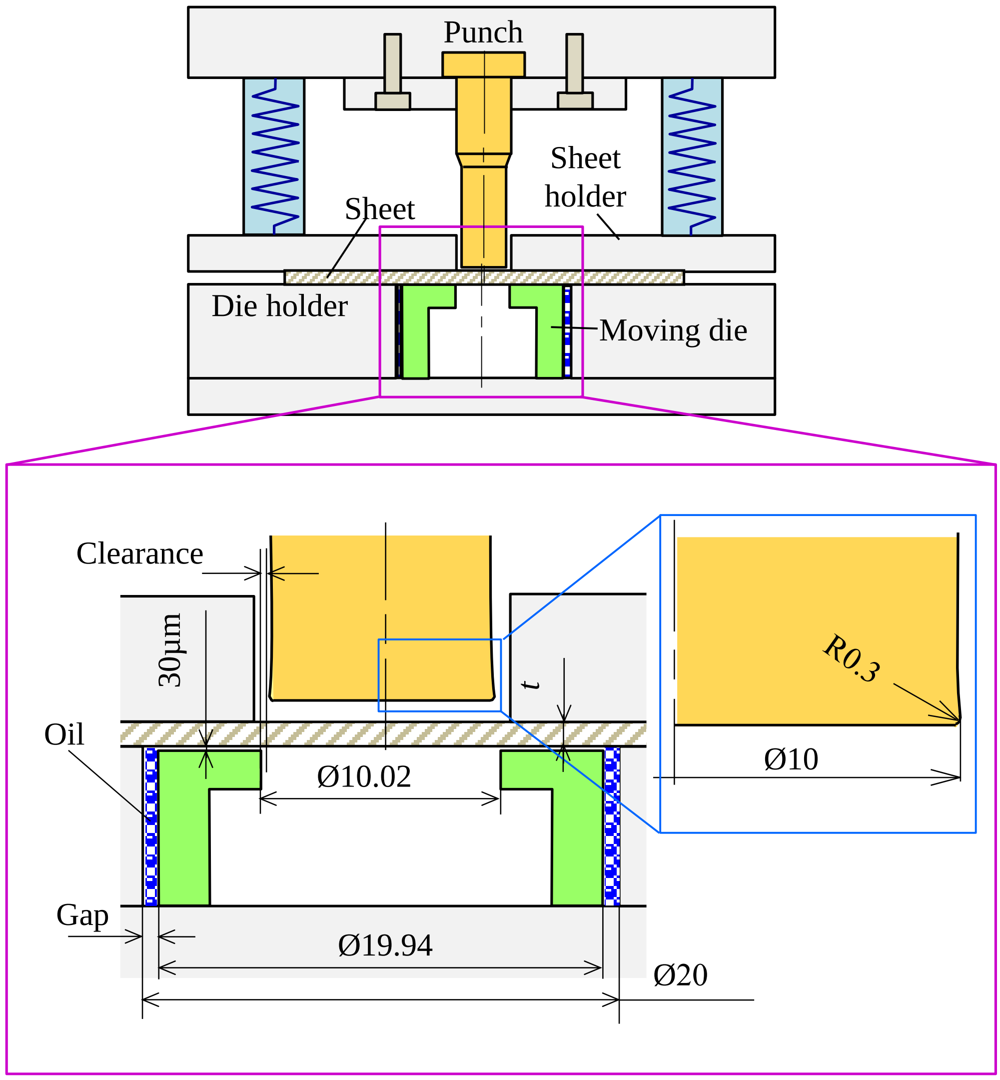


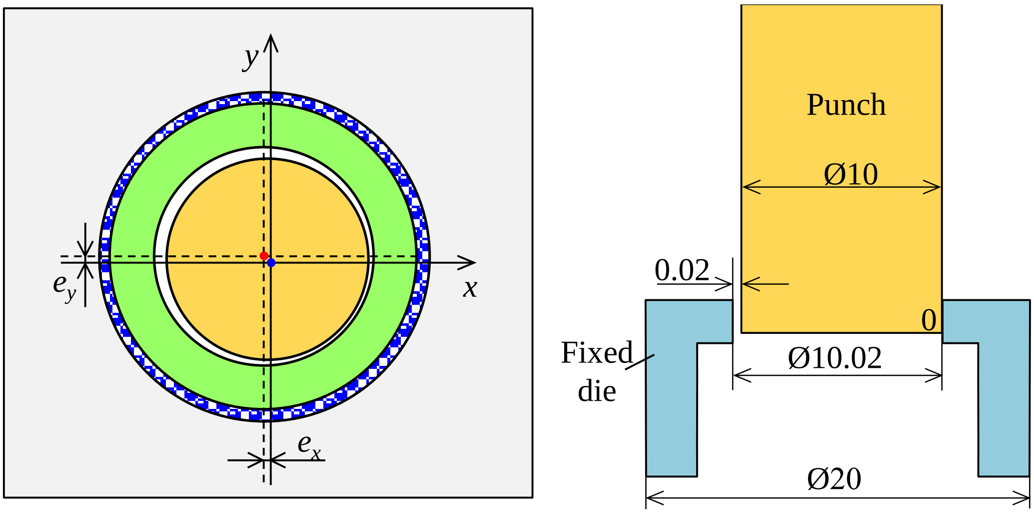
Fig. 3.2. Approach for automatic centring with moving die in small clearance punching using punch having small round edge. (a) Initial eccentricity of punch and moving die, (b) action of different left and right forces, (c) shift of moving die and (d) concentricity of punch and moving die.

3.3.2. Experimental procedure

The dimensions of the tools used for automatic centring are illustrated in Fig. 3.3 (a), where e_x and e_y are the eccentricities of the die to the punch in the x and y-directions, respectively (see Fig. 3.3 (b)). The punch having a small round edge was used to prevent the contact between the punch and die during punching. The diameter of the punch and the inner diameter of the die were 10 and 10.02 mm, respectively. In the concentric condition, the clearance between the punch and die was 0.8 % of the sheet thickness (10 μm). Since the clearance is small, it is difficult to set the punch and die concentrically, i.e. the maximum eccentricity of the die to the punch was 20 μm (see Fig. 3.3(c)). For automatic centring, the moving die having a smaller outer diameter than that of the diameter of the holder was employed. As the maximum eccentricity of the die to the punch was 20 μm, the gap was chosen to be 30 μm. The gap between the upper surface of the moving die and sheet was set to assist the shift of the die, 30 μm. For a comparison, punching without centring with the fixed die was carried out.



(a)



(b) (c)

Fig. 3.3. (a) Dimension of tools for automatic centring with moving die, (b) eccentricity of die and (c) maximum eccentricity between punch and fixed die.

The procedure for setting the initial eccentricity of the die to the punch for the experiment is shown in Fig. 3.4. Although the diameter of the die holder was slightly larger than that of the fixed die for setting by press fitting, the set die did not move. The two displacement sensors, Dx and Dy were placed on the die holder for θ = 180 and 270°, respectively. The punch was shifted until the edge of the punch touched the die at θ = 180°, the origin of Dx (see Fig. 3.4(a)). To set the eccentricity in the x-direction to be 7 μm, the punch was slightly shifted until a displacement of 3 μm in Dx (see Fig. 3.4(b)). This procedure was repeated for Dy and θ = 270° to set the eccentricity of 7 μm in the y-direction. As both displacements of Dx and Dy were 3 μm, the bolts of the punch holder were tightened. The fixed die was replaced with the moving die having a smaller outer diameter for automatic centring (see Fig. 3.4(c)).

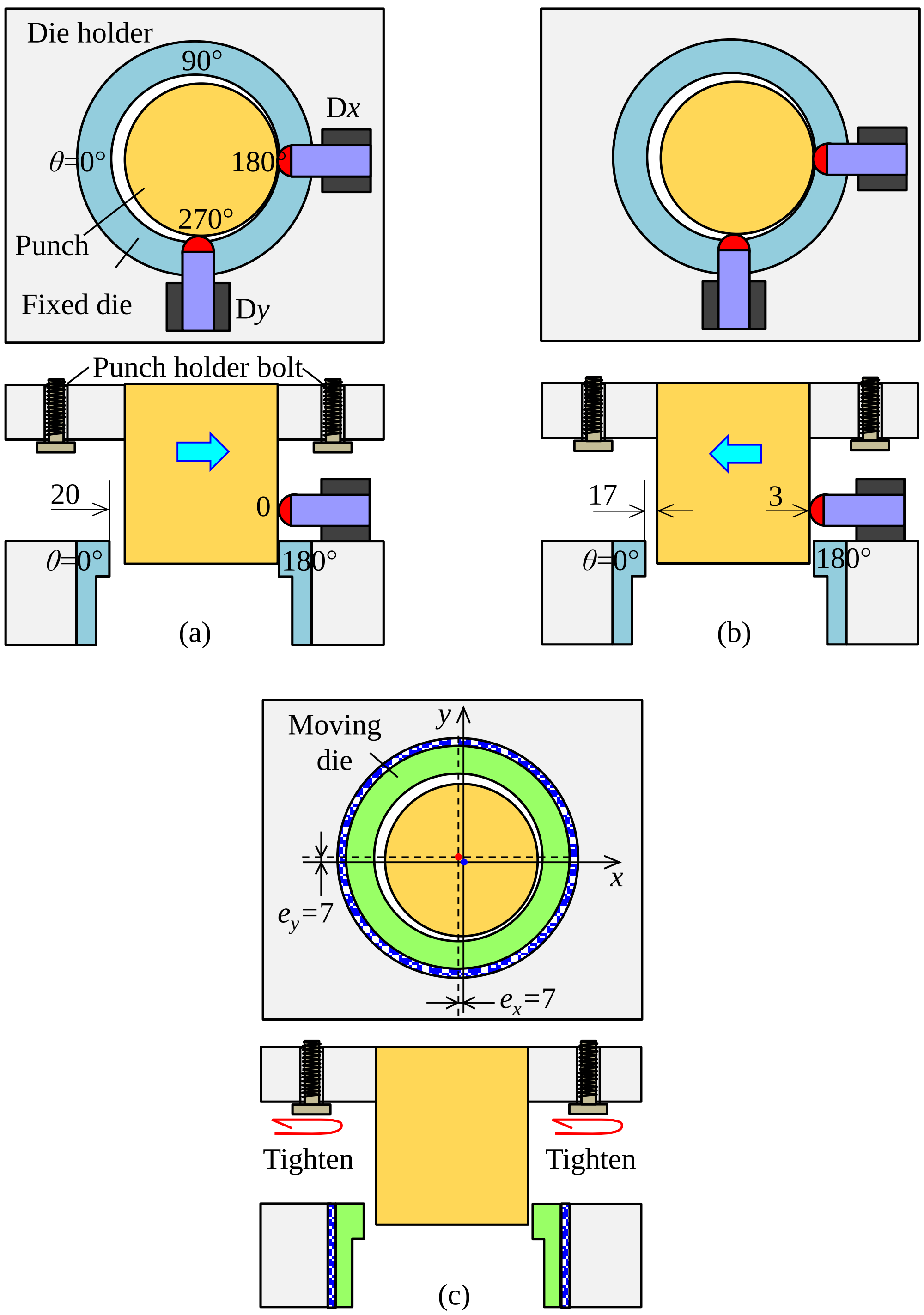


Fig. 3.4. Procedure to set the initial status of eccentricity. (a) punch shift until touch edge of die (b) set eccentricity of 7 μm and (c) tighten bolts of punch holder and replace fixed die with moving die.

An Al–Si coated 22MnB5 steel sheet was punched under a small clearance. The length, width, and thickness of the sheet were 40, 30, and 1.2 mm, respectively as shown in Fig. 3.5. The die-quenched steel sheet employed for the cold punching operation was produced by sandwiching the 22MnB5 steel sheet heated at 900 °C between cold flat dies. The mechanical properties of the die-quenched steel sheet are given in Table 3.1.

Table 3.1.

Mechanical properties of die-quenched steel sheets used for punching with automatic centring.

Material	Thickness [mm]	Tensile strength [MPa]	Elongation [%]	Hardness [HV20]
Al-Si coated 22MnB5	1.2	1504	5.0	504

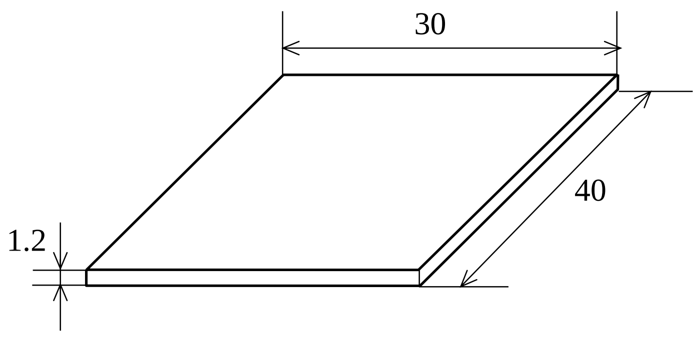


Fig. 3.5. Dimension of die-quenched steel sheet for small punching clearance punching with automatic centring.

The conditions of small clearance punching of the die-quenched steel sheet are given in Table 3.2. The sheets were punched with a TiCN-coated punch using an 800 kN CNC servo press. The Vickers hardness of the TiCN-coated punch was 3000 HV. For automatic centring with a moving die, the gap between the moving die and die holder was filled with a sulphur additive lubricant. The moving die was eccentric to the punch for -7 and 7 µm in the x and y-directions, respectively.

Table 3.2.

Conditions of punching with automatic centring of die-quenched steel sheets.

Punch material	TiCN-coated SKH51
Die material	SKD11
Clearance to thickness ratio, c [%]	0.8
Punching speed [mm/s]	75
Filling media of gap	Sulphur additive lubricant
Eccentricity in x- and y-directions [µm]	e_x= -7, e_y= 7

3.4. Result of punching without centring for initially eccentric condition

3.4.1 Finite element simulation of punching without centring

Finite element simulation of the punching process without centring using the fixed die for the eccentric condition was simulated using the DEFORM 3D software to examine the effect of the eccentricity. The fixed die was eccentric to the punch only in the *x*-direction. The punch, sheet holder and die holder were assumed to be rigid and the sheet and the die were divided into the tetrahedral elements (see Fig. 3.6). The conditions used for the calculation are given in Table 3.3.

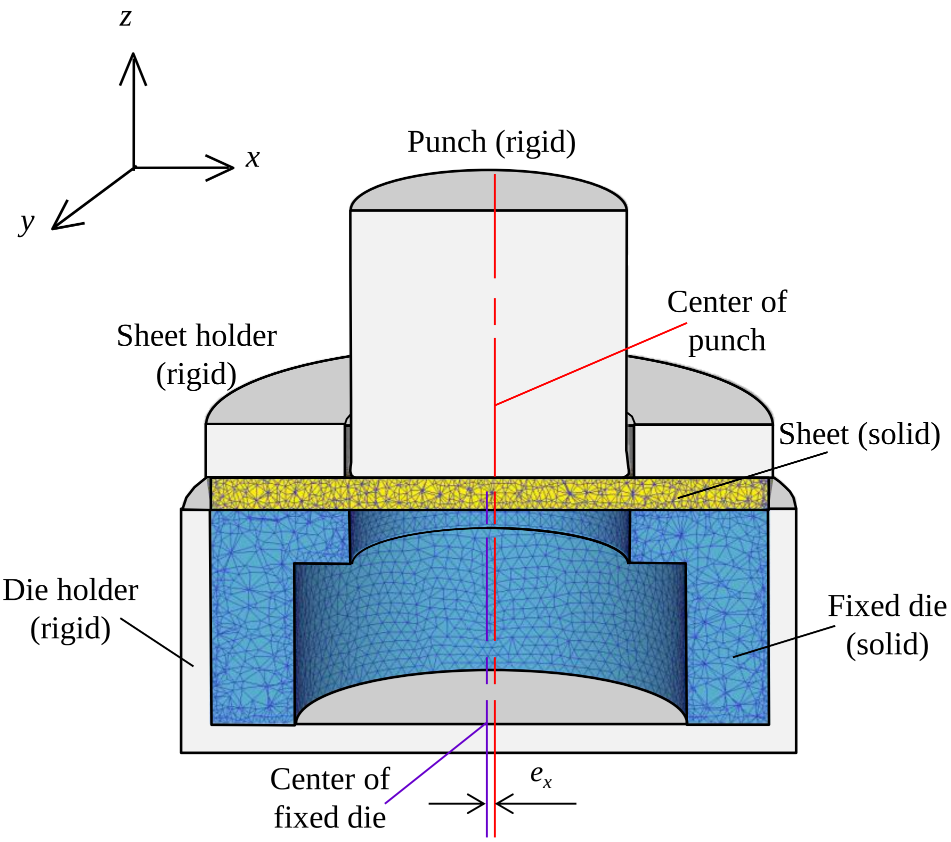


Fig. 3.6. Finite element simulation of punching without centring for initially eccentric condition.

Table 3.3.

Conditions used for finite element simulation of punching without centring with fixed die.

Flow stress [MPa]	$\sigma = 2430\varepsilon^{0.13}$ MPa
Coefficient of friction	0.1
Element mesh number of workpiece	100,000
Element mesh number of fixed die	100,000
Eccentricity [μm]	e_x = -3, -7, -10 e_y = 0

Since the die is fixed to be eccentric to the punch in the *x*-direction, the forces acted to the right and left halves of the die are imbalanced. The forces in the *x*-direction acted to the right and left halves of the die acting on the surface of the fixed die are given by:

$$F_x = \int (\sigma_x cos\theta + \tau_{xy} sin\theta)\, \mathrm{d}A, \quad (1)$$

where σ_x and τ_{xy} are the normal and shear stresses and A is the area of the interface between the die and sheet. The imbalanced force for eccentric punching is calculated as the difference between the right and left forces.

To examine the effect of eccentricity on the imbalanced force acting on the fixed die during the indentation of the punch, the calculation was performed until a punch stroke of s = 0.6 mm, because the moving die is mainly shifted during the early stage of indentation. The eccentricity of the fixed die to the punch was constant during punching. The relationship between the imbalanced force calculated by the finite element simulation and the punch stroke for different eccentricities in the *x*-direction is given in Fig. 3.7. As the punch stroke and the eccentricity increase, the imbalanced force increases. Therefore, the die is shifted by the imbalanced force when the die is not fixed

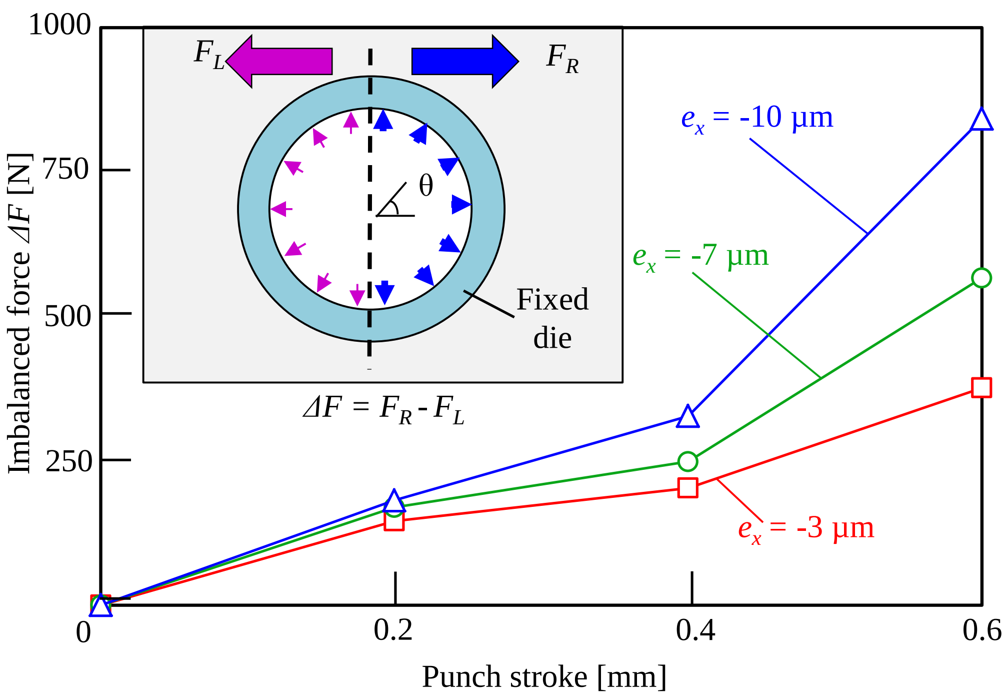


Fig. 3.7. Relationship between imbalanced force calculated by finite element simulation and punch stroke for difference eccentricities in *x*-direction.

3.4.2. Shearing behaviours for punching without centring

The crack propagation for punching without centring using fixed die for a different punch strokes, *s* is shown in Fig. 3.8. The punch was set to eccentric to the die in the x-direction for e_x = -7 μm. The crack propagation was observed from both of the punch and die edges for θ = 0 and 180° and at a different punch stroke. Since the punc hand die was eccentric i.e. the clearance for θ = 0° is smaller than that of θ = 180°, the crack was initiated from the edge of the die and observed only for θ = 0° for *s* = 0.4 mm. For *s* = 0.7 mm, the cracks are caused from both edges of the punch and die for θ=0°.

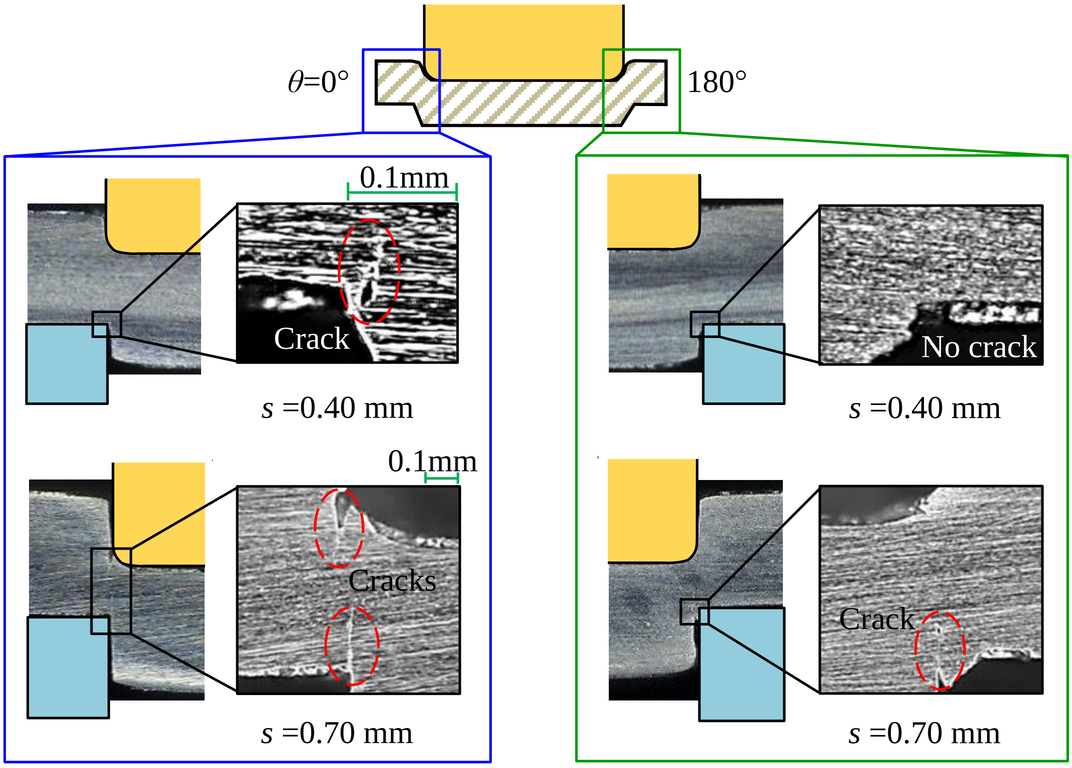


Fig. 3.8. Crack propagation for punching without centring using fixed die for different punch stroke.

3.4.3. Quality of sheared edge for punching without centring

The surface of the sheared edge of the die-quenched steel sheet in punching without centring using the fixed die is given in Fig. 3.9, where n is the number of strikes. The punch was set to be eccentric to the fixed die for ex = -7 and ey = 7 μm in the x and y-directions, respectively. The die-quenched steel sheet was manually fed after each strike, and the punching speed was 75 mm/s. Since the clearance between θ = ± 90° is larger, a large fracture surface was observed on the sheared edge.

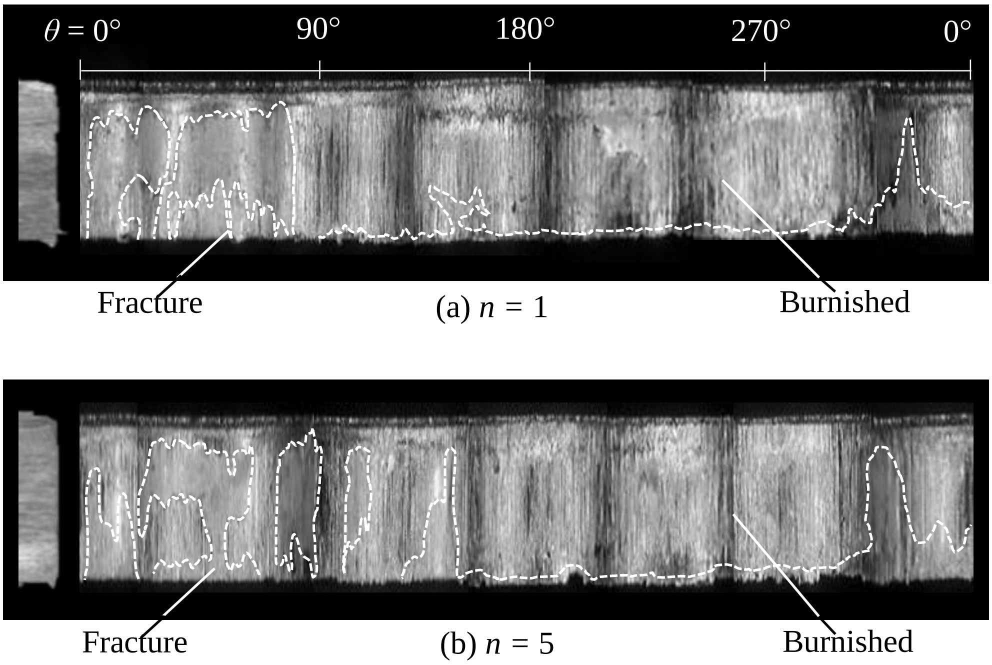


Fig. 3.9. Surface of sheared edge of die-quenched steel sheet in punching without centring using fixed die for (a) n = 1, (b) n = 5 and v = 75 mm/s.

3.5. Result of punching with automatic centring for initially eccentric condition

3.5.1. Punching load-stroke curve

The punching load-stroke curves for punching without and with automatic centring are shown in Fig. 3.10. The maximum punching load for both punching conditions was almost the same and occurred around 0.7 mm of the punch stroke. However a slightly sharp increment of punching load was observed for punching without centring for punch stroke around 1.0 mm.

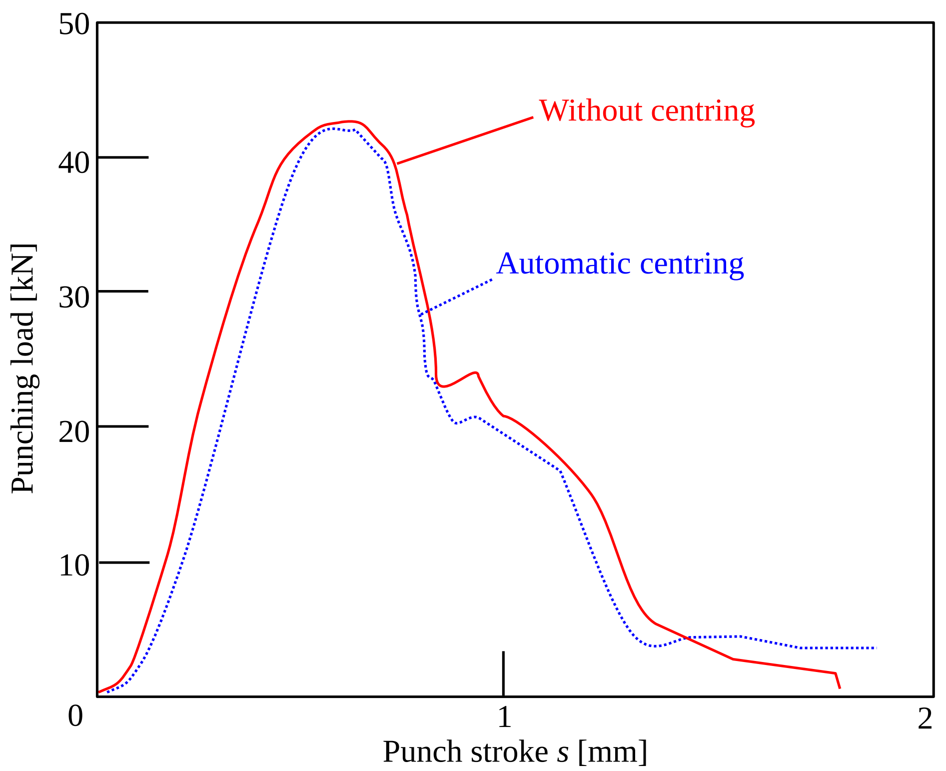


Fig. 3.10. Punching load-stroke curves for punching without and with automatic centring.

3.5.2. Quality of sheared edge for punching with automatic centring

In small clearance punching with automatic centring, the initial eccentricity of the punch and moving die was e_x = -7 and e_y = 7 μm, and was the same with that without centring. The punching speed was 75 mm/s. The surface and cross-section of the sheared edge of the die-quenched steel sheets for automatic centring are given in Fig. 3.11. Since the shift of the moving die for n = 1 was still insufficient to achieve the concentric position, the rough fracture surface was large. The moving die continued to shift and became concentric with the punch after several strikes. A large burnished surface was obtained and the fracture surface was considerably reduced for n = 5.

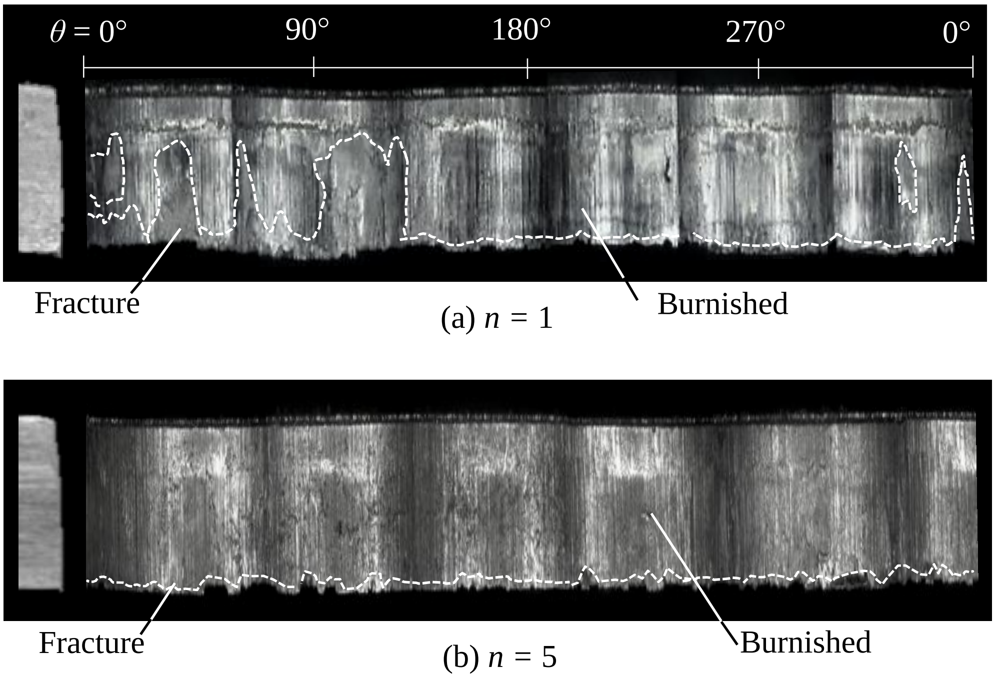


Fig. 3.11. Surfaces of sheared edge of die-quenched steel sheets for automatic centring with moving die for (a) n = 1, (b) n = 5 and v = 75 mm/s.

3.5.3. Variation of die movement with punch stroke

The relationship between the shift of the moving die and the number of strikes for automatic centring is shown in Fig. 3.12. The initial eccentricity of the moving die to the punch was e_x = -7 and e_y = 7 μm, respectively, and the number of strikes was n = 10. The experiment was carried out three times, and the averages of the measured values are shown. Since the used displacement sensors are very sensitive, a slow punching speed of 5 mm/s was employed to measure the shift of the die. The two displacement sensors having resolution of 0.1 μm were placed at θ = 180 and 270° to measure the shift of moving die in the x and y-directions, respectively. As the number of strikes increases, the eccentricity decreases, and the punch and die were concentric above n = 5.

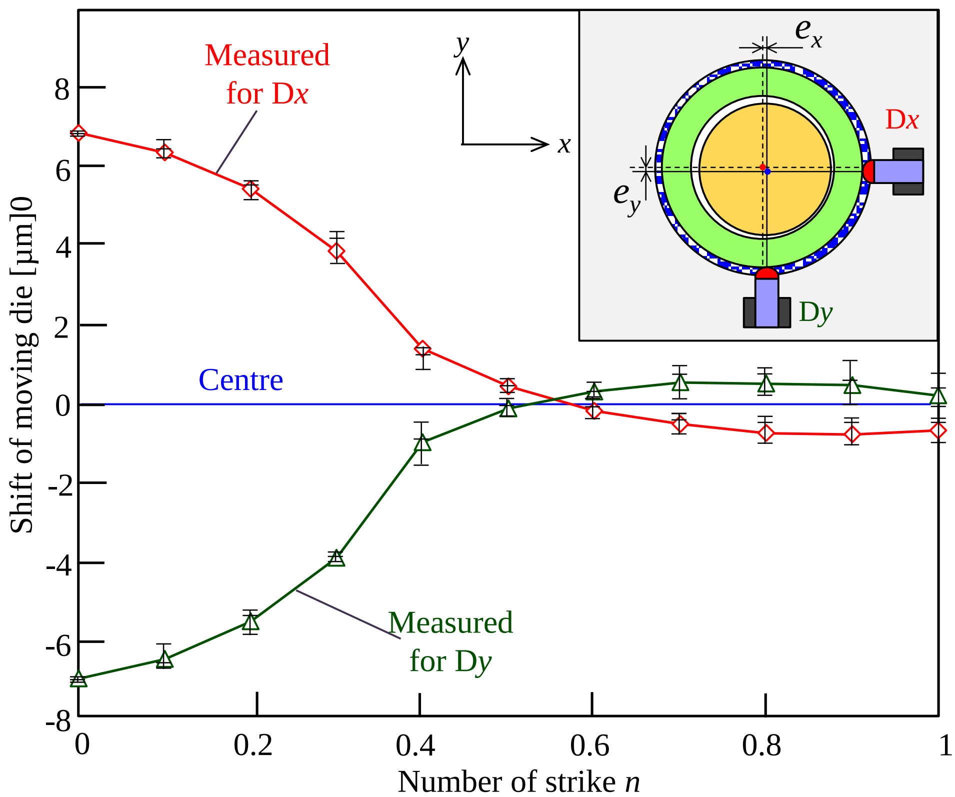


Fig. 3.12. Relationship between shift of moving die and number of strikes for automatic centring for e_x = -7 and e_y = 7 μm and v = 5 mm/s.

3.6. Mechanical properties of punched sheet

3.6.1. Average Vickers hardness

The distributions of Vickers hardness in the thickness direction around the sheared edge for punching with automatic centring are shown in Fig. 3.13, where *y* is the distance from the sheared edge. The hardness was measured for every 0.15 mm from the surface of the sheet in the thickness direction. The hardness around the sheared edge for *y* = 0.05 mm was increased as compared to the original hardness of the sheet due to the influence of ironing with the punch which caused work-hardening. For the measurement point of *y* = 0.15 and 0.4 mm showed almost the same hardness of the sheet prior to punching.

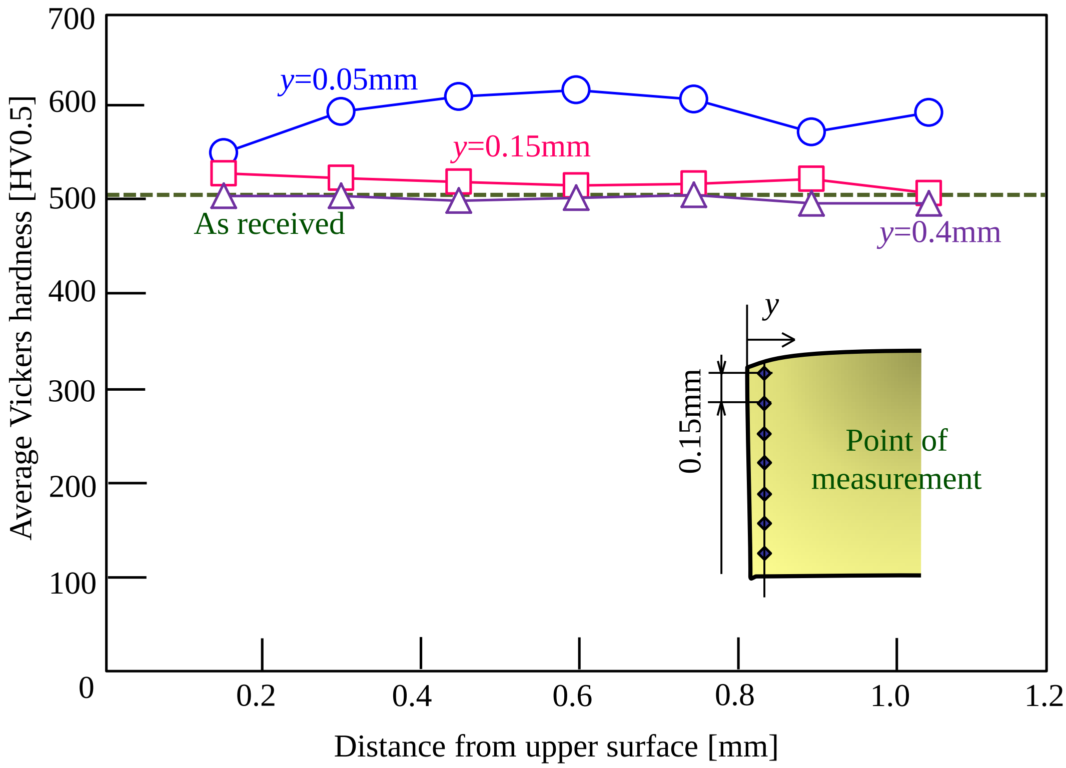


Fig. 3.13. Distributions of Vickers hardness in thickness direction around sheared edge for punching with automatic.

3.6.2. Fatigue strength

To examine the effect of punching without centring and with automatic centring, the bending fatigue test was carried out. The procedure and dimensions of specimen for the bending fatigue test are shown in Fig. 3.14. The punched sheets were bent for a moment of 2.02 N･m. and at a frequency of 25 Hz. In the fatigue bending test, the sheet underwent repeated bending under elastic deformation, and the test was finished for the occurrence of cracks. Five specimens were punched without centring and with automatic centring for $e_x = -7$, $e_y = 7$ µm and v = 75mm/s. The specimens of n = 1, 3, and 5 were selected for the test.

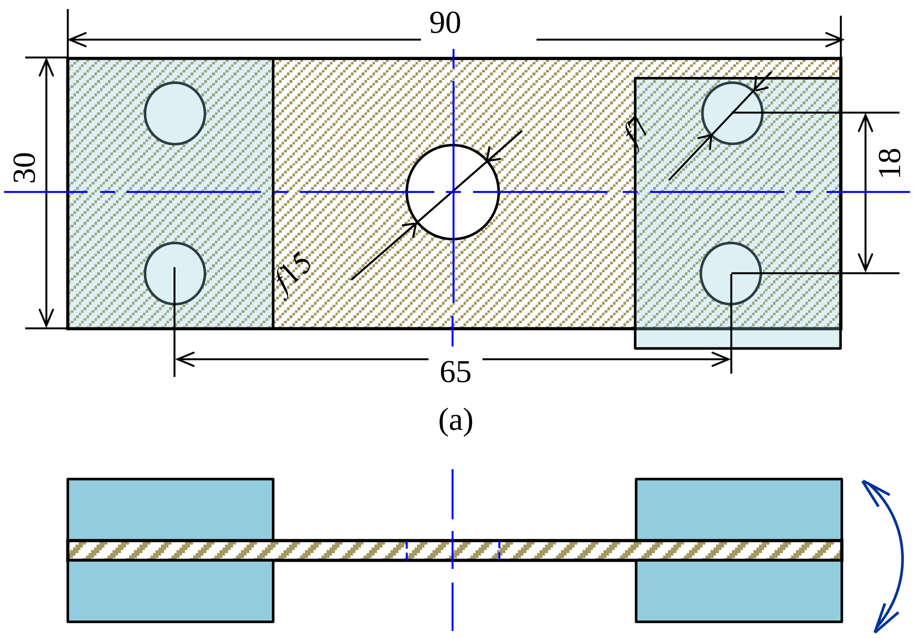


Fig. 3.14. Procedure of bending fatigue test. (a) Dimension of specimen and (b) bending moment used for test.

The number of cycles to failure of the punched sheets without centring and with automatic centring is given in Fig. 3.15. The large rough fracture surface on the sheared edge for the specimen without centring accelerated the initiation of the crack. Since automatic centring was effective in reducing the rough fracture surface, the fatigue strength of the punched sheet was improved. The average number of cycles to failure for punching with automatic centring was about 2 times larger than that without centring.

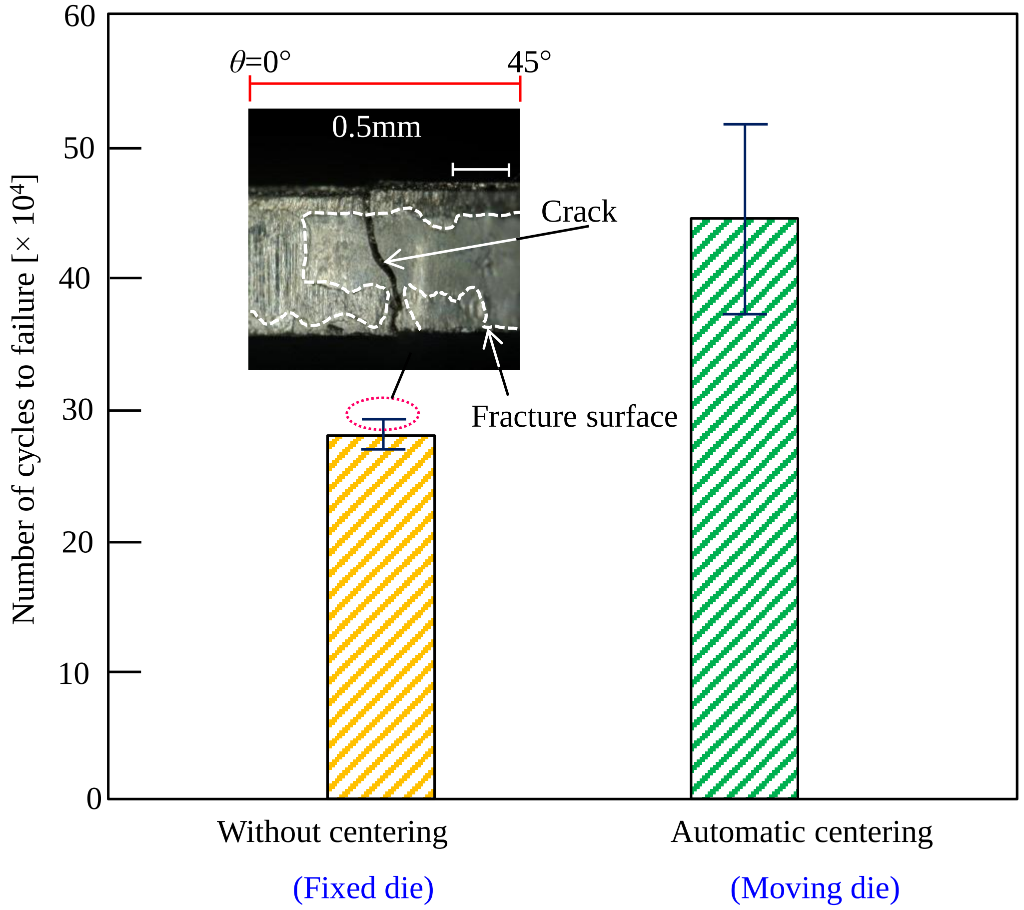


Fig. 3.15. Number of cycles to failure of punched sheets without centring and with automatic centring for e_x = -7 and e_y = 7 μm and v = 75 mm/s.

3.6.3. Delayed fracture

In punching of die-quenched steel parts, the risk of delayed fracture is high. The delayed fracture times around the sheared edge for punching without centring and with automatic centring are shown in Fig. 3.16, where the delayed fracture time is the time from the soak of the sheet in the 35 % concentration hydrochloric acid to the visual observation of cracks. Three specimens of punching without centring and with automatic centring were immersed in the hydrochloric acid solution at room temperature, and the average delayed fracture time was measured. For punching without centring, the cracks were observed at the sheared edge just after 1.5 hours of immersion, and were propagated from the fracture surface. However, for punching with automatic centring, the delayed fracture was prevented. No crack was observed even after 24 hours of immersion.

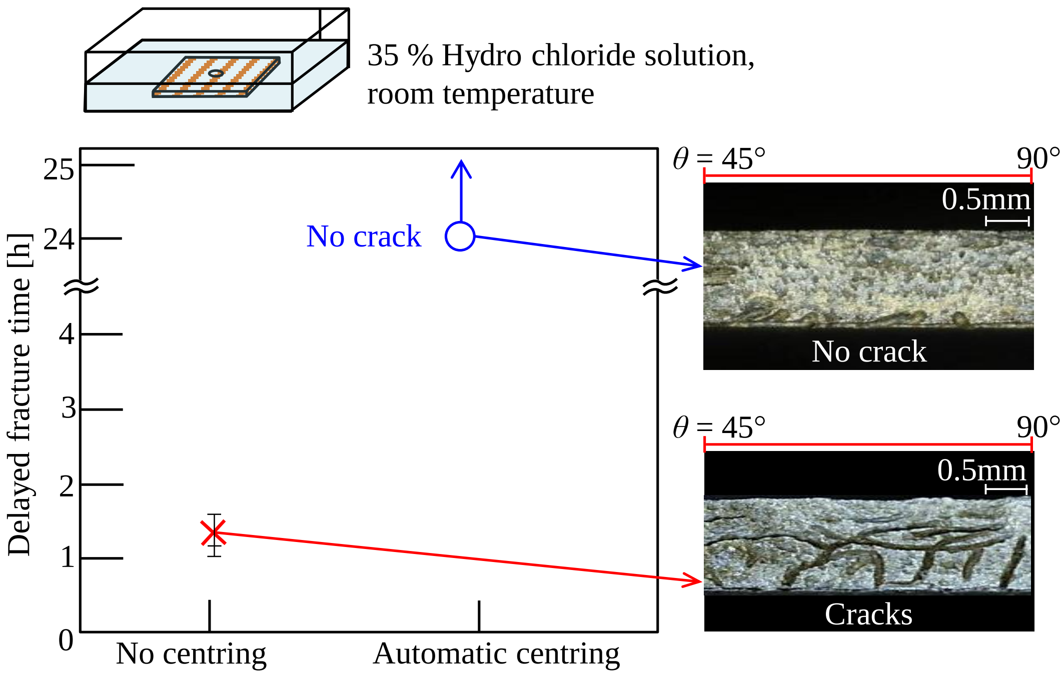


Fig. 3.16. Delayed fracture times around sheared edge for punching without centring and with automatic centring.

3.7. Conclusions

Although small clearance was effective for a high quality sheared edge in punching of die-quenched steel sheets, setting of tool was difficult due to small clearance between the punch and die and thus tends to make the punch and die eccentric. The automatic centring was developed for correcting the eccentricity between the punch and die and eliminate the problem of eccentricity. A moving die was utilised to automatically correcting the eccentricity of the die to the punch. The following conclusions can be drawn:

1) The setting of a gap between the moving die and holder allowed the die to shift by the imbalanced force, and thus the punch and die become concentric after several strikes.
2) For small clearance punching without centring with the fixed, even a small eccentricity of punch to die will result in low sheared edge quality.
3) As the moving die and punch reach the concentric position, a large and uniform burnished surface in the circumference direction was produced for punching with automatic centring.
4) The large burnished surface at the sheared edge for punching with automatic centring increase the fatigue strength of the sheet and prevent the occurrence of delayed fracture.

Chapter 4
Repeated punching of die-quenched and ultra-high strength steel sheets by automatic centring

4.1. Introduction

The die-quenched and ultra-high strength steel sheets are desirable for the reduction of weight and an improvement of safety standards for vehicle passengers. For car body parts made of die-quenched and ultra-high strength steel sheets, multiple holes are made for joining, attachment, painting, etc. Although the die-quenched and ultra-high strength steel sheets are punched to make the holes on the automobile body panels, it is not easy to punch ultra-high strength steel parts due to their high strength [40-43]. For the high strength and low ductility of the sheets, the quality of the sheared edge is not high and the resulting short life of production tools is not favourable for car makers [44-48].

Therefore, laser cutting is the most common but expensive method used to make multiple holes on the body panel [58]. The quality of the cut surface made by laser cutting is dependent on various parameters such as cutting speed, power of the beam emitted by the generator, type of gas, amount of gas pressure, laser pulse rate, laser pulse energy, etc. [78-83]. In spite of improvements in processing time, it is an unattractive method due to its high installation cost especially when used for mass production and complex shapes [84]. However, for mass production, the conventional punching process is more preferable for making multiple holes on ultra-high and die-quenched steel parts since it is fast and of lower cost.

To overcome these problems, a small clearance punching process that uses a punch having a small round edge was developed to improve the quality of the sheared edge [107]. Due to the small clearance, the tensile stress in the shearing region during punching is reduced and thus the onset of cracks is delayed for ultra-high strength steel sheets that have small ductility. Since the setting of tools for small clearance punching is not easy in a practical punching operation, an automatic centring punching process was developed to correct the eccentricity of the punch to the die.

In the present study, a cold repeated small clearance punching process of die-quenched steel sheets by a punch having a small round edge was developed to improve the quality of the sheared edge in punching multiple holes. Since the small clearance and automatic centring exhibits high performance in the single strike punching operation, this method was employed for repeated punching of die-quenched and ultra-high strength steel sheets. The quality of the sheared edge and punch condition were investigated.

4.2. Experimental procedure of repeated punching

The tool used for repeated punching of die-quenched steel sheets with automatic centring is illustrated in Fig. 4.1. The punch is attached to the punch holder and the moving die was held by the die holder. The sheet was fed by the automatic feeder. The number of strokes per minute for the feeder and the punching speed were 20 and 75 mm/s, respectively. For a comparison, repeated punching of die-quenched steel sheets using fixed was carried out.

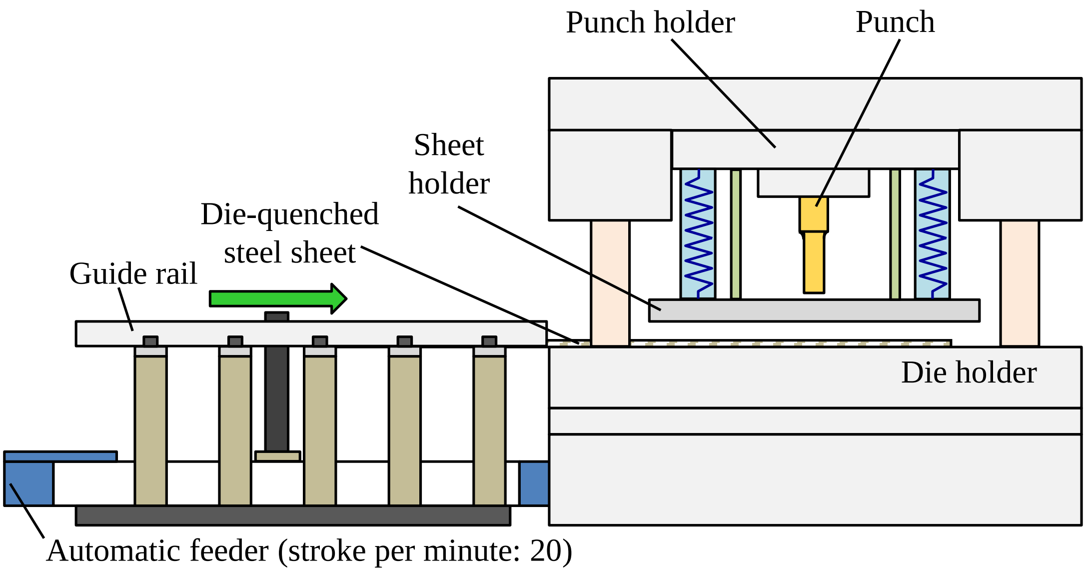


Fig. 4.1. Tools for repeated punching with automatic centring.

The JSC980Y ultra-high strength and Al–Si coated 22MnB5 die-quenched steel sheet having 400, 30 and 1.2 mm in length, width and thickness, respectively was repeatedly punched under a small clearance as shown in Fig. 4.2. The die-quenched steel sheet employed for the cold repeated punching operation was produced by sandwiching the 22MnB5 steel sheet heated at 900 °C between cold flat dies. The mechanical properties of JSC980Y and die-quenched steel sheet are given in Table 4.1.

Table 4.1.

Mechanical properties of die-quenched and ultra-high strength steel sheets.

Material	Thickness (mm)	Tensile strength (MPa)	Elongation (%)
Al-Si coated 22MnB5	1.2	1504	5.0
JSC980Y	1.2	1071	12.8

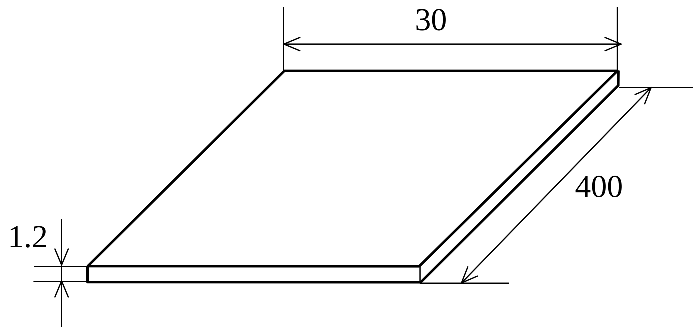


Fig. 4.2. Dimension of die-quenched steel sheet for repeated punching with automatic centring.

The conditions of repeated punching without and with automatic centring sheet are given in Table 4.2. The sheets were punched with an 800 kN CNC servo press. The Vickers hardness of the TiN, TiCN and TiAlN-coated punch were 2200, 3000 and 3500 HV, respectively

Table 4.2.

Conditions of punching of repeated punching without and with automatic centring.

Punch material (without automatic centring)	TiN and TiAlN coated SKH51
Punch material (with automatic centring)	TiCN-coated SKH51
Die material	SKD11
Clearance to thickness ratio, c [%]	0.8
Punching speed [mm/s]	75

4.3. Result of repeated punching without centring

4.3.1. Punching load and stripping force

Repeated slight clearance punching of die-quenched steel sheet was carried out to investigate the punch life. The punching load and stripping force-stroke curves of punching without centring for fifth strike are shown in Fig. 4.3. The punching load was linearly increased until it reached maximum point at punch stroke around 0.8 mm and decreased until the scrap was separated from the sheet. For the elastic recovery of the hole and eccentricity of the punch to the fixed die, the punch contacted the sheet during returned to its initial position, and thus a sudden increase in stripping force was observed.

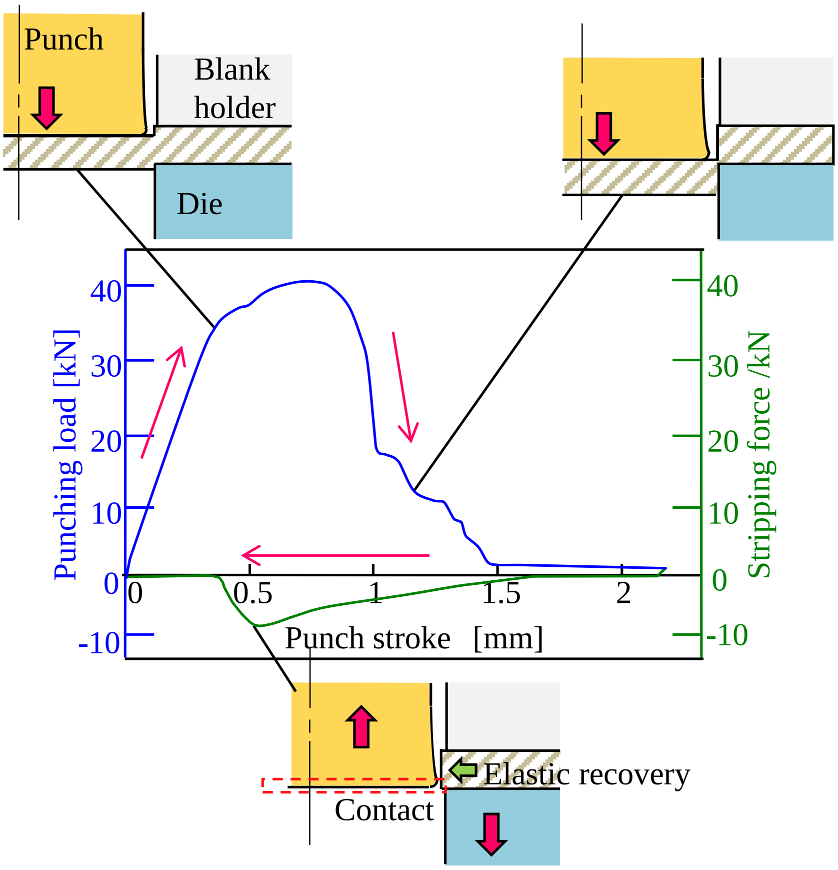


Fig. 4.3. Punching load and stripping force-stroke curves of punching without centring for fifth strike.

The movement of punch after stripping in repeated punching without centring is given in Fig. 4.4, where θ is the measured angel and n is the number of strike. A displacement sensor having a sensitivity of 0.1 μm was placed at the position of θ= 45° to measure the movement of punch after stripping. It was observed that the punch was slightly shifted towards θ= 225° after *n* = 5.

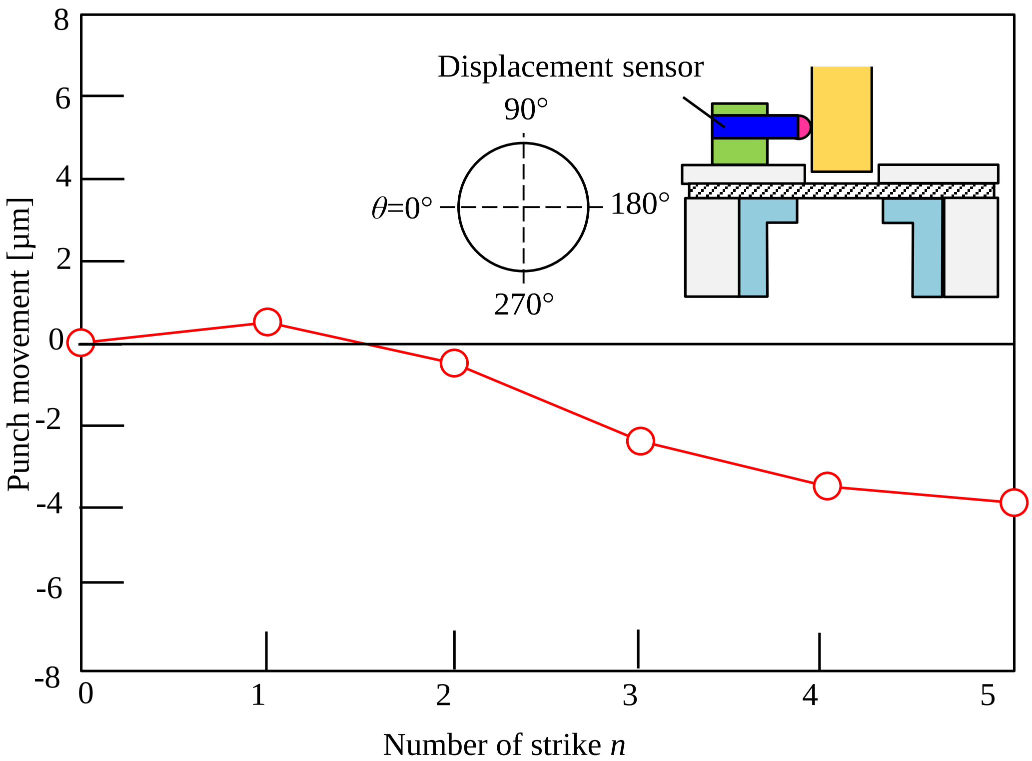


Fig. 4.4. Movement of punch after several strike in repeated punching without centring measured for θ= 45°.

The relationship between average stripping force and the number of strike in repeated punching without centring is given in Fig. 4.5. Since the punch is slightly shifted after every strike, the stripping force was increased with increase of the number of strike.

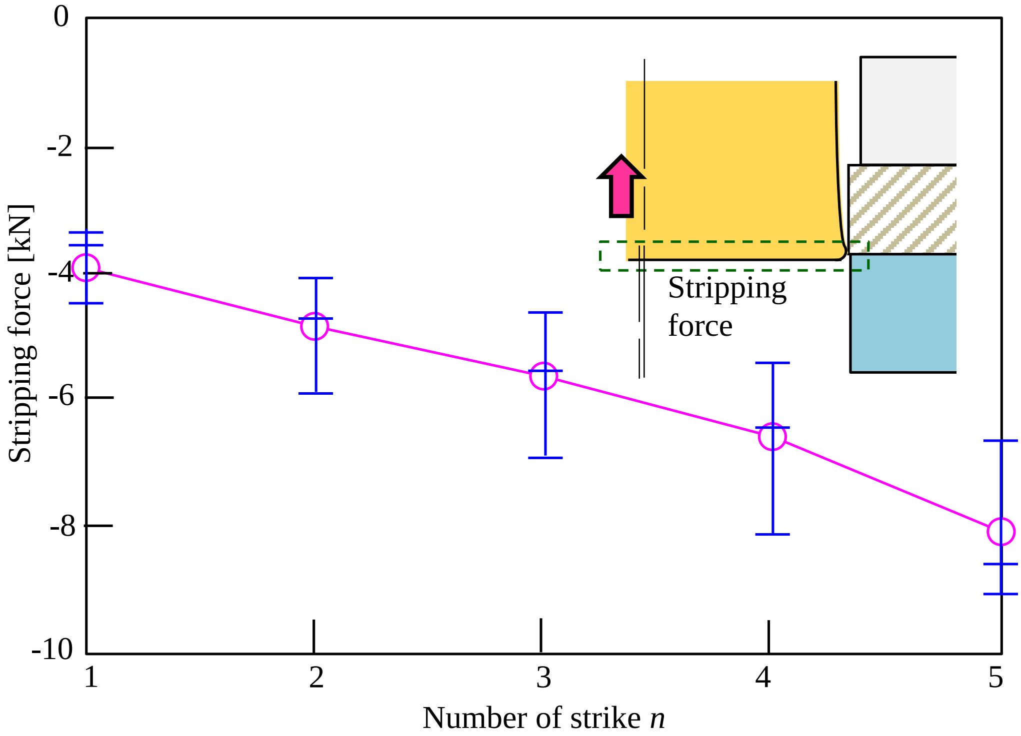


Fig. 4.5. Relationship between average stripping force and number of strike in repeated punching without centring.

4.3.2. Broken of punch in repeated punching without centring

Repeated slight clearance punching of die-quenched steel sheet was carried out with TiN and TiAlN-coated punch. The punch material was made of tungsten carbide. Both punches were having a corner radius of R= 0.3 mm. Since the punch was slightly moved after several strike and the fixed position is remain the same, the punch contacted the contracted sheet during stripping. The TiN and TiAlN-coated punches were broken at the bottom part after the 11th and 32nd strikes, respectively as shown in Fig. 4.6.

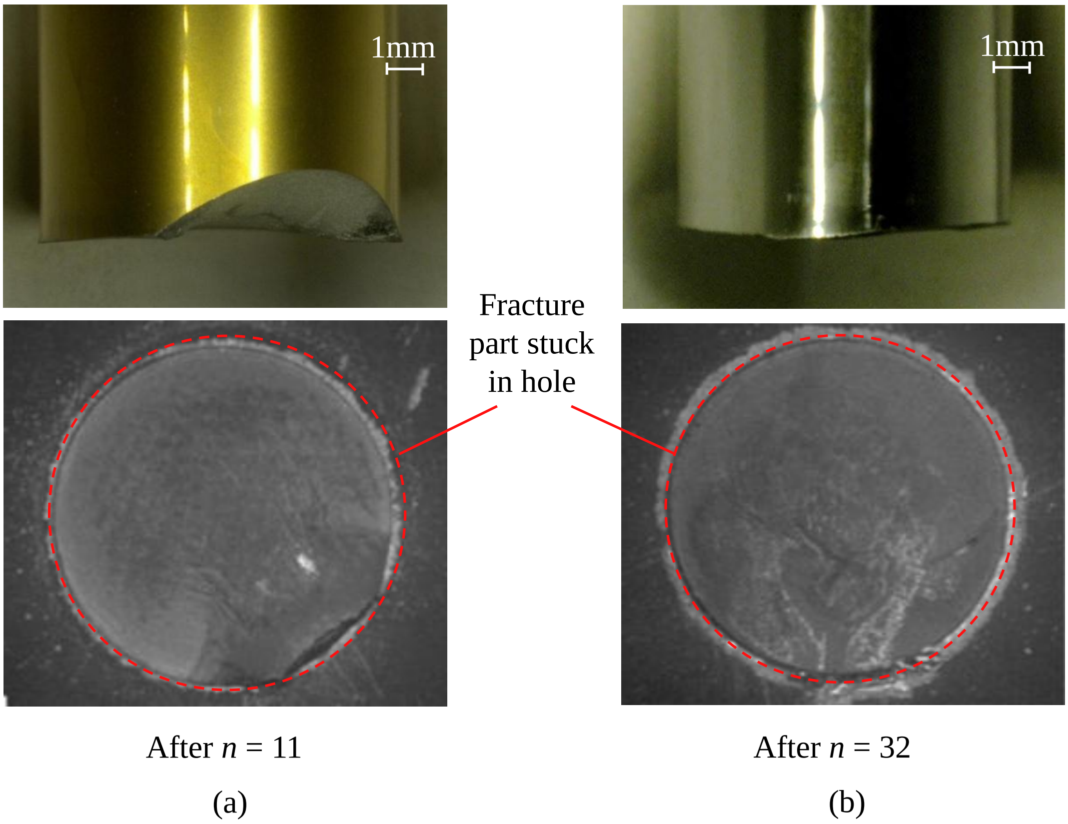


Fig. 4.6. Broken of punch in repeated punching with fixed die for (a) TiN and (b) TiAlN-coated punches.

The reason of broken of punch in slight clearance punching of die-quenched steel sheets is illustrated in Fig. 4.7. The elastic recovery makes the punched hole contracted. The punch was slightly shifted from its original position after several number of strikes and thus becomes eccentric to the die. Therefore the punch tip hits the sheared edge during release. For a frequent contact between the punch tips and contracted hole, the punch is broken.

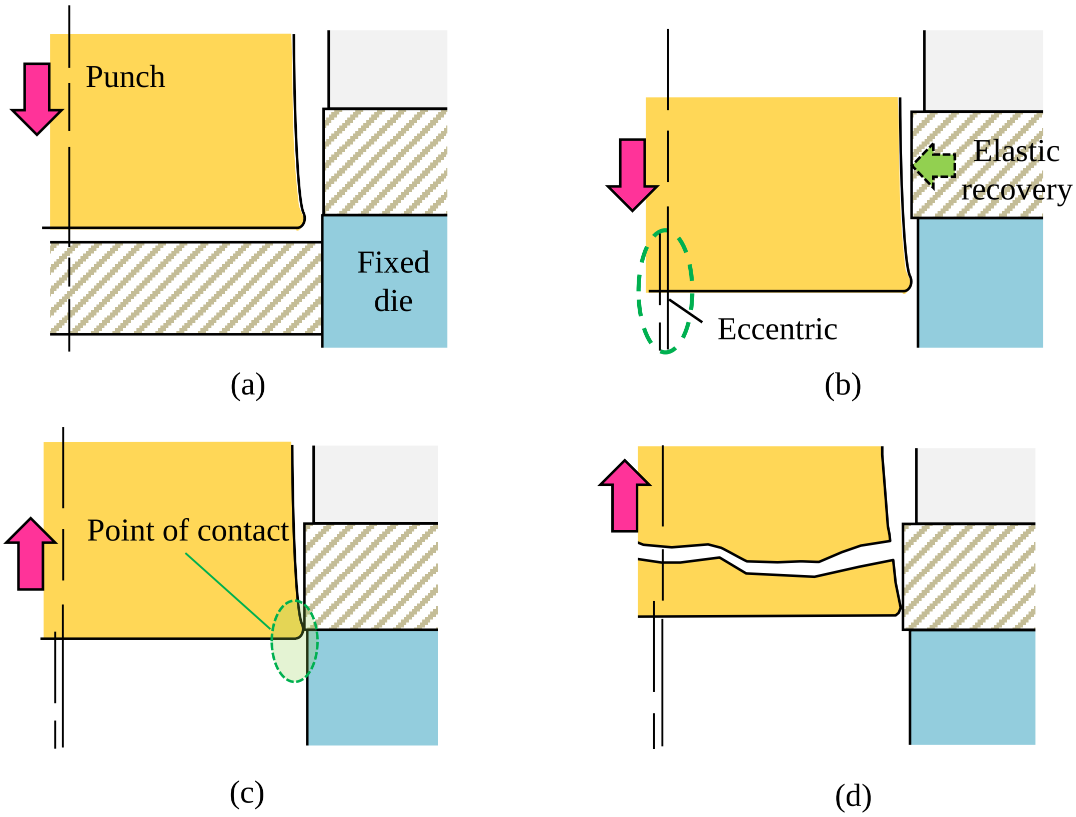


Fig. 4.7. Broken of punch. (a) Separation of scrap; (b) elastic recovery and occurrence of eccentricity after several strikes; (c) punch tips contact with sheared edge and (d) punch broken.

4.4. Result of repeated punching with automatic centring

4.4.1. Quality of sheared edge

Repeated small clearance punching with automatic centring was carried for both ultra-high strength and die-quenched steel sheets with the same punching condition. The surface of sheared edge of JSC980Y steel sheets and die-quenched for *n* = 100 is shown in Fig. 4.8, where *n* is number of strike. For the JSC980Y steel sheets the burnished surface was small even with high number of strikes. Whereas for the die-quenched steel sheets, the amount of fracture surface was large

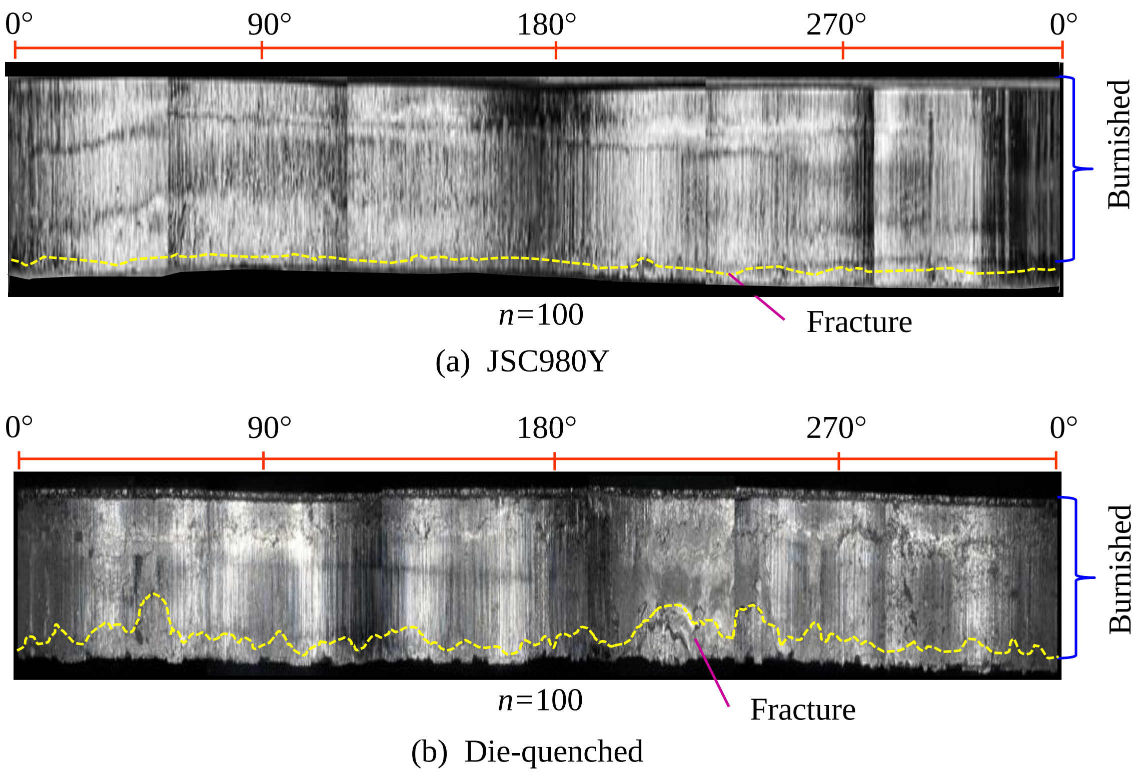


Fig. 4.8. Surface of sheared edge of (a) JSC980Y and (b) die-quenched steel sheets for *n* = 100.

The sheared edge surface of JSC980Y for repeated punching with automatic centring for n = 100, 200, 300, 400 and 500 are given in Fig. 4.9. The burnished surfaces remained large even with the increase of number of strike. However for n = 400 and 500, an increase in fracture surface was observed.

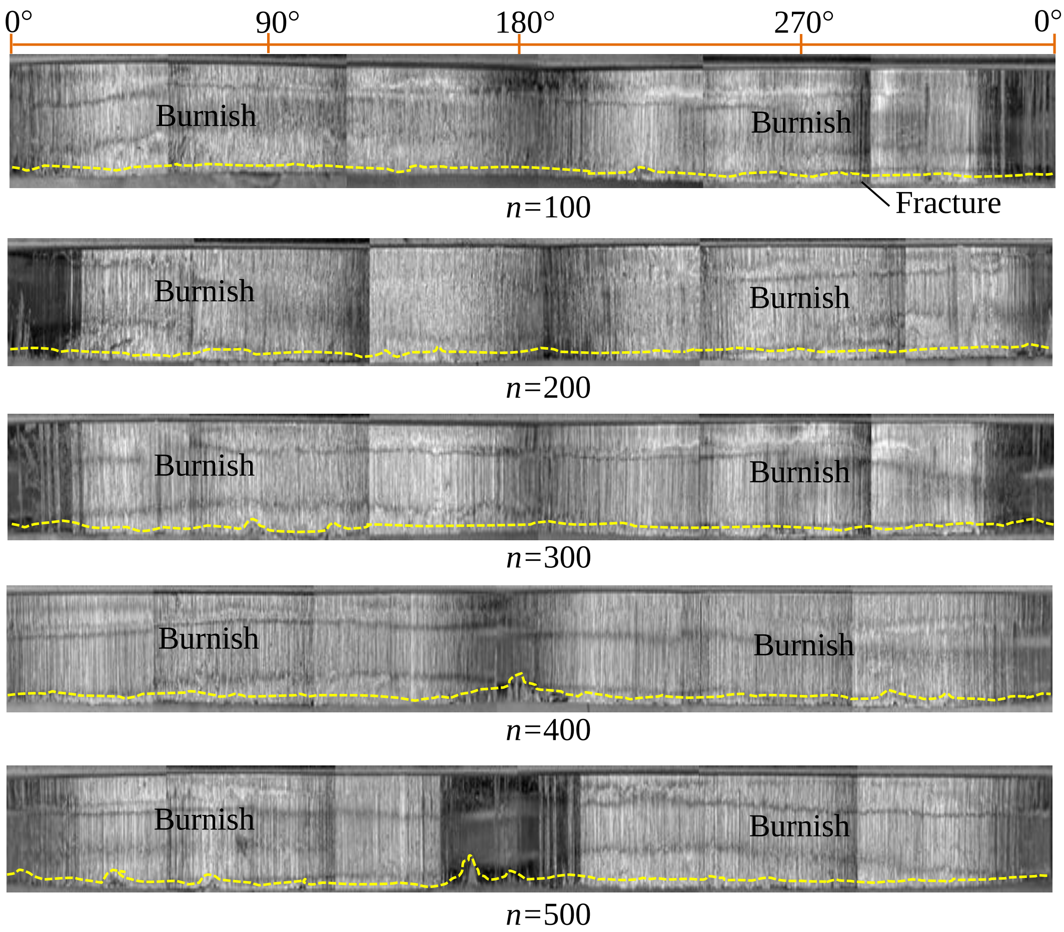


Fig. 4.9. Sheared edge surface of JSC980Y for repeated punching with automatic centring.

The percentages of the rollover, burnished and fracture depths and burr height on the sheared edge of die-quenched steel sheet for repeated punching with automatic centring for is given in Fig. 4.10. The percentage of the burnished surface was decreased with the increase of number of strike as observed for n = 100, 200 and 300. For n = 400 and 500, secondary burnished and fracture surfaces was appeared at the sheared edge. The higher strength of the die-quenched steel sheets makes the quality of the sheared edge lower as compared to the JSC980Y steel sheets in the repeated punching process.

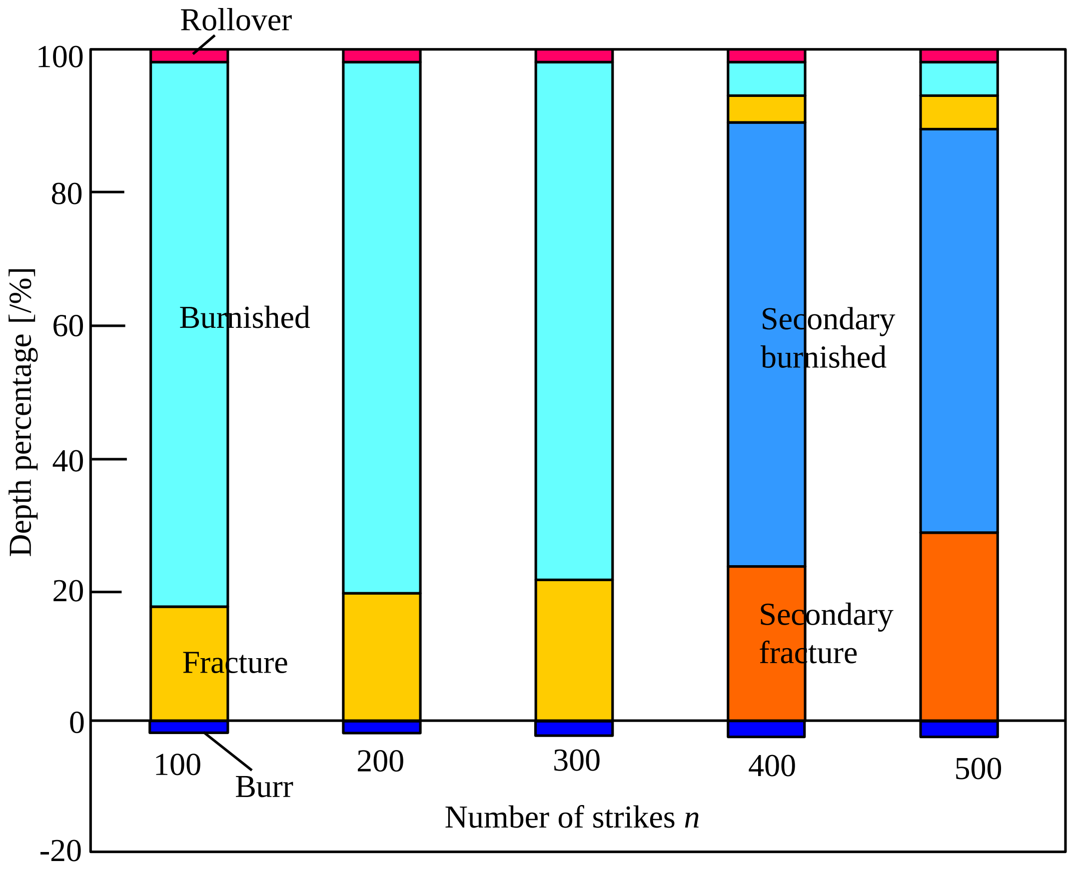


Fig. 4.10. Percentages of the rollover, burnished and fracture depths and burr height on sheared edge of die-quenched steel sheet for repeated punching with automatic centring.

The cross section and sheared edge surface of die-quenched steel sheet for n = 500 is shown in Fig. 4.11. The sheared zones with fracture and secondary fracture surfaces were clearly observed at the sheared edge. The quality of the burnished and secondary burnished surfaces was low.

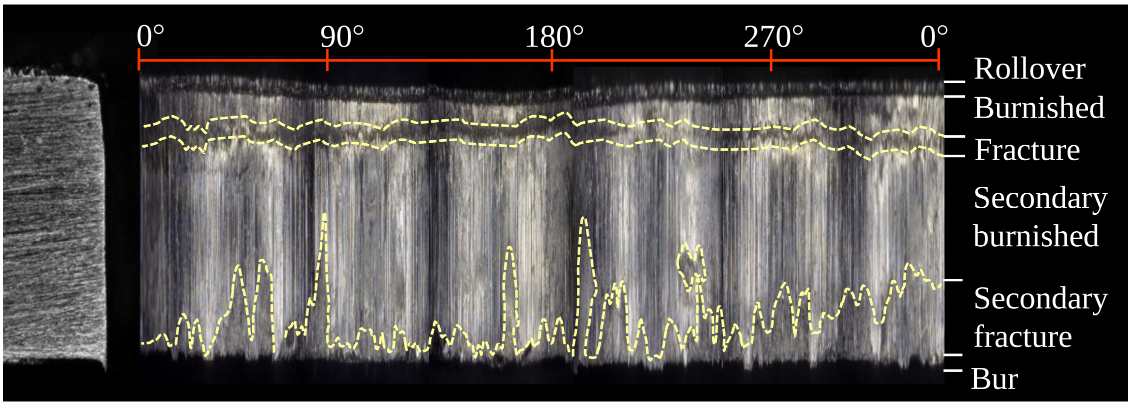


Fig. 4.11. Cross section and sheared edge surface of die-quenched steel sheet for n = 500.

4.4.2. Punch and die after repeated punching

The surface of punches of repeated punching with automatic centring of JSC980Y steel and die-quenched steel sheet after n = 500 are given in Fig. 4.12. For punching JSC980Y, a small galling of less than 0.5 mm in height was observed at the punch surface after n = 500. For punching die-quenched steel sheet, the galling at the punch surface was large and the height of the galling was measured more than 1 mm. The galling at the punch surface is caused by the adhesion of the material i.e. die-quenched steel sheet during punching.

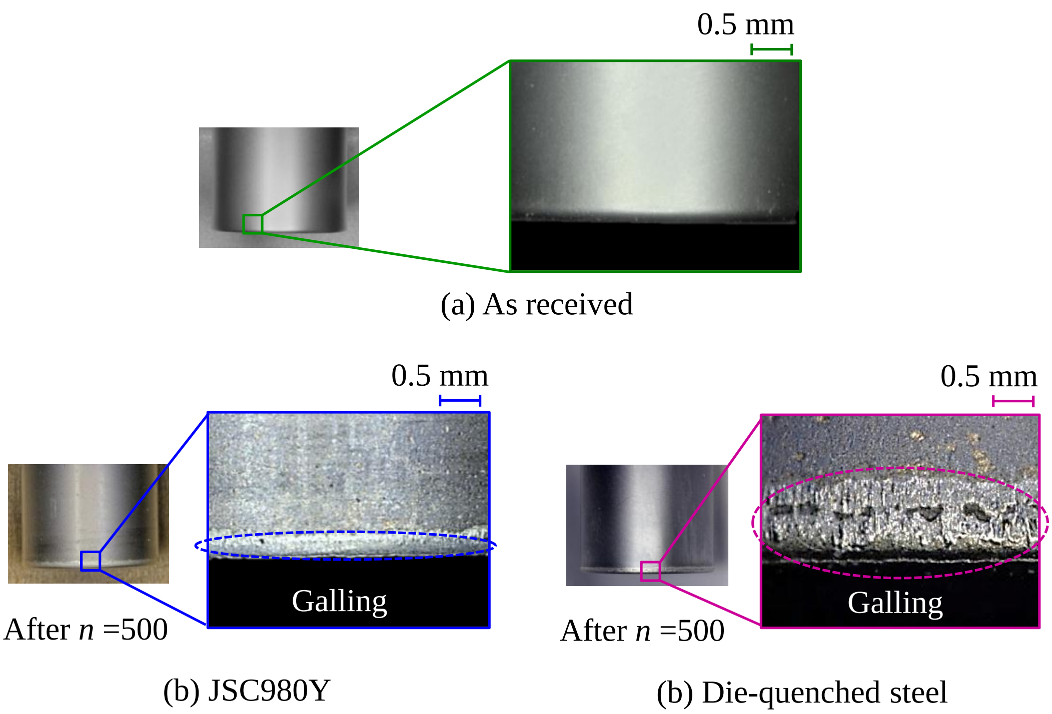
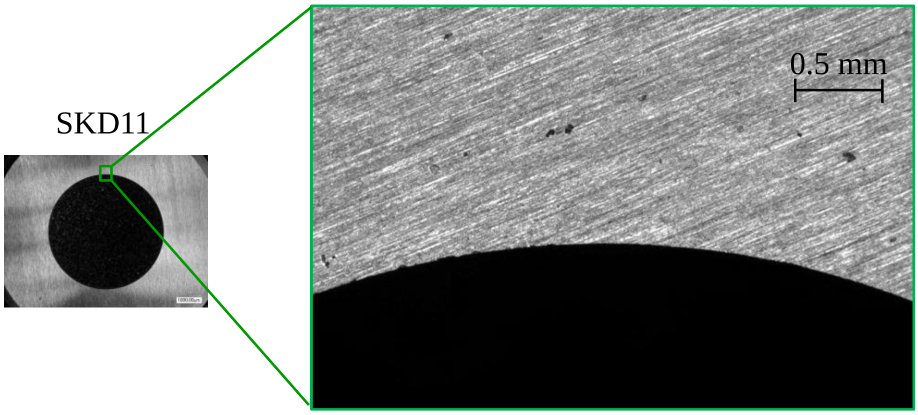
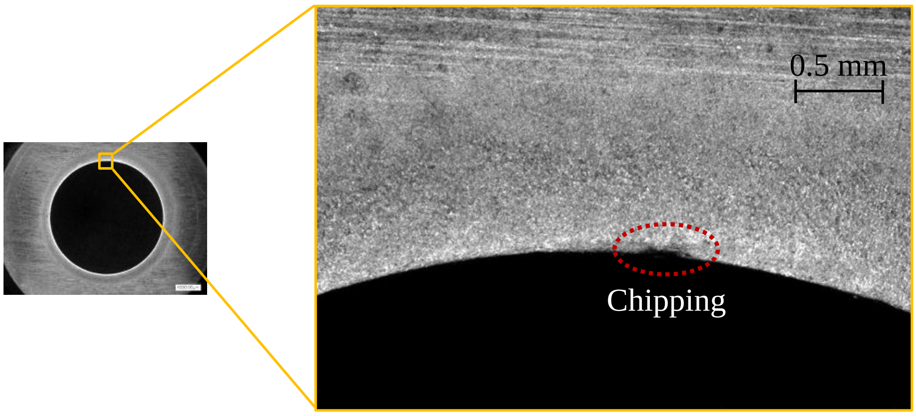


Fig. 4.12. Surface of punches of repeated punching with automatic centring of JSC980Y steel and die-quenched steel sheet after n = 500.

The surface of the die of repeated punching with automatic centring of die-quenched steel sheet after n = 500 is shown in Fig. 4.13. Since the strength and hardness of the die-quenched steel sheet was very high and the deformation behaviour in punching of die-quenched parts of 1500 MPa is severer, the quality of the upper surface of the die deteriorates. Small chipping was observed at the die after n = 500.



(a) As received



(b) After n=500

Fig. 4.13. Surface of die of repeated punching with automatic centring of die-quenched steel sheet after n = 500

4.5 Improvements of punch life in repeated punching of die-quenched steel sheets

4.5.1. Gradually increase punching speed in initial strike

To improve the quality of the sheared edge in repeated punching with automatic centring of die-quenched steel sheet, the sheets were punched by a gradual increase in punching speed in the initial strikes. The percentages of the rollover, burnished and fracture depths and burr height on the sheared edge without and with the gradual increase in punching speed in the initial strikes are given in Fig. 4.14. The depth percentage of sheared edge was measured for θ = 0, 90, 180 and 270° and the averages of the measured values are shown. By gradually increasing the punching speed in the early strikes, the punch and die became concentric. A higher percentage of the burnished surface was obtained as compared to the constant high punching speed. The gradual increase of punching speed method was applied for first five strikes (n = 1 until 5). For the next strike (n = 6 until 50), the high punching speed of 75 mm/s was kept. This method was repeated for the next 50 strikes.

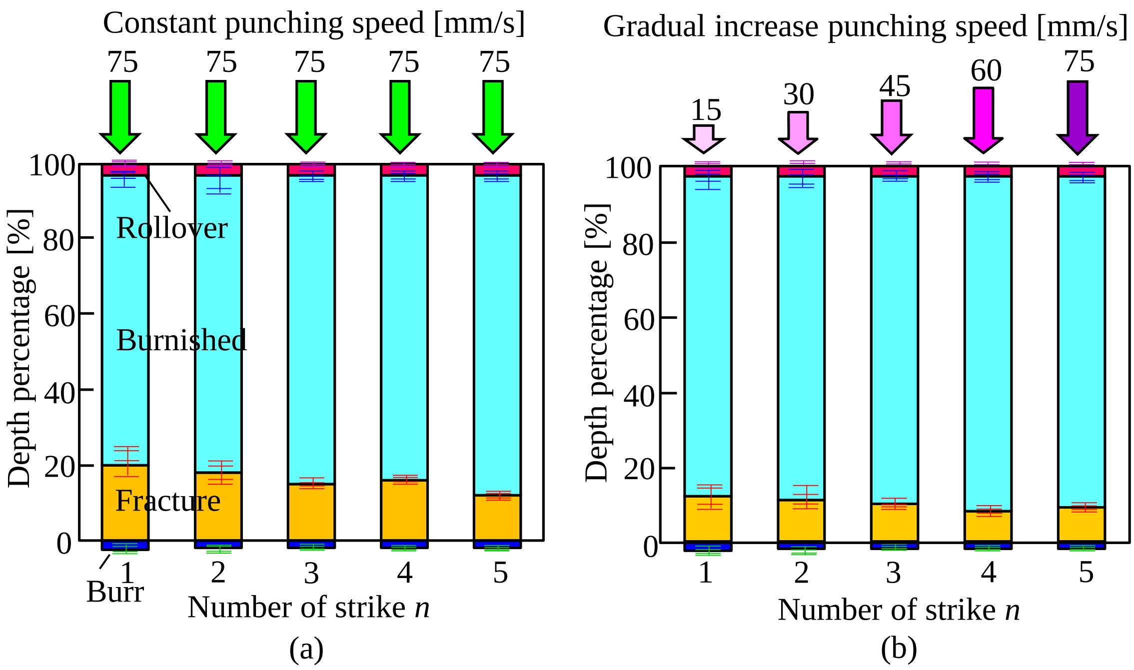


Fig. 4.14. Percentages of rollover, burnished and fracture depths and burr height on sheared edge for (a) without and (b) with gradual increase in punching speed in initial strikes.

4.5.2. Lubrication of punch

Since the die-quenched steel sheet has high strength and hardness, the punch tends to fail. To improve the punch life, the surface of the punch is lubricated with sulphur additive lubricant. The procedure for lubricating the punch surface with a sulphur additive lubricant is illustrated in Fig. 4.15. The sponge was placed in a container and moistened with the lubricant.

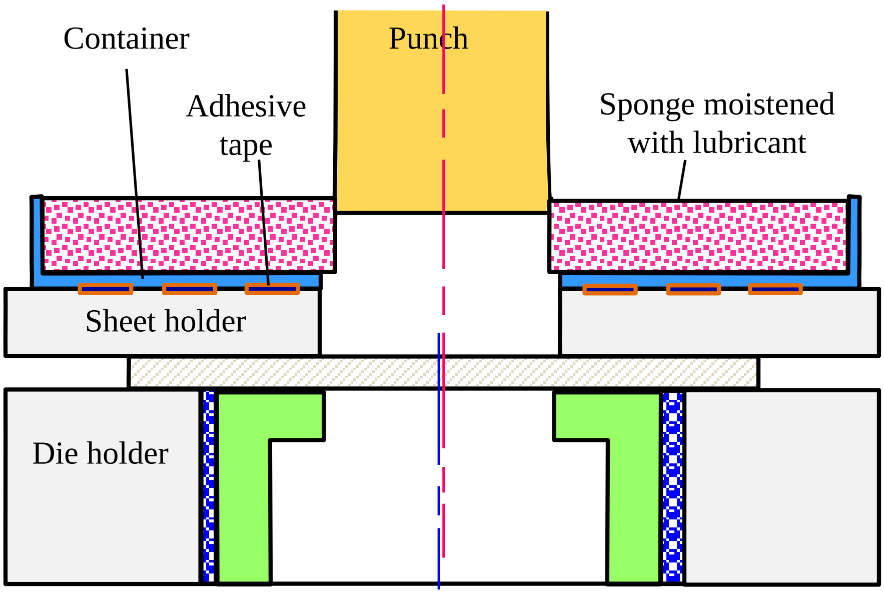


Fig. 4.15. Procedure for lubricating punch surface with sulphur additive lubricant.

4.5.3. Comparison of punching using punch without and with lubricant

The repeated punching with automatic centring using both punches without and with the lubricant were carried out for n = 100. The percentages of the rollover, burnished and fracture depths and burr height at the sheared edge for punching using punches without and with the lubricant are compared in Fig. 4.16. Since friction was high for the punch without lubrication, the fracture surface increases with the increase in strike number. By lubricating the punch, friction was reduced, and thus, the fracture surface remains low even if the strike number increases.

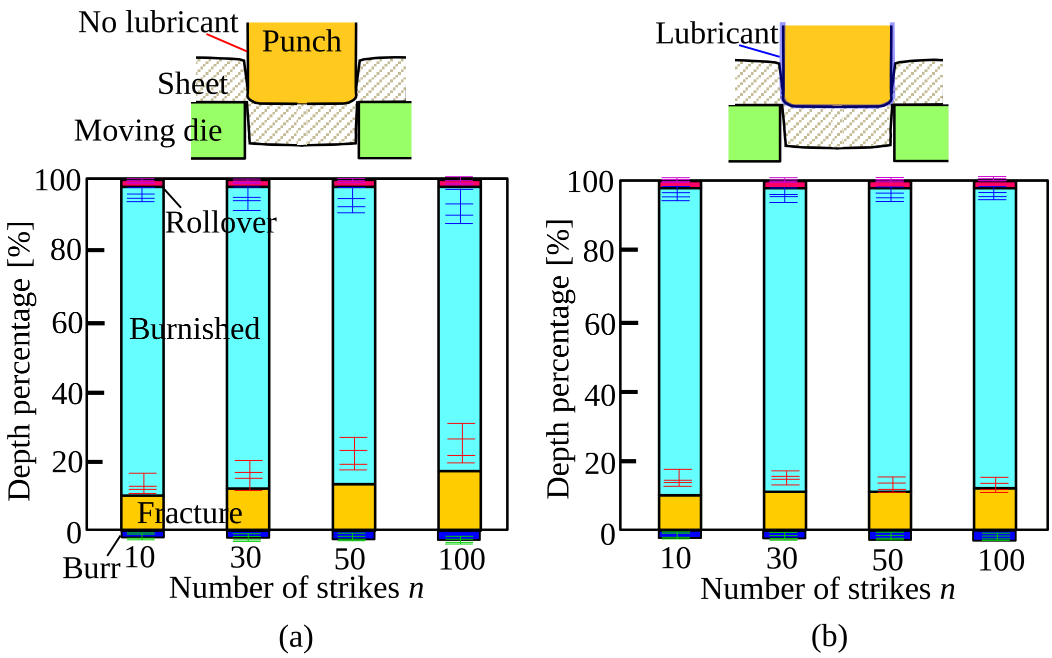
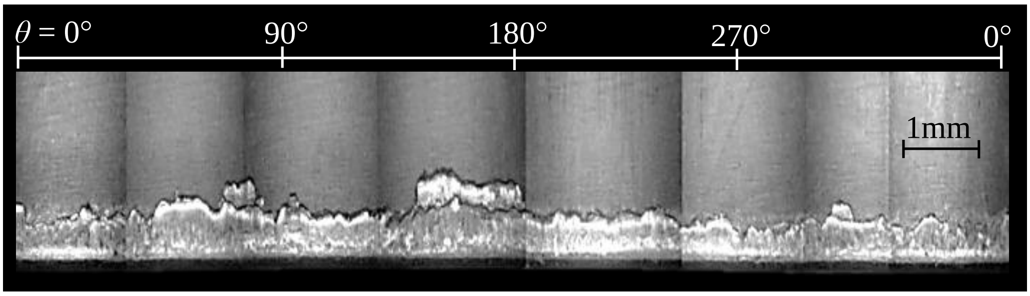
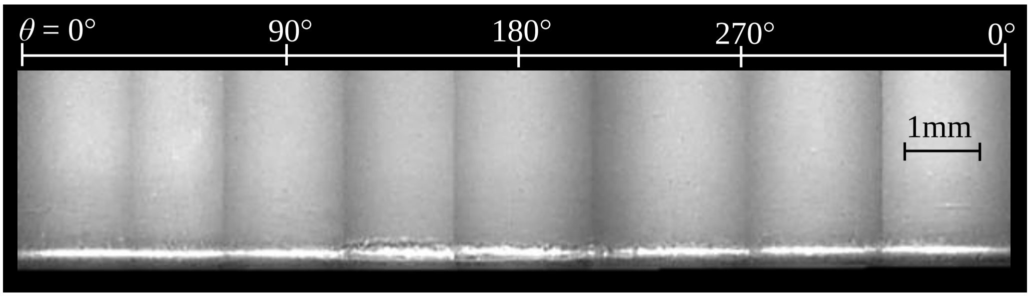


Fig. 4.16. Percentages of rollover, burnished and fracture depths and burr height on sheared edge for repeated punching using punches (a) without and (b) with lubricant.

The surfaces of the punches for punching die-quenched steel sheet using punch without and with lubricant after n = 100 are given in Fig. 4.17. Considerable galling was observed at the tip of the punch without the lubricant after n = 100. Galling in the punch was prevented with the lubricant.



(a)



(b)

Fig. 4.17. Surfaces of punches (a) with and (b) without lubricant after n = 100.

4.5.3. Quality of sheared edge and punch surface

The die-quenched steel sheets were repeatedly punched using punch with lubricant until *n* = 500, and the surfaces of the sheared edges are shown in Fig. 4.18. The large smooth burnished surface remained until *n* = 500.

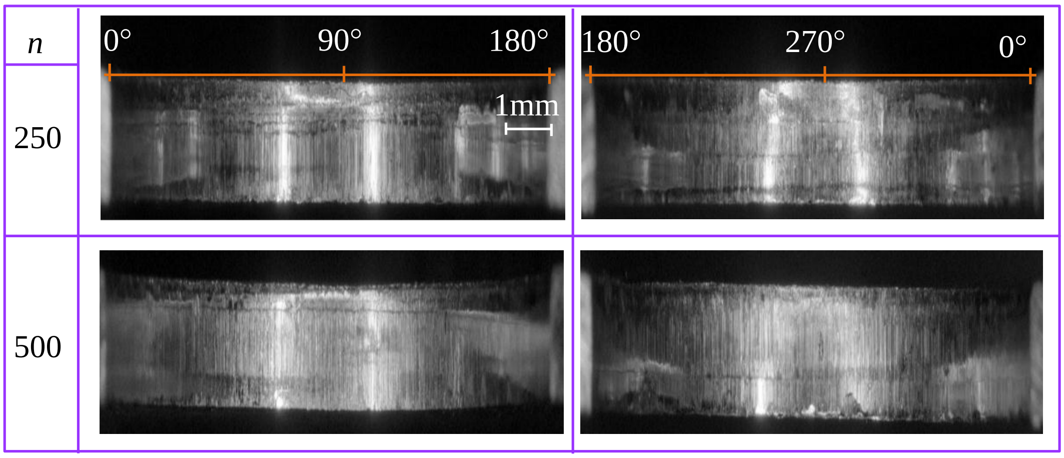


Fig. 4.18. Surface of sheared edges of die-quenched steel sheets for repeated punching with automatic centring using punch with lubricant.

The surface of the punch for repeated punching with automatic centring and punch with lubricant for n = 500 is shown in Fig. 4.19. Although galling occurred around the punch edge due to high strength of the sheet, the chipping of the punch edge was prevented even for a high number of strikes.

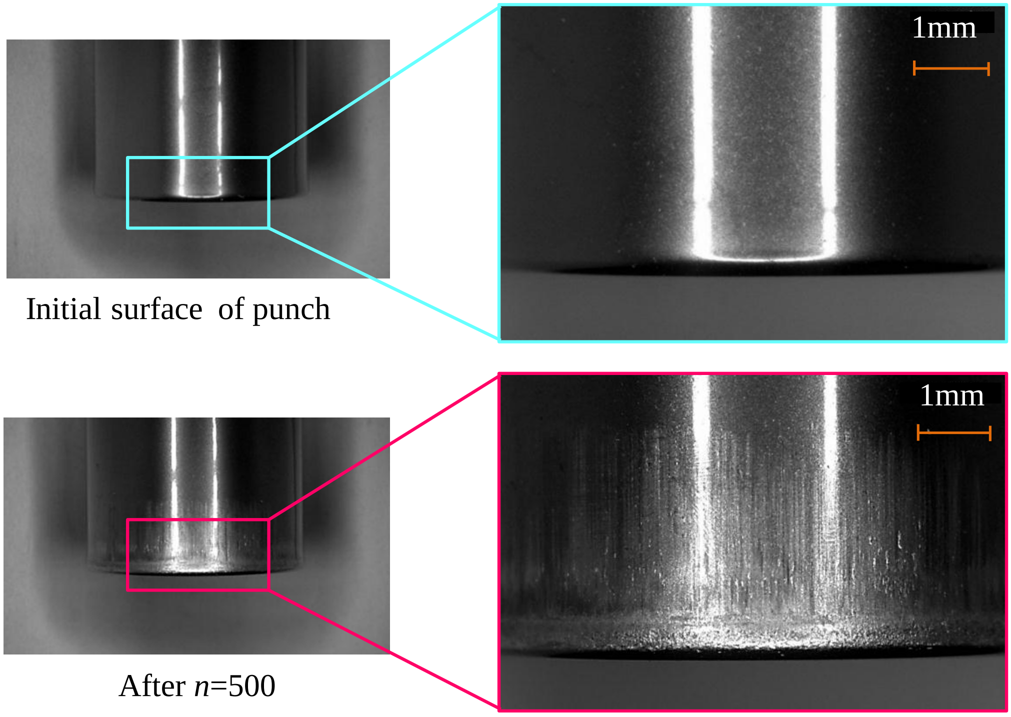


Fig. 4.19. Surface of punch for repeated punching with automatic centring with punch with lubricant after n = 500.

4.6. Conclusions

Since the car parts are usually consist of multiple holes for joining, attaching, painting, etc, the number of punching is increases. The small clearance punching process of die-quenched steel sheet having high specific strength was found effective for low number of strike and produces a high quality of sheared edge. For punching a much higher number of hole, the repeated small clearance punching process was developed to investigate the quality of the sheared edge and tools. The obtained results are as follows:

1) For repeated small punching of die-quenched steel sheet with the fixed die, the number of strike was low and the punch was broken for the occurrence of eccentricity between the punch and die after several strikes.
2) The number of strike was high in repeated punching of die-quenched steel and ultra-high strength steel sheets by combination of small clearance and automatic centring using a moving die.
3) Although the number of strike was high for die-quenched steel sheet, the high strength and hardness of the sheet deteriorate the quality of the sheared edge surface and punch life as the number of strike increases.
4) The decrease in punching speeds in the initial strikes is effective to initiate the high quality of the sheared edge in repeated punching of die-quenched steel sheet.
5) By lubricating surface of punch, galling was reduced and increased the tool life.

Chapter 5

Reductions of flying speed of scrap and noise in trimming of ultra-high strength steel sheets

5.1. Introduction

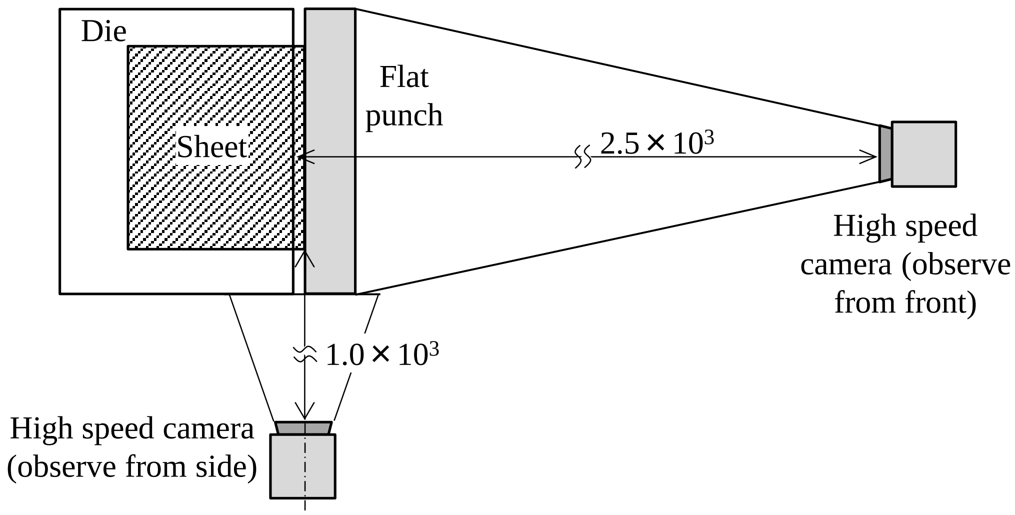
In the automotive industry, a car body panel is usually formed by drawing a flat sheet into the desired shape. The formed parts, especially the larger sized parts of the car such as the A, B, C, D-pillars, roof rails, front members, etc., usually require a post finishing process such as trimming to remove the scrap portions. During trimming the scrap portions are usually simultaneously trimmed using a single punch stroke. Thus, the way of restraining the unnecessary portion i.e. the scrap portion and the separation of the material is different from conventional shearing or blanking [95-96]. Since the application of ultra-high strength steel sheets is the current trend for the automobile industry, the trimming process becomes difficult due to the large forming load and decrease in tool life [47-57]. In trimming of ultra-high strength steel sheets, the flying speed of the scrap is large due to the high strength, and thus the scrap jump out from a disposal.

During removal of the scrap portion, the noise from the trimming process is a problem especially when trimming hard material such as high strength steel sheets. The trimming operation also becomes noisy due to high trimming load. An excessive exposure to high noise level, mainly for workers on the production line, might affect their health in the long-term. Not only the machine, but the process itself contributes to unsafe working conditions with its high level of noise [101-106]. An adequate noise level in industrial plants is usually not more than 100 dB and a noise level above 135 dB might result in hearing loss [101. Although ear protection devices are compulsory, the level of sensitivity to the dangers present in the workplace is reduced due to the high level of noise.

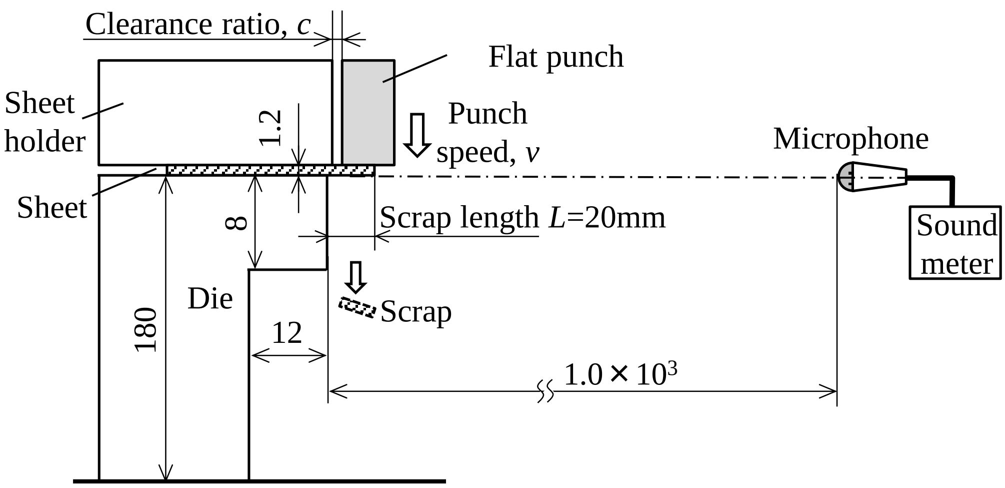
In the present study, the flying behaviour of the scrap in trimming of ultra-high strength steel sheet with the flat punch was investigated and the level of noise during trimming was measured. The effects of clearance, trimming speed and strength of the sheet were examined. The new punch shapes having inclined part were introduced to reduce the flying speed of the scrap and the noise level.

5.2. Observation of flying behaviour and measurement of noise of scraps

The method to observe the flying speed and to measure the noise level of during trimming is shown in Fig. 5.1. The trimming of the sheet was performed using a flat punch. Deformation behaviour of the trimming process was observed from the front and side using the high speed camera. A sound meter was used to measure the sound level of trimming process.



(a) Observation of scrap falling behavior from side (top view).



(b) Measurement of sound level using sound meter.

Fig. 5.1. Experimental setup for observing flying speed of scrap and measuring noise level.

The recording conditions for observing trimming process are given in Table 5.1. The high speed camera used is CMOS K4 with a frame rate per second of 800. The specifications of the sound meter to record the sound level during trimming are given in Table 5.2.

Table 5.1.

Recording condition using high speed camera.

Camera type	High speed digital camera CMOS K4
Gain [dB]	0
Shutter speed,[μs]	1.163
Frame rate [fps]	800
Resolution	640 x 480

Table 5.2.

Specifications of the sound meter.

Noise level range [dB]	25 ~ 130
Sampling frequency [kHz]	48

The mechanical properties of the sheet used for trimming are given in Table 5.3. The sheets used are from 780MPa to 1180Mpa grade steel plate. The length, width, and thickness of the sheet were 80, 60, and 1.2 mm, respectively as shown in Fig. 5.3.

Table 5.3.

Mechanical properties of ultra-high strength steel sheets used for trimming.

Material	Thickness [mm]	Tensile strength [MPa]	Elongation [%]
JSC780YN	1.2	813	17.3
JSC980YN	1.2	1004	12.6
JSC1180YN	1.2	1242	8.1

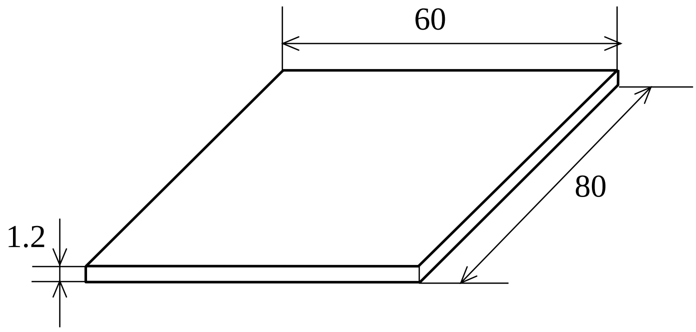


Fig. 5.2. Dimension of sheet for trimming.

The conditions of trimming of ultra-high strength steel sheet with a flat punch are given in Table 5.4. The punch and die were made of high-speed tool steel having a hardness of HRC60. The clearance ratio to the sheet thickness and scrap length *L* were changed for 5 - 25 % and 5 - 20 mm, respectively for trimming with flat punch. For other experiment, the clearance ration and scrap length was keep for 10% and 20 mm, respectively. The trimming speed for all experiments was 48 mm/s.

Table 5.4.

Conditions of trimming of ultra-high strength steel sheets.

Die material	SKH51
Punch material	SKH51
Clearance to thickness ratio, c [%]	5-25
Punching speed [mm/s]	48
Scrap length, *L* [mm]	5-20

5.3. Results of trimming with flat punch

5.3.1. Deformation and flying behaviour of scrap

The deformation and flying behaviour of the scrap in trimming of JSC980YN sheet observed from the front and side view for *c* = 10%, *L* = 20 mm and *v* = 48 mm/s are given in Fig. 5.3(a) and (b), respectively. The scrap was fell from the starting point of trimming and reached about 180 mm down just in 56 ms. The trimming speed was very high of about 2500 mm/s. the scrap was rotated for many times during starting of trimming until it reached the lower plate of the die.

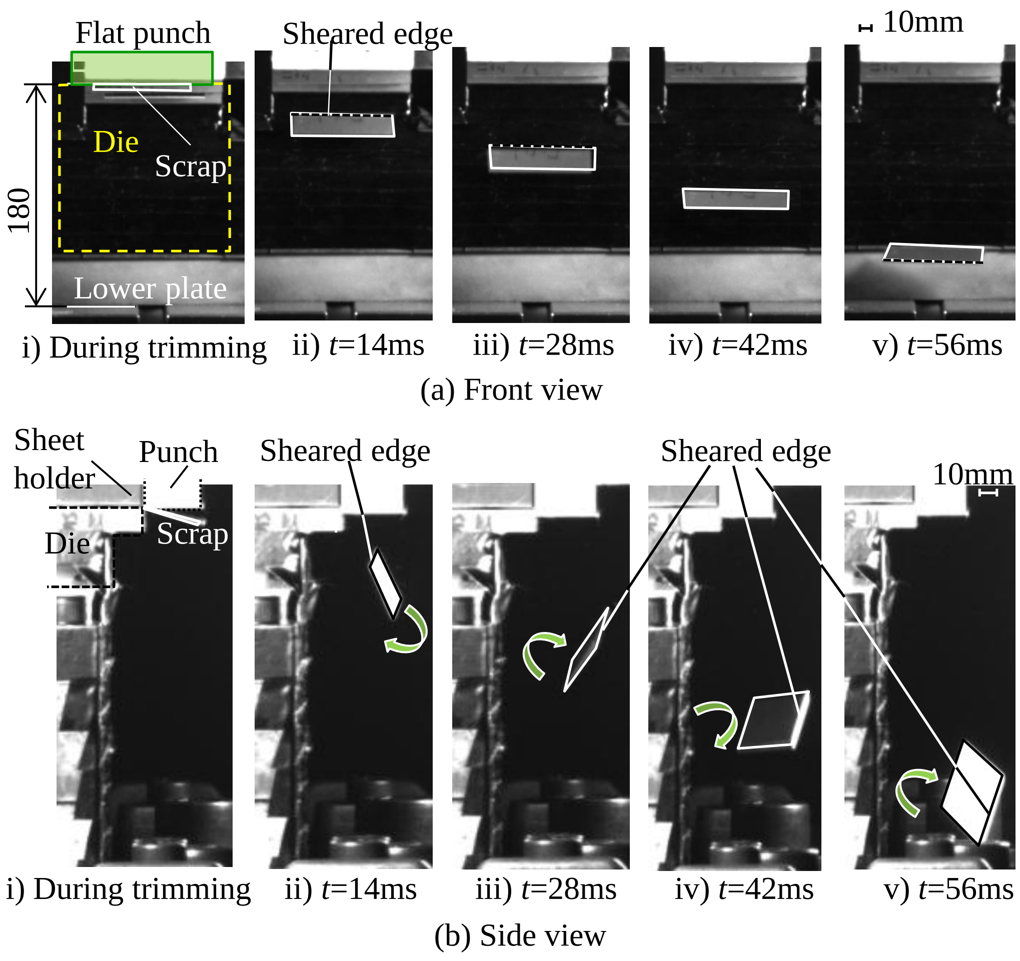


Fig. 5.3. Deformation and flying behaviour of scrap in trimming of JSC980YN sheet for *c* = 10%, *L* = 20 mm and *v* = 48 mm/s.

The trimming load-punch stroke curves for different strength steel sheets are shown in Fig. 5.4. The maximum trimming load for all sheets was occurred at the punch stroke around 1 mm. As the strength of the sheet increases the trimming load was increased.

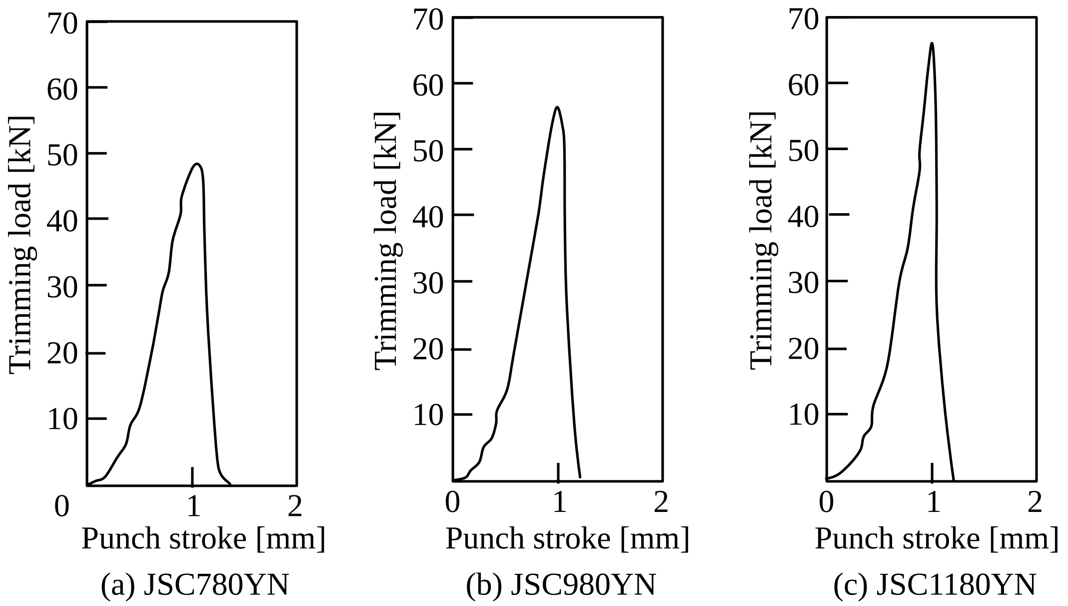


Fig. 5.4. Trimming load-punch stroke curves for different strength steel sheets for c = 10% and L = 20 mm.

5.3.2. Flying speed and sound level of scrap

The relationship between the flying speed of scrap and maximum trimming load for different strength of steel sheets is given in Fig. 5.5. The free fall speed of the sheet was about 850 mm/s. For trimming the sheets with v = 48 mm/s, the flying speed of the scrap was increase more than two times than that of the free fall. For the higher strength of JSC1180YN, the maximum trimming load and flying speed was greatest among the three types of the sheet and almost 1.5 times higher than that of JSC780YN.

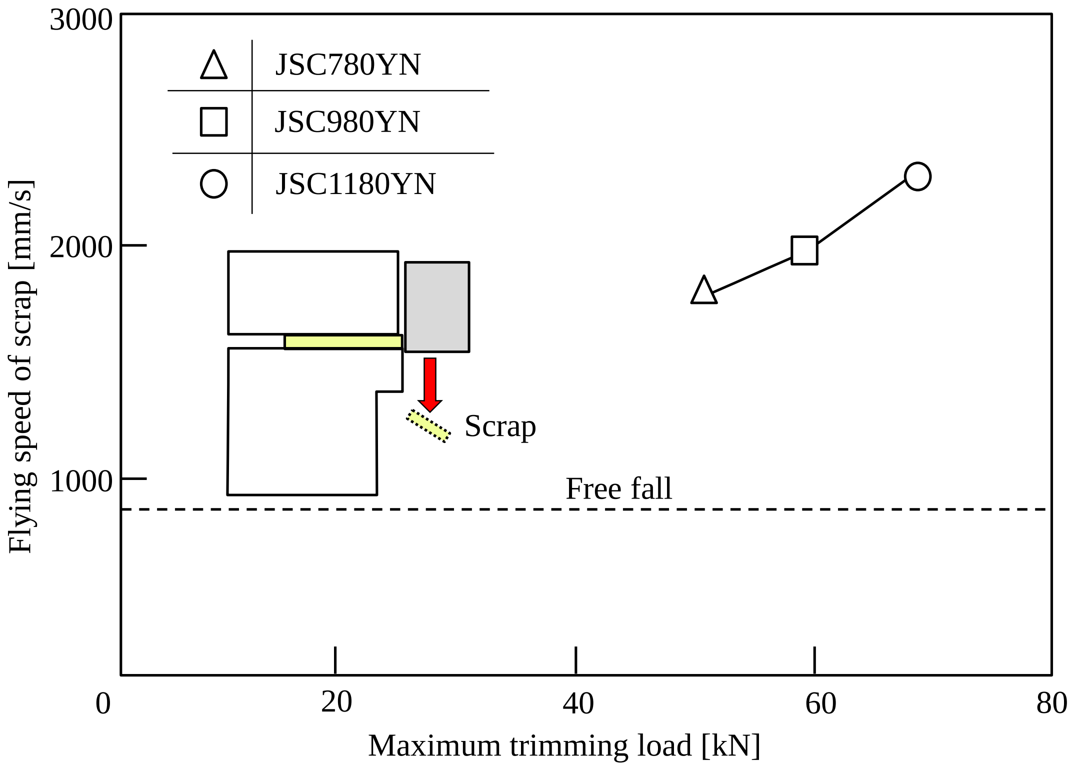


Fig. 5.5. Relationship between flying speed of scrap and maximum trimming load for different strength of steel sheets for c = 10 %, L = 20 mm, and v = 48 mm/s.

The relationship between the maximum sound pressure level and maximum trimming load for different strength of steel sheets is shown in Fig. 5.6. The sound level of the press machine 80 dB. The sound level was larger with increase of the tensile strength of the steel sheet.

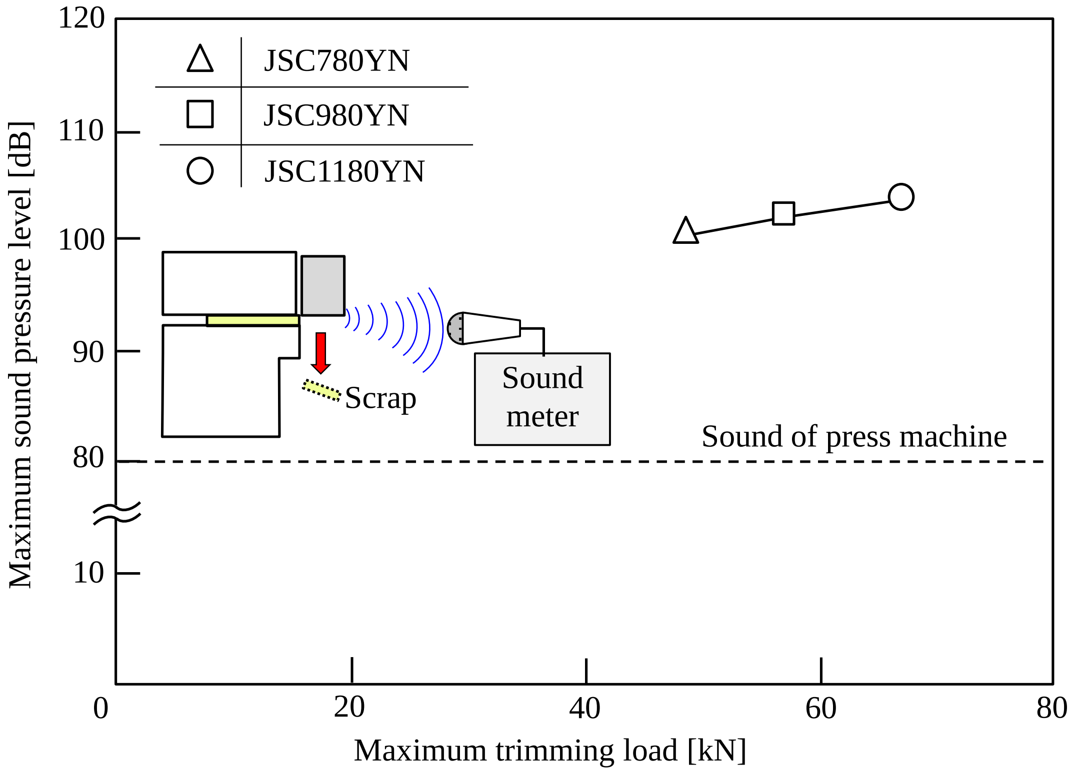


Fig. 5.6. Relationship between maximum sound pressure level and maximum trimming load for different strength of steel sheets for c = 10 %, L = 20 mm, and v = 48 mm/s.

5.3.3. Effects of clearance

The effects of clearance on the bending angle of different strength sheets for L = 20 mm, and v = 48 mm/s are given Fig. 5.7 where α is bending angle of the sheet just before being cut off as a scrap. The bending angle was increased with the increased of the clearance. In addition, the bending angel was decreased with the increase of the tensile strength of the steel sheet. As the bending angle was more than 35 %, the falling scrap was collided with the die wall.

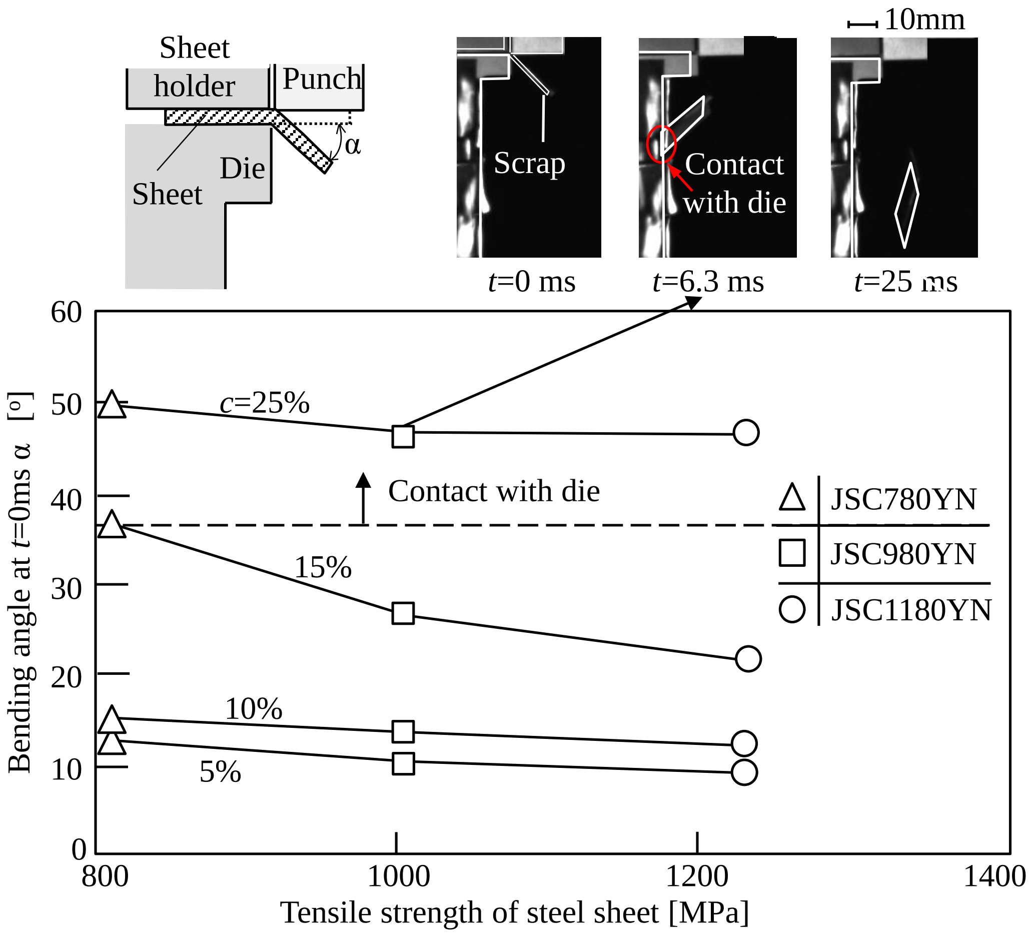


Fig. 5.7. Effects of clearance on bending angle of different strength steel sheets for L = 20 mm, and v = 48 mm/s

The cross section and depth percentage of the sheared edge surface Cfor trimming with different clearance ratio are shown in Fig. 5.8. The burnished surface was larger for trimming with *c* = 10 %. However the fracture surface was increased with the increase of the strength of the sheet. The burr formation were large and for trimming with *c* = 25 %and the height is almost five time than that of *c* = 10 %. The large burr height and fracture surface increase the tendency of cracking of the trimmed part.

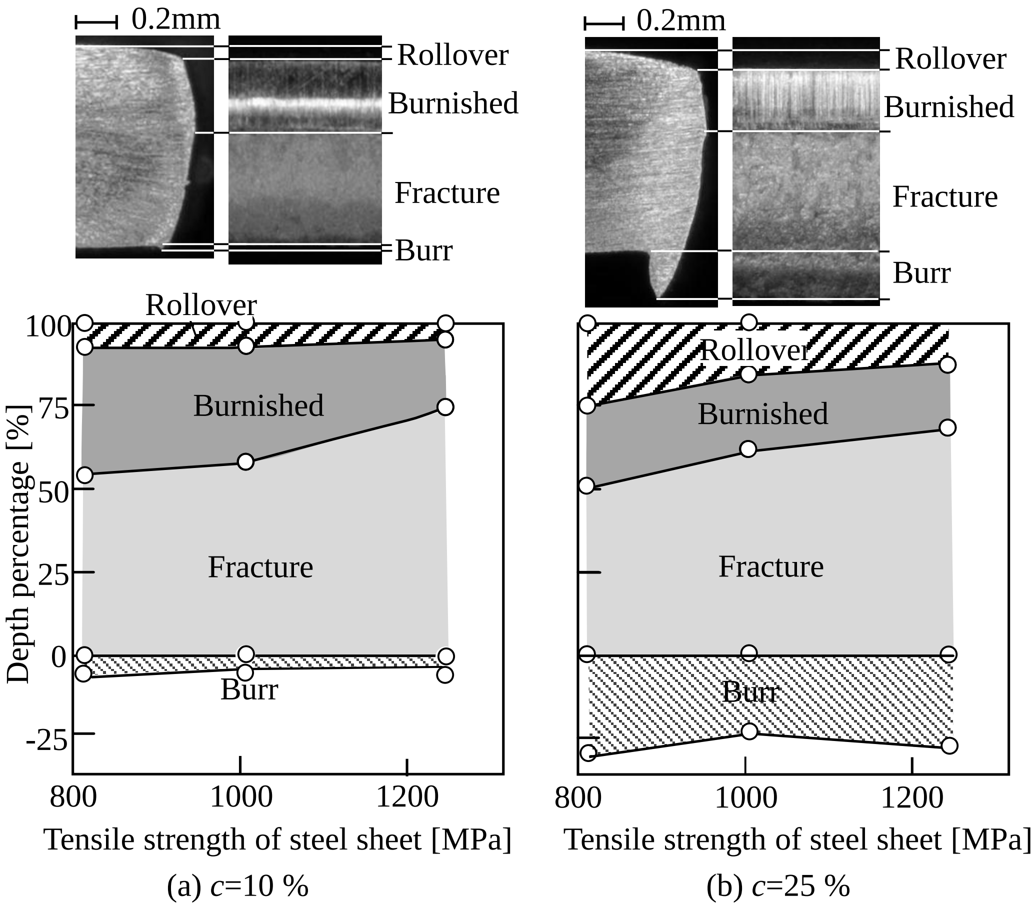


Fig. 5.8. Cross section and depth percentage of the sheared edge of for trimming different strength steel sheets for *c* = 10 and 25 %, *L* = 20 mm and *v* = 48 mm/s.

The relationship between the flying speed of the scrap of different strength steel sheets and clearance ratio for L = 20 mm, and v = 48 mm/s are given Fig. 5.9. The flying speed of the scrap decreased with the increases of the clearance ratio. The velocity of the scrap for the steel sheet with a higher tensile strength was higher in all clearance conditions.

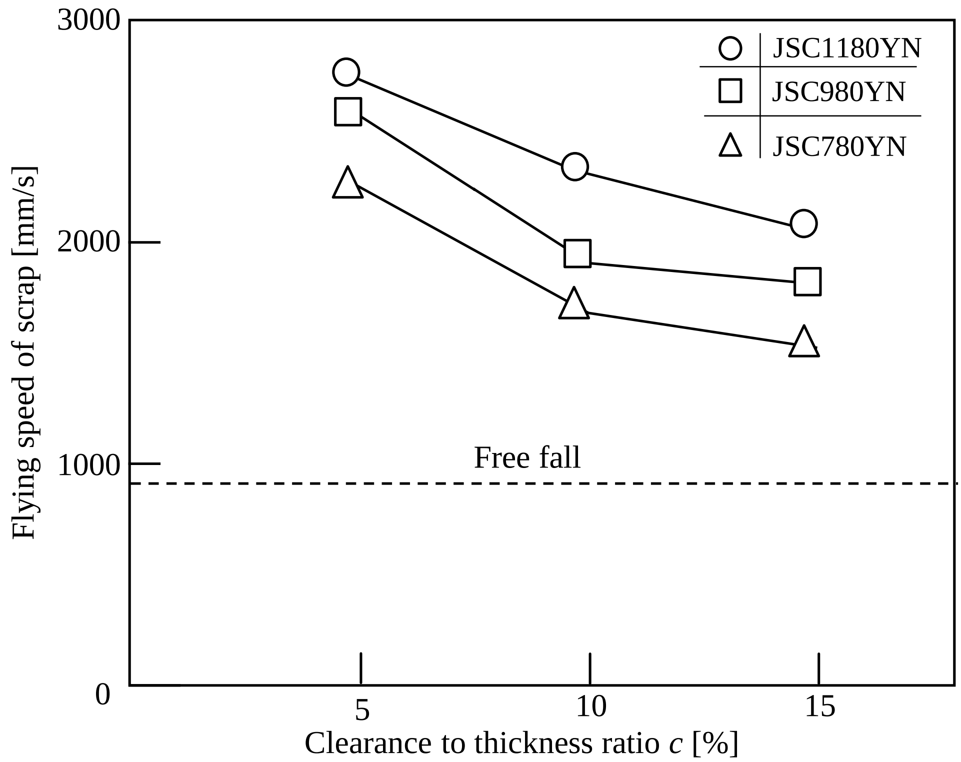


Fig. 5.9. Relationship between flying speed of scrap of different strength steel sheets and clearance ratio for L = 20 mm, and v = 48 mm/s

The effects of the length of the scrap L on the flying speed of the scrap for v = 48 mm/s are given Fig. 5.7. The longer the scrap the larger the weight and thus the speed was also decreased. The large trimming load acting on the scrap with higher strength steel sheet make the smaller size and weight scrap to fall and fly with a higher speed.

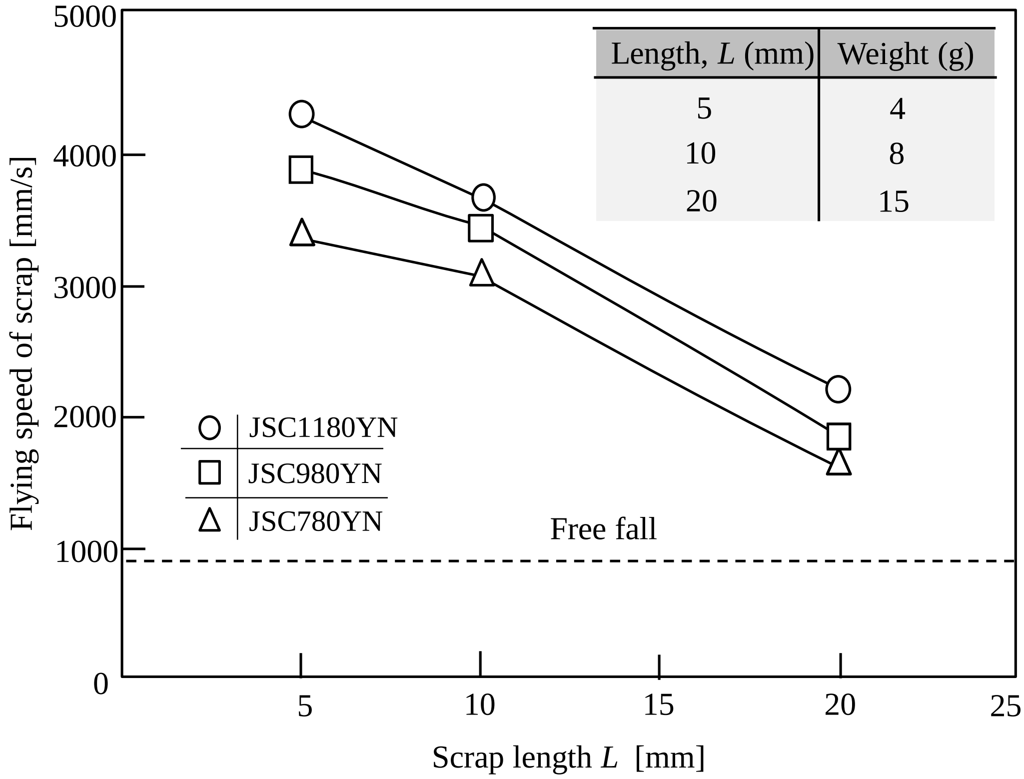


Fig. 5.10. Effects of the length of scrap on the flying speed of the scrap for v = 48 mm/s.

5.4. Reduction of flying speed and noise level

5.4.1. Deformation behaviour of scrap for trimming with different punch shapes

To reduce the flying speed of scrap and noise level of trimming process, the bevel and flat-bevel punch were developed. The comparison of deformation behaviours for trimming with different punch shapes are illustrated in Fig. 5.11. For trimming with the flat punch, all zones of the sheet are simultaneously and uniformly trimmed. Thus the trimming load and flying speed of the scrap is large. For the bevel punch, only a local zone of the sheet is in contact with the punch during trimming. The sheet is gradually trimmed until the scrap is separated and therefore the trimming load and the flying speed of the scrap is low. For the flat-bevel punch, the flat part of the punch uniformly trimmed the sheet in the initial stage, followed by a gradually trimming as the inclined part of the flat-bevel punch is reached. As a result the punching load and flying speed of the scrap is reduced.

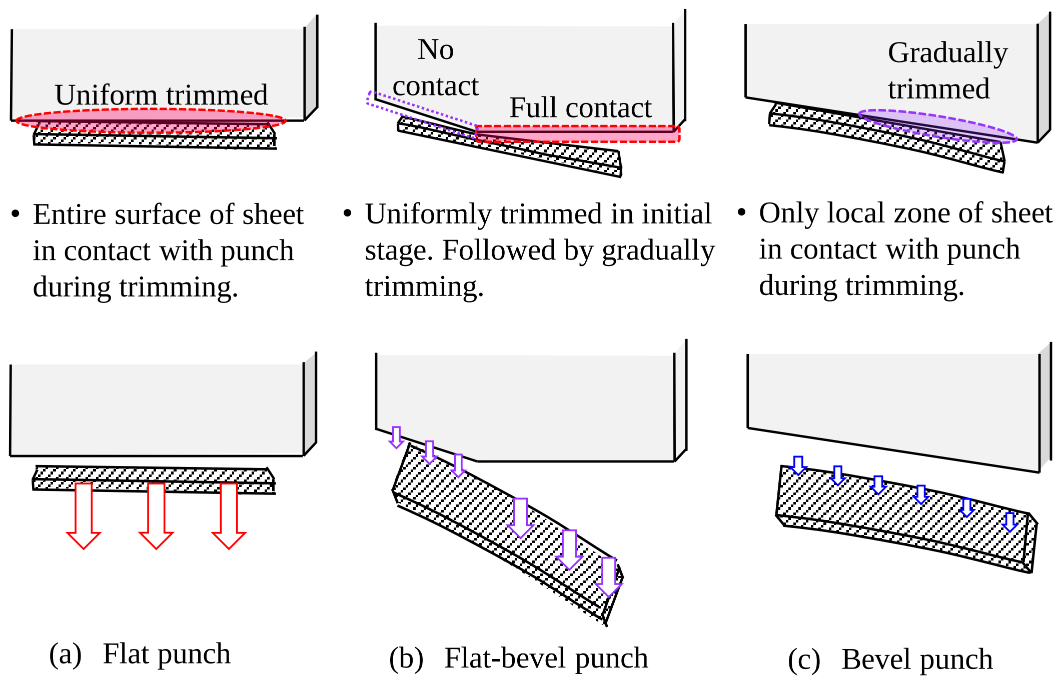


Fig. 5.11. Deformation behaviour of sheet for trimming with different punch shapes

5.4.2. Flat-bevel and bevel punch

To reduce the flying speed of the scrap and noise level of during trimming, the inclined and flat-bevel punch were developed. The dimensions of the flat-bevel and bevel punch were shown in Fig. 5.12, where θ is the inclined angle of the punch. The bevel punch consists of three inclined angles of 1, 5, and 10° whereas only θ = 5° for the flat-bevel punch. The effects of these punches on the flying behaviour and flying speed of scrap and sound level were investigated

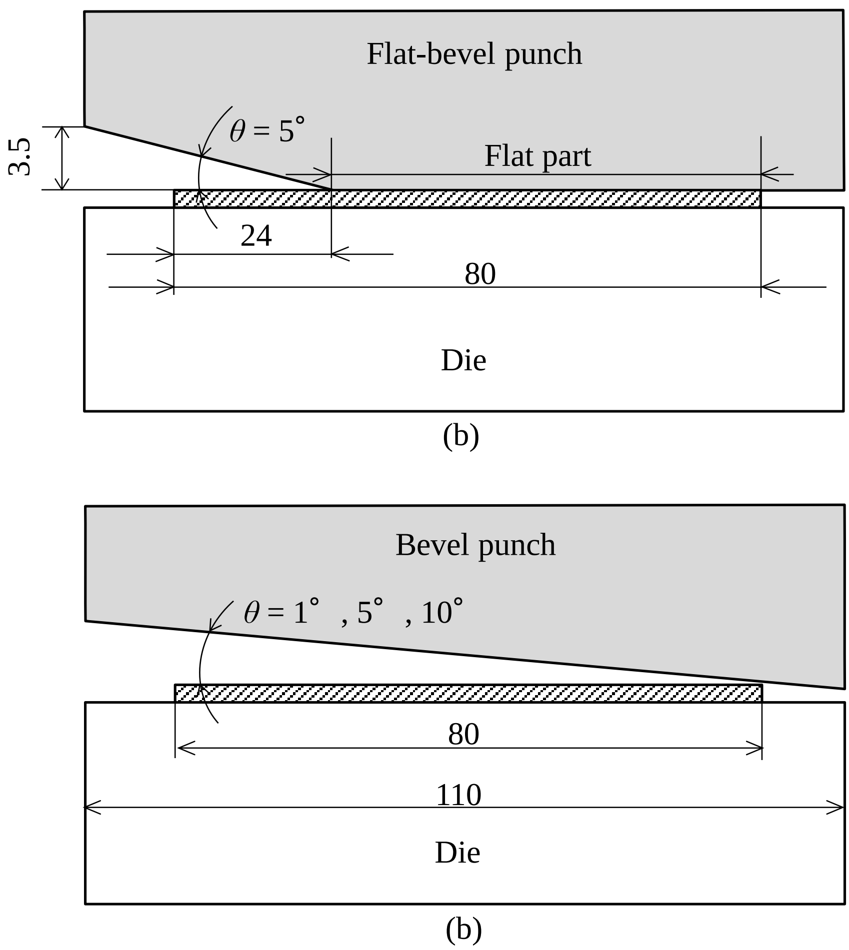


Fig. 5.12. Dimensions of flat-bevel and bevel punches.

5.4.3. Flying behaviour for trimming with flat-bevel and bevel punches

The deformation and flying behaviour of the scrap in trimming of JSC980YN sheet with flat-bevel punch observed from the front for c = 10%, L = 20 mm and v = 48 mm/s are given in Fig. 5.14. In the initial stage of trimming, the flat part of the flat-bevel punch uniformly trimmed the sheet. When the trimming process reached the inclined part of the flat-bevel punch, the sheet was gradually trimmed. The scrap was dropped and remained slightly inclined after separated from the sheet. However the fallen scrap was rotated during dropping down.

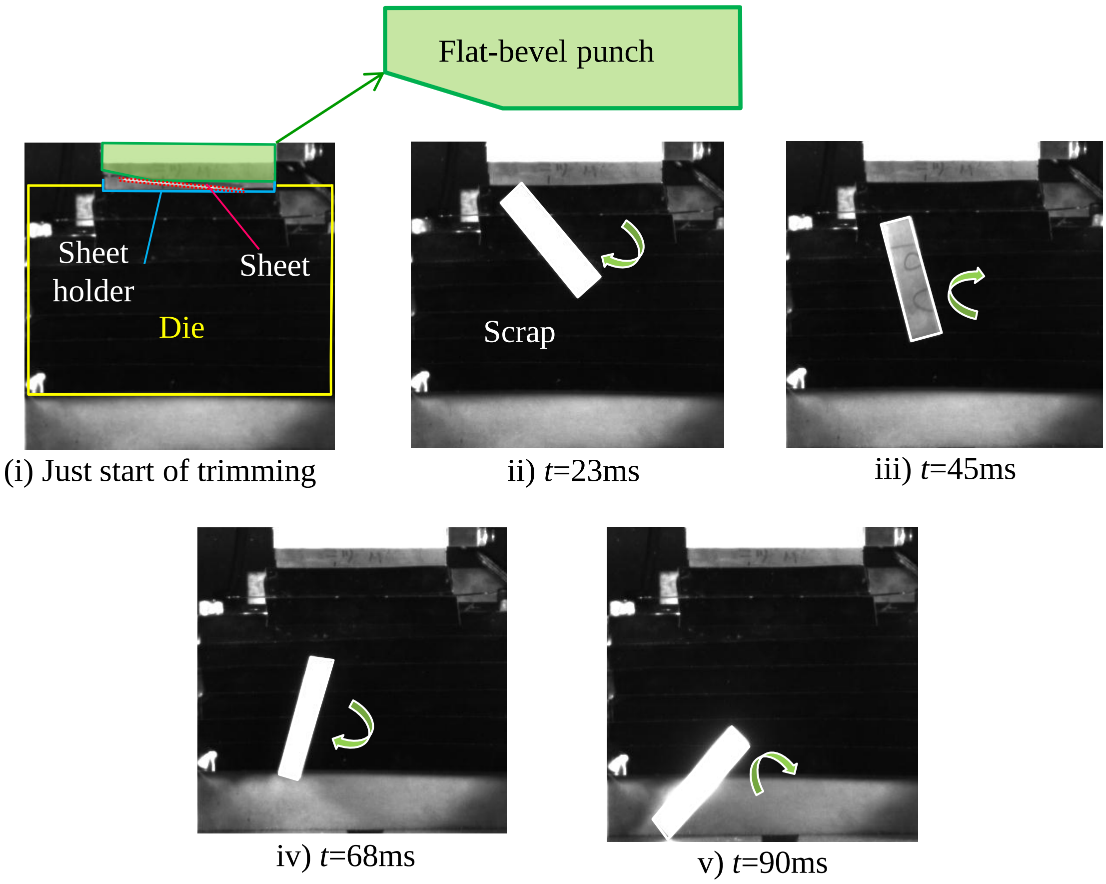


Fig. 5.13. Deformation and flying behaviour of scrap in trimming of JSC980YN sheet with flat-bevel punch observed from the front for c = 10%, L = 20 mm and v = 48 mm/s.

The deformation and flying behaviour of the scrap in trimming of JSC980YN sheet with bevel punch observed from the front for c = 10%, L = 20 mm, v = 48 mm/s and θ = 10° are given in Fig. 5.14. The scrap was gradually trimmed from one end of the sheet. The scrap was dropped without rotating and remained slightly inclined after separated from the sheet. The scrap trimming with the inclined reached the lower plate of the die in 90 ms as compared to just 56 ms for trimming with the flat punch (see Fig. 5.3).

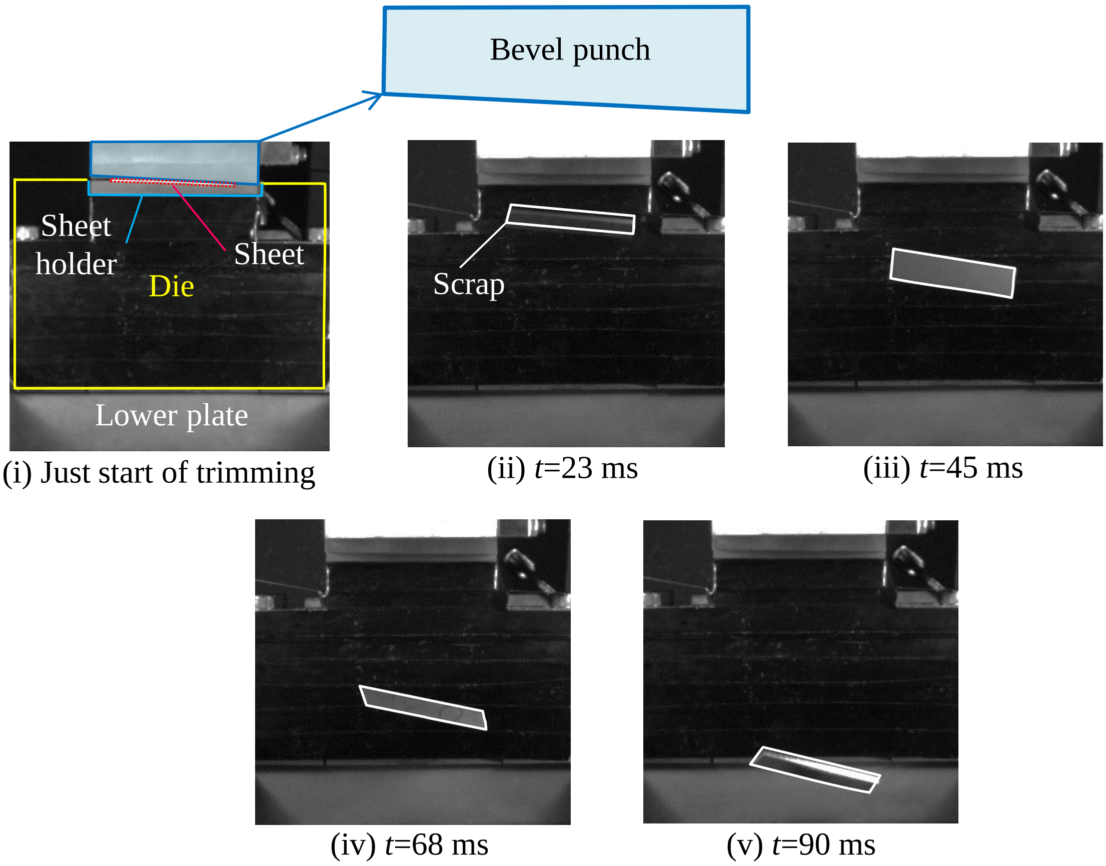


Fig. 5.14. Deformation and flying behaviour of scrap in trimming of JSC980YN sheet with bevel punch observed from the front for c = 10%, L = 20 mm, v = 48 mm/s and θ = 10°.

5.5. Result of trimming with different punch shapes

5.5.1. Quality of sheared edge and trimming load

The depth percentage of the sheared edge surface of different strength steel sheets for trimming with the flat-bevel punch are shown in Fig. 5.16. The sheared edge surface was observed from the left to the right parts of the trimming process. The burnished surface was decreased with the increased of strength of the steel sheet. A separated small burnished surface at the fracture surface was observed and became smaller with the increased of the strength of the steel.

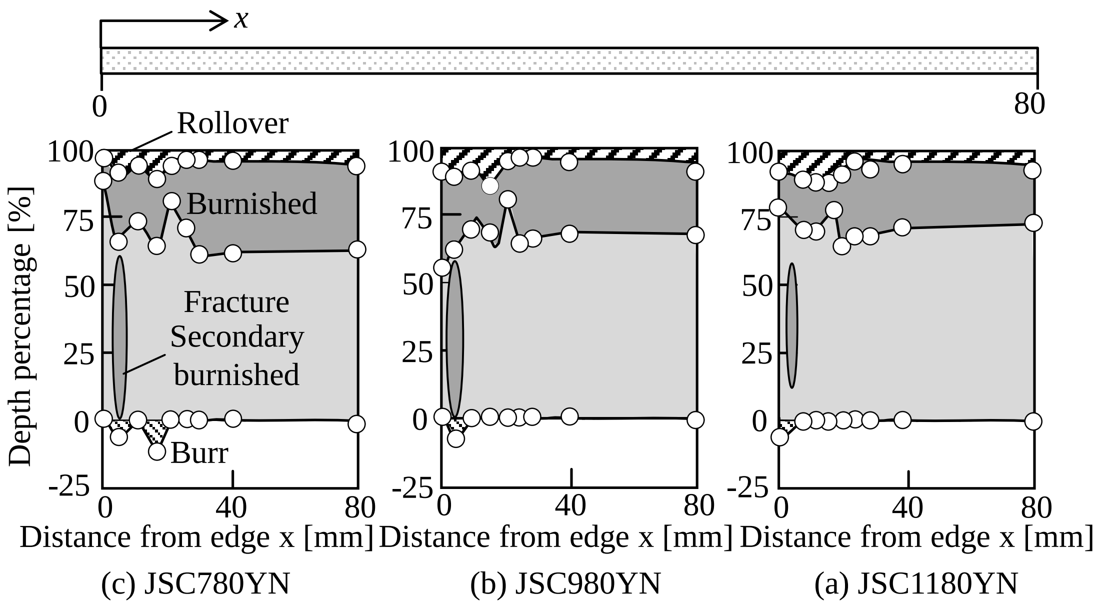


Fig. 5.15. Depth percentage of sheared edge surface of different strength steel sheets for trimming with flat-bevel punch.

The depth percentage of the sheared edge surface of different strength steel sheets for trimming with the bevel punch are shown in Fig. 5.15. The sheared edge surface was observed from the left to the right parts of the trimming process. The burnished surface was larger at the right part of the trimming zone i.e. the zones which was initially of trimmed. The burnished surface was decrease as the bevel punch move further to trim the other zones. For the increase of the strength of the steel sheet, the fracture surface increased.

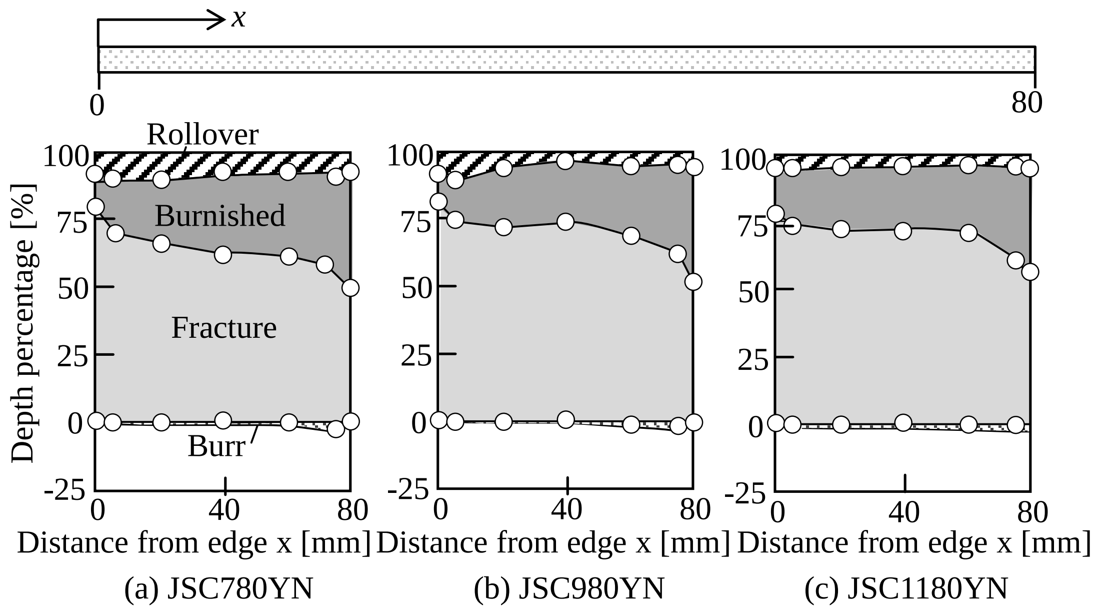


Fig. 5.16. Depth percentage of sheared edge surface of different strength steel sheets for trimming with bevel punch.

The trimming load-punch stroke curves for different punch shapes are shown in Fig. 5.17. The trimming load is largest for trimming with the flat punch followed by the flat-bevel punch because a large force was needed to uniformly trimming the scrap. For the bevel punch, the trimming load was drastically reduced of about only 1/5 of the maximum trimming load of the flat punch because of the scrap was gradually trimmed. The trimming load was further reduced with the increased of the inclined angle. However the trimming stroke became longer.

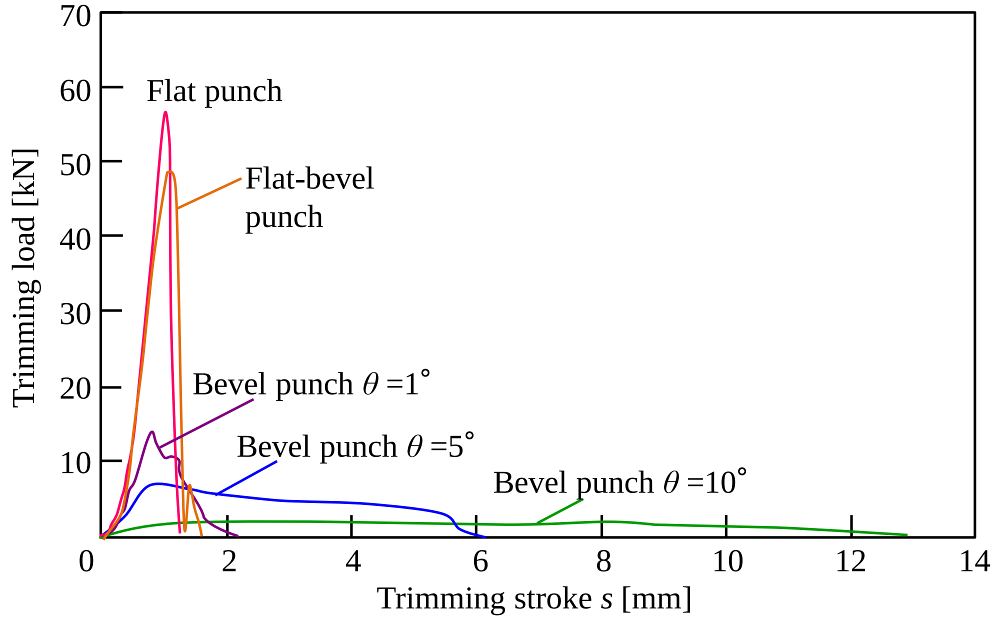


Fig. 5.17. Trimming load-punch stroke curves for different punch shapes.

5.5.2. Flying speed of scrap and sound level

The relationship between the flying speed of the scrap and the different strength steel sheets for trimming with different punch shapes are given Fig. 5.18. The flying speed of the scrap was highest for trimming with the flat punch. The velocity of the scrap decrease significantly for trimming with the inclined and flat-bevel punch. The flying speed of the scrap were dropped almost half of trimming with the flat punch for trimming with the flat-bevel and bevel punch of θ = 5 and 10 °. However the flying speed of the scrap was increased for the increase in the tensile strength for all punch shapes.

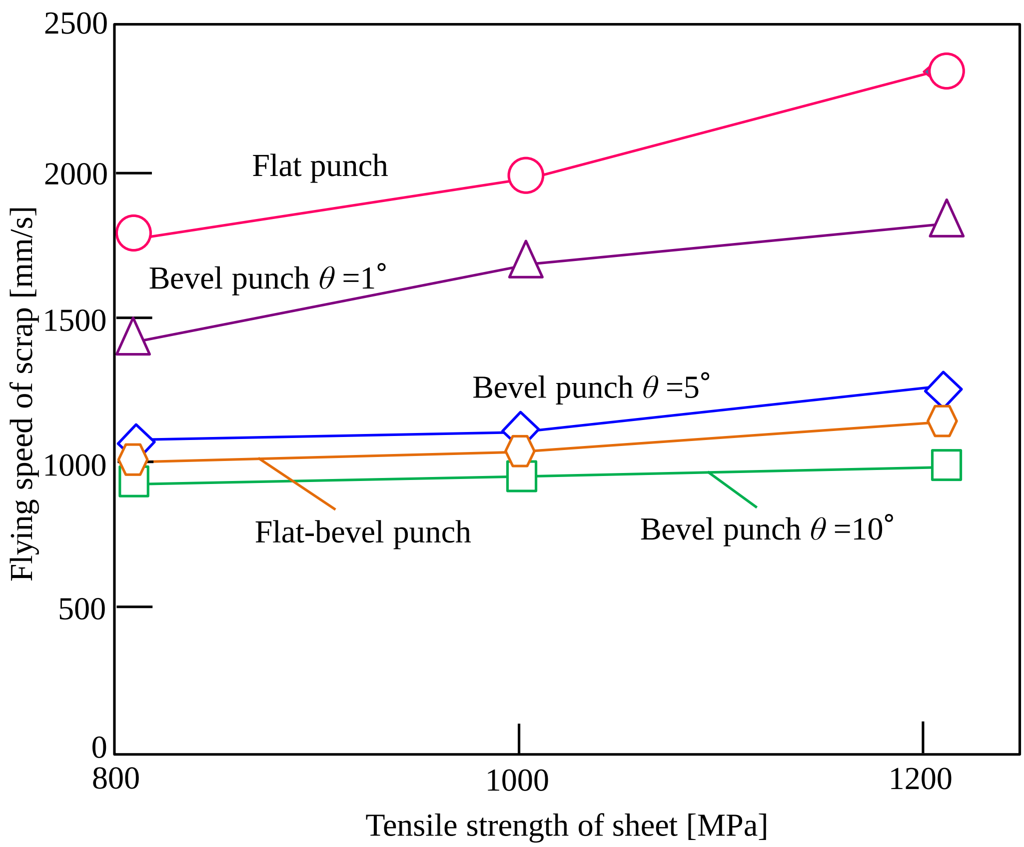


Fig. 5.18. Relationship between flying speed of the scrap and different strength steel sheets for trimming with different punch shapes.

The relationship between the maximum sound pressure level and the different strength steel sheets for trimming with different punch shapes are given Fig. 5.19. The sound level of trimming was highest for trimming with the flat punch followed by the flat-bevel punch. The sound level was dropped for trimming with the bevel punch. The increases in the inclined angle of the punch decreases the sound pressure level .The sound level was increased with the increase in the tensile strength for all punch shapes.

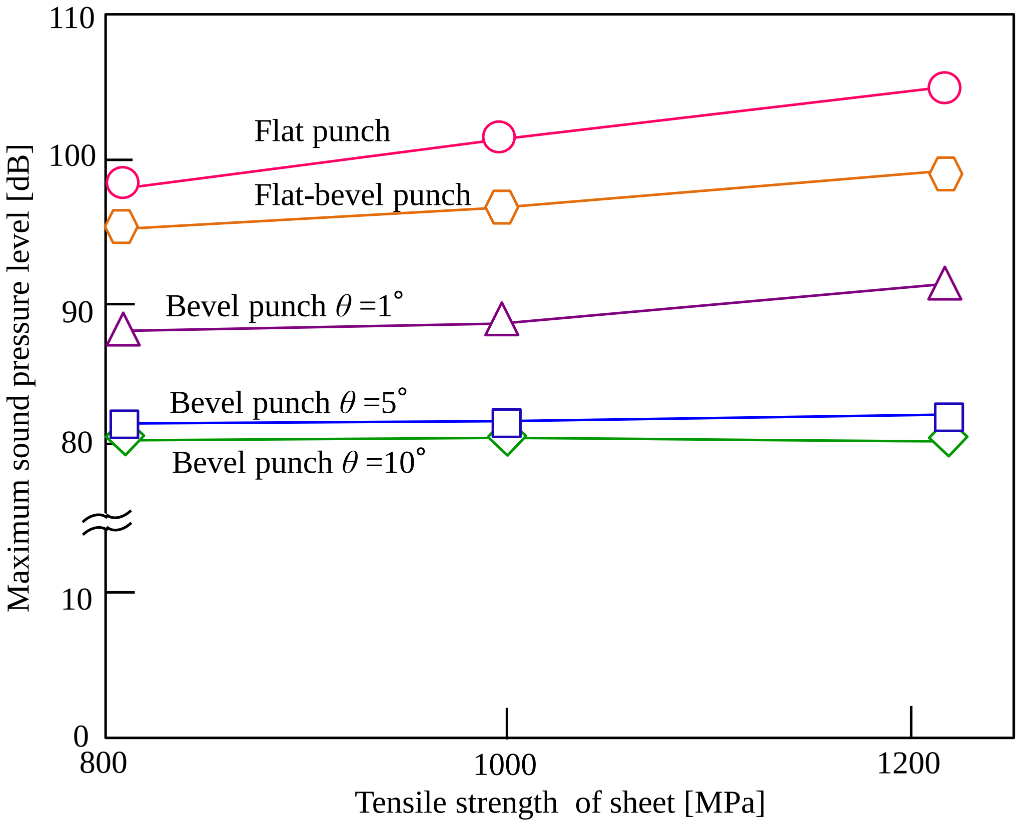


Fig. 5.19. Relationship between maximum sound pressure level and different strength steel sheets for trimming with different punch shapes

5.7. Conclusions

The application of ultra-high strength steel parts for the car body was significantly increased. The drawn parts usually need finishing process to remove the undesired parts. In the present study, the scrap falling behaviour and noise level in trimming of ultra-high strength steel sheet were investigated and the following results were obtained:

1) The flaying speed of the scrap and noise level were increased with strength of the sheet and trimming load for trimming with the flat punch.
2) Flat-bevel punch is effective to reduce the flying speed of the scrap. However the flat part of the punch is less effective to reduce the noise level than that of the bevel punch.
3) Only a local zone of the sheet is in contact with the punch during trimming with the bevel punch. Therefore the sheet is gradually trimmed until the scrap is separated, and thus the trimming load, flying speed, and noise is low.
4) The inclined angle of 1 - 5° for the bevel punch is the best for the reduction of flying speed of the scrap and noise level without compromising the length of the trimming stroke.

Chapter 6
Prevention of chipping and edge fracture in trimming of ultra-high strength steel sheets having curved shape

6.1. Introduction

For a reduction in weight and improvement in the crash safety of automobiles, the use of high strength steel sheets, which have a high specific strength for making the body-in-white parts, has increased remarkably [40-43]. After stamping, the formed parts such as the A, B, C, D-pillars, roof rails, front members, etc. require subsequent processing such as trimming to remove the scrap portion. The body panel of the car usually consists of complex and curved shapes providing for an attractive exterior design and to optimize performance. With trimming of ultra-high strength steel parts that have complex and curved shapes and since the sheet is of high strength, the load is large and consequently the quality of the trimmed edge deteriorates.

By optimizing the parameters such as clearance, shear angle and the sheet positioning angle, a reduction in the cutting force in the sheeting of the advanced high strength steel sheets can be obtained [48].The quality of the trimmed edge, especially the formation of the burr, is important in the trimming process to minimize the tendency for edge cracking [95-99]. The burr formation varies for different materials depending on their particular metallurgical properties [100]. The pre-existent cracks and defects generated at the cut edges due to trimming and shearing has a significant effect on the fatigue behaviour of ultra-high strength steel sheets.

In this study, the trimming behaviour and observation of occurrence of chipping and edge fracture in trimming of ultra-high strength steel sheets having a curved shape were investigated. The effects of trimming with a flat punch on the trimmed part quality were observed. The method to prevent the chipping, edge fracture and curvature on the trimmed edge of the sheet was proposed.

6.2. Experimental procedure

The dimensions of the sheet and tools used in trimming of high and ultra-high strength steel sheets having a curved shape are given in Fig. 1. The curve L-shaped sheet had 55, 40 and 1.2 mm in length, width and thickness, respectively and the curved angle of the sheet was 120°. The radius of the curved zone *R* was changed for 1 until 10 mm for further investigation of chipping.

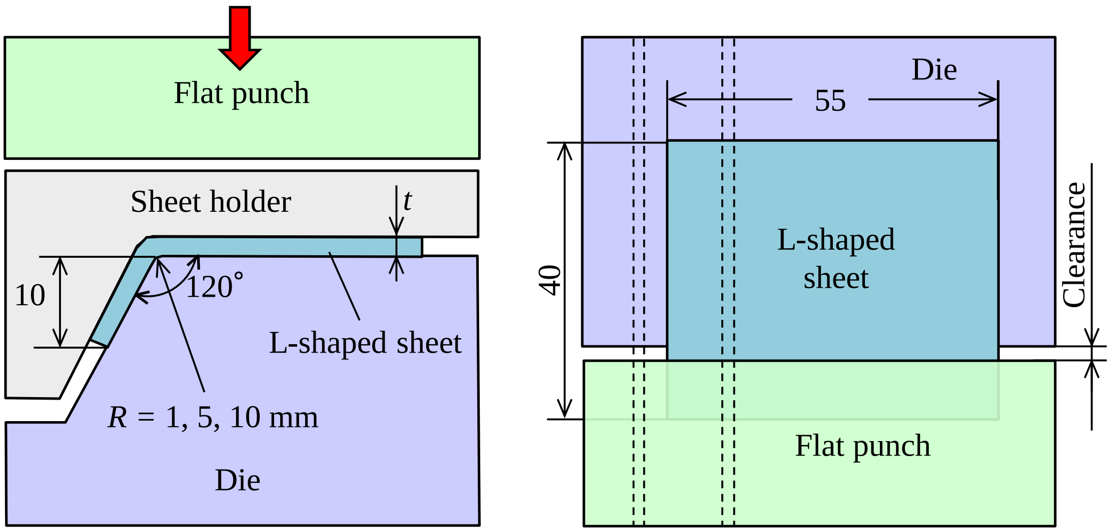


Fig. 6.1. Dimensions of sheet and tools used in curved trimming of ultra-high and high strength steel sheets.

The mechanical properties of the high strength and ultra-high strength steel sheets are given in Table 6.1. The thickness of the steel sheet used for the experiment is 1.2 mm and the weight is between 22 to 24 gram.

Table 6.1.

Mechanical properties of high strength and ultra-high strength steel sheet.

Material	Thickness [mm]	Tensile strength [MPa]	Elongation [%]
JSC590YN	1.2	629	26.2
JSC780YN		813	17.3
JSC980YN		1004	12.6
JSC1180YN		1242	8.1

The conditions of trimming of high strength steel and ultra-high strength steel sheets having a curved shape are given in Table 5.2. The flat punch, die and sheet holder are made of SKH11 and having hardness of HRC50 after heat treatment. The trimming speed for the experiments was 4 mm/s. The clearance ratio between the punch and die was set for 10% of the thickness of the sheet.

Table 5.2.

Conditions of trimming.

Punch material	SKH11
Die material	SKH11
Punching speed [mm/s]	4
Clearance to thickness ratio, c [%]	10

The process of making the curved shape at the sheet corner is shown in Fig. 6.2. The sheet was held and clamped between a sheet holder and flat die. The punch was moving down for 8 mm to make a curved angle of 120° at the sheet corner.

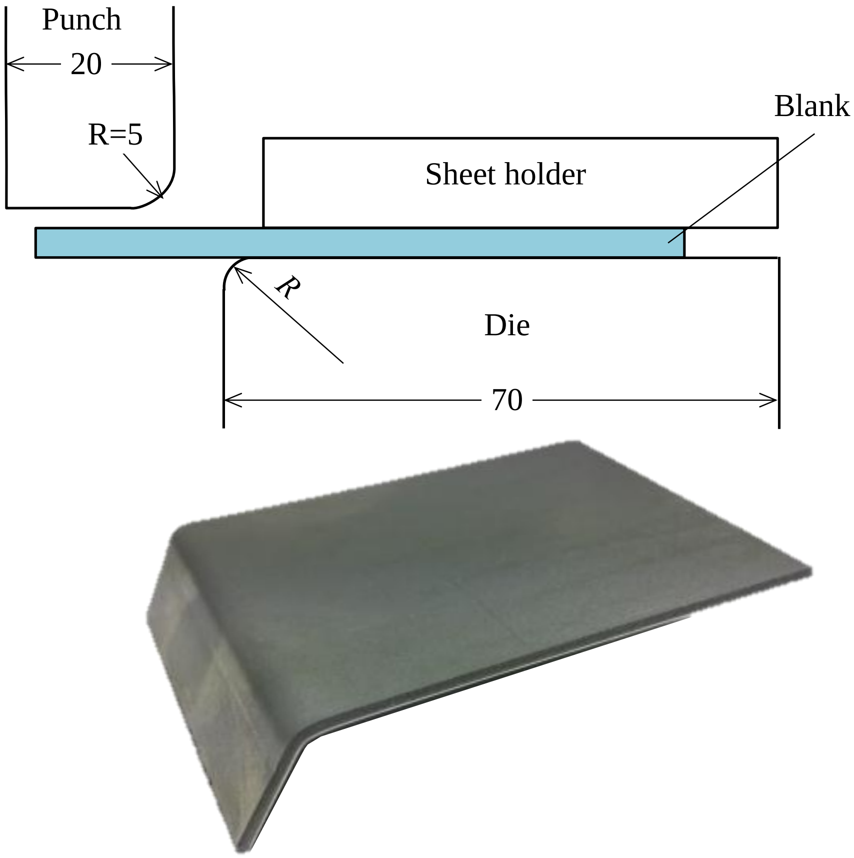


Fig. 6.2. Process of making of curved shaped at steel sheet.

6.3. Results of trimming with flat punch

6.3.1. Chipping and deformation behaviour

The relationship between the number of trimming and occurrence of chipping for different strength steel sheets for trimming with the flat punch is given in Fig. 6.3. Ten pieces of sheet from different steel types were trimmed. The occurrence of chipping was visually observed. For JSC590YN and JSC780YN steel type, no chipping occurred. However for JSC980YN and JSC1180YN sheets, chipping was observed at the curved zone and also at the lower part of the inclined. A further analysis has found that the cracks and chipping at the sheet was occurred at the punch stroke of s = 8 - 9 mm, i.e. the stroke at which a sudden increase in trimming load was occurred (see Fig. 6.6).

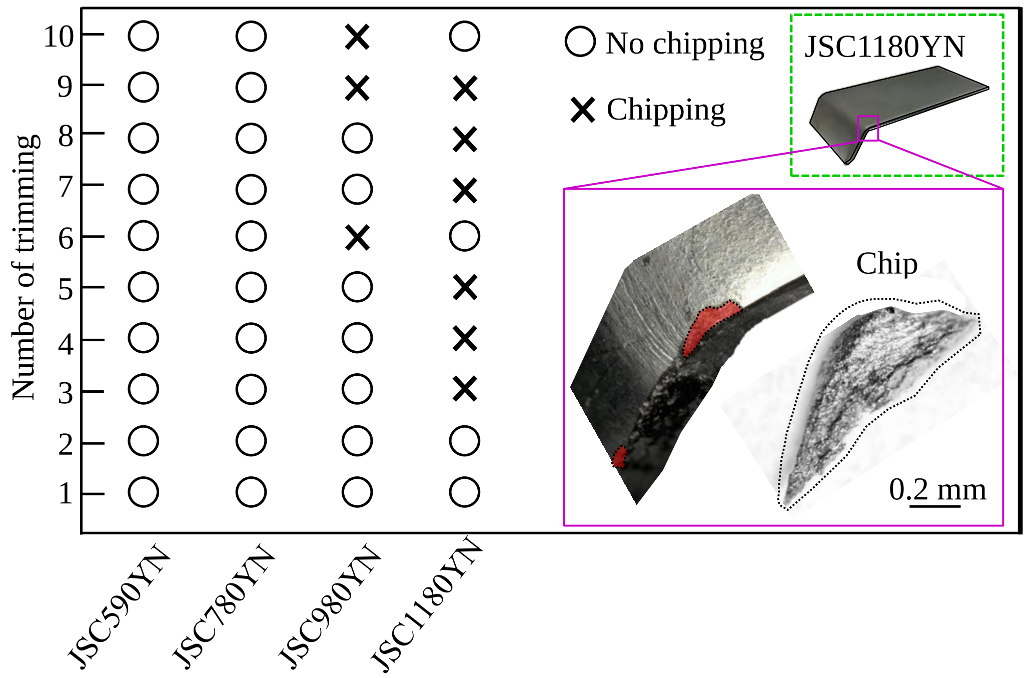


Fig. 6.3. Relationship between the number of trimming and occurrence of chipping for different strength steel sheets for trimming with flat punch for R = 1 mm.

Besides chipping, the lower part of the inclined zone was also bent. The relationship between the bent height and different strength steel sheets is shown in Fig. 6.4, where ΔL is the bent height of at the lower part of the inclined zones. Since JSC590YN is more ductile, the bent at the lower part of the inclined zone was larger. The bent height was decreased with increases of the strength of the steel sheet. Facture and chipping was also observed at the bent zones for JSC1180YN.

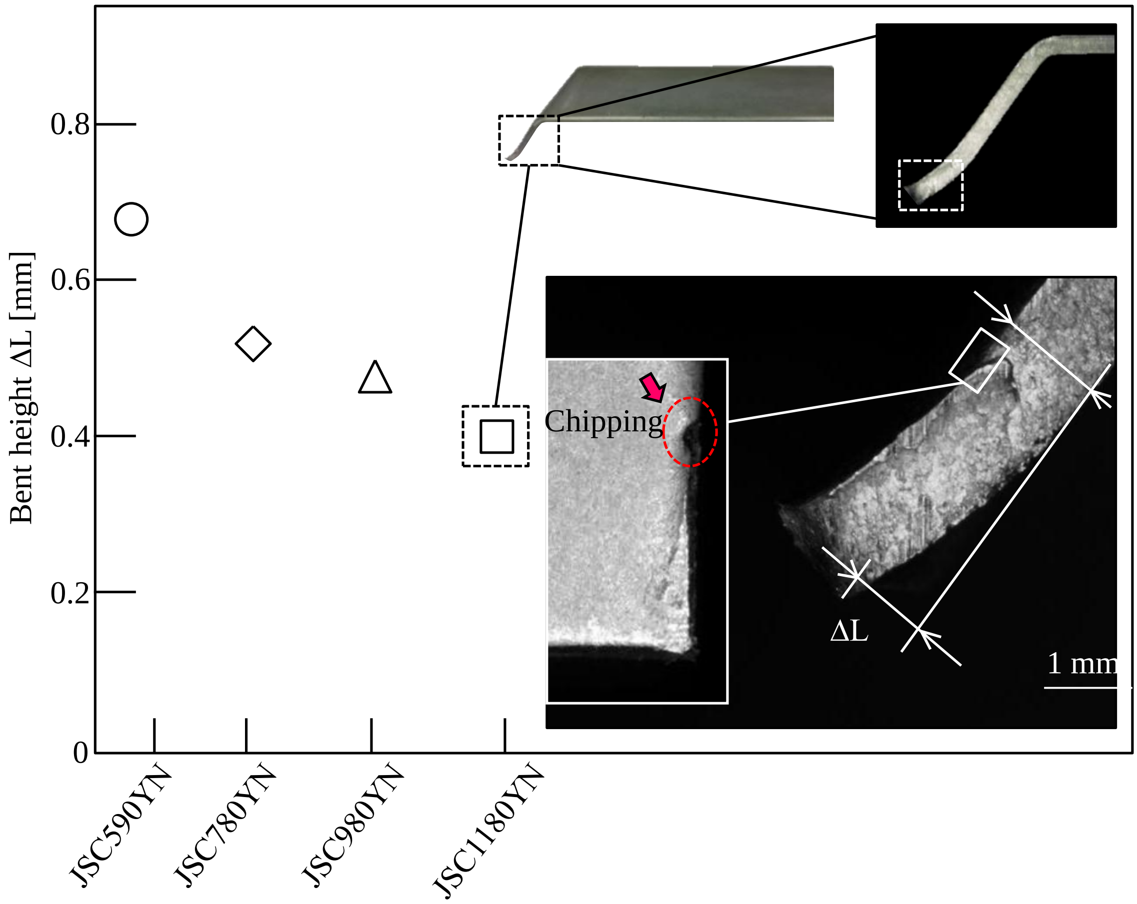


Fig. 6.4. Relationship between bent height and different strength steel sheets

The deformation behaviours of the L-shaped JSC1180YN steel sheet for trimming with flat punch for R = 1 mm are shown in Fig. 6.5, where s is the punch stroke. For s = 1.5 mm, the flat zone of the scrap was separated from the sheet by shearing. As the punch stroke is increases, the deformation becomes larger. Not only shearing, the inclined zone was also bent and twisted towards the die with the increase of the punch stroke. The cracks were propagated from both upper and lower parts of the inclined zones. As the flat punch moved more downwards and almost separating the trimmed and scrap parts, the cracks at the upper and lower parts were not in the same line as observed for s = 9.0 mm which might cause chipping and fracture at the lower zone.

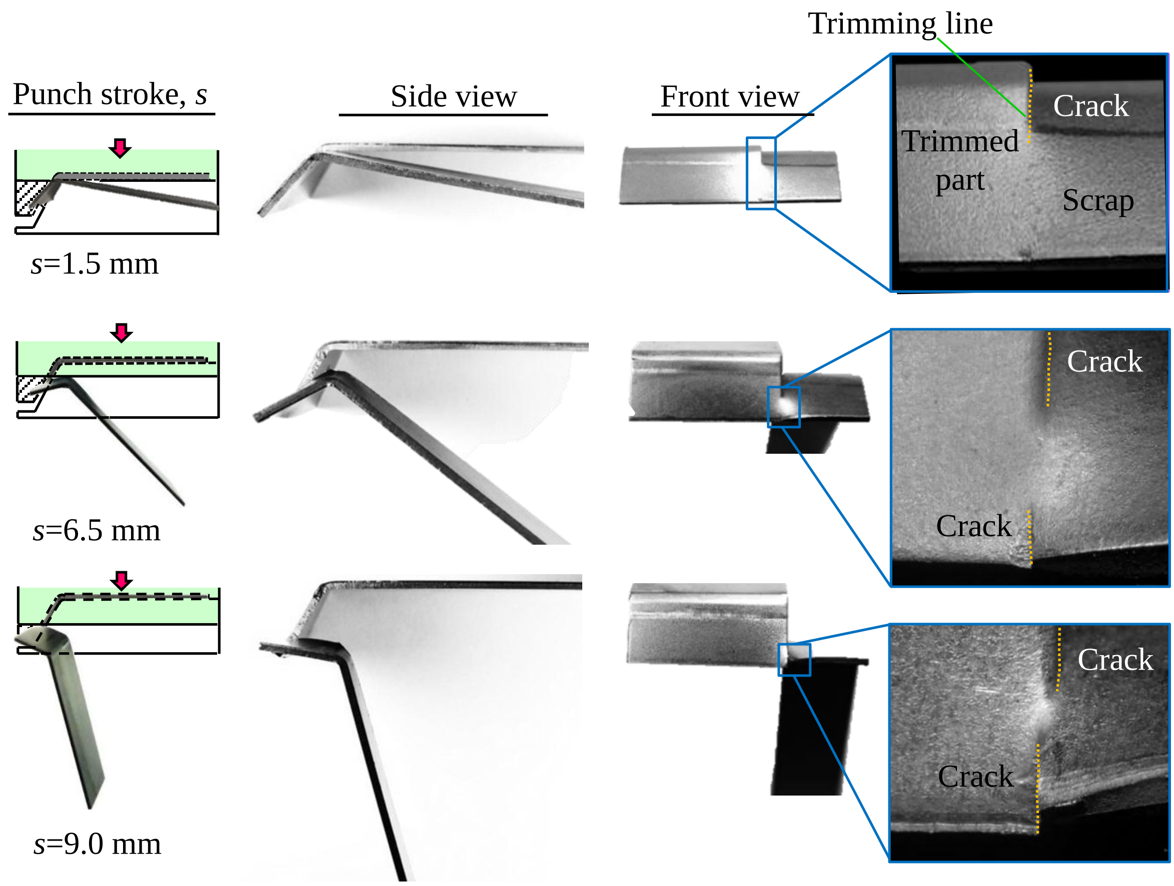


Fig. 6.5. Deformation behaviours of L-shaped JSC1180YN steel sheet for different punch strokes for R = 1 mm.

The trimming load-stroke curves for trimming different strength steel sheets with the flat punch for R = 1 mm are shown in Fig. 6.6. The maximum trimming load was highest for the JSC1180YN sheet and decreases with the decrease of the strength of the steel sheet. For the punch stroke s = 8 - 9 mm, a sudden increases of the trimming load was observed.

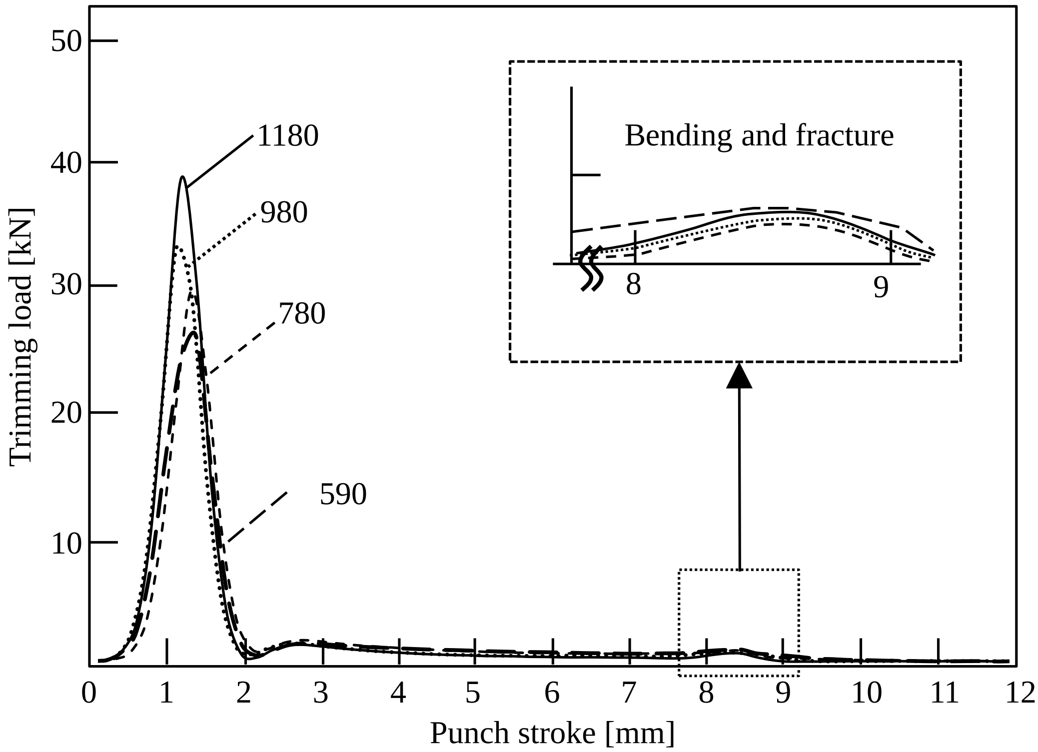


Fig.6.6. Trimming load-stroke curves for trimming different strength steel sheets with flat punch for R = 1 mm, c – 10 % and v = 4 mm/s.

The sheared edge surfaces of JSC590YN and JSC1180YN steel sheets at the inclined, curved and flat zones for trimming with the flat punch are given in Fig. 6.7. Since the JSC1180YN sheet has higher strength, the burnished surface was small and fracture surface was large especially at the inclined and curved zones. The burnished surface was large for the JSC590YN sheet.

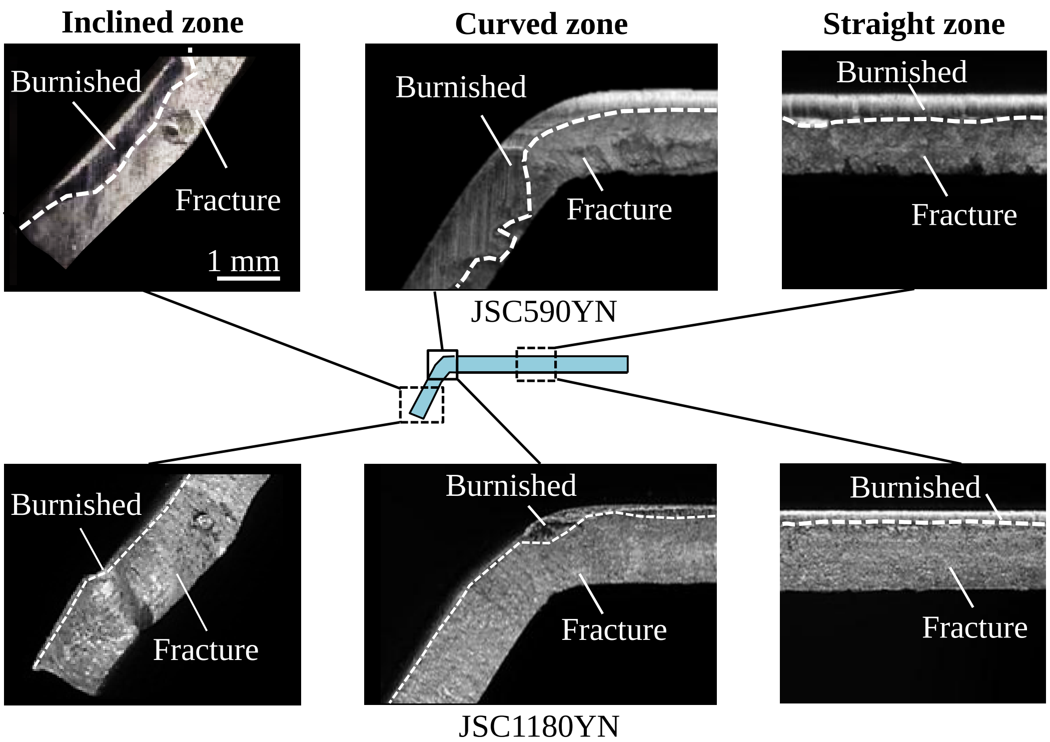
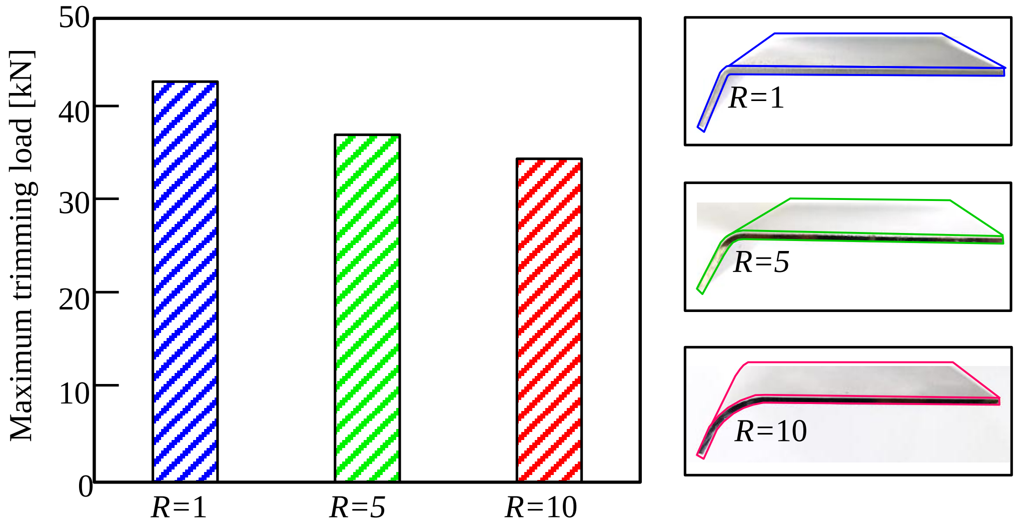


Fig. 6.7. Sheared edge surfaces of JSC590YN and JSC1180YN steel sheets at inclined, curved and flat zones for trimming with flat punch.

6.3.2. Effect of radius of curved zone

The effects of the radius of the curved zones on the occurrence of chipping for trimming JSC1180YN steel sheet is given in Fig. 6.8. Only the sheet with a radius of curved zones of 1 mm occurred chipping. The maximum trimming load was decreased with the increases of the radius of the curved zones.



Chipping	R=1	R=5	R=10
	Yes	No	No

Fig. 6.8. Effects of radius of curved zones on occurrence of chipping for trimming JSC1180YN steel sheet.

6.4. Prevention of chipping and defect of trimmed part

6.4.1. Prevention of chipping with spring

To prevent the occurrence of chipping in trimming with the flat punch, the coil spring was installed and placed under the sheet. The conditions of trimming the L-shaped JSC1180YN steel sheet with the coil springs are illustrated in Fig. 6.9. Two coil springs having a spring rate of 20N/mm were placed for 2 mm below the flange of the sheet. The coil springs have a function to counter the bending of the scrap which causes chipping of JSC1180YN steel sheet.

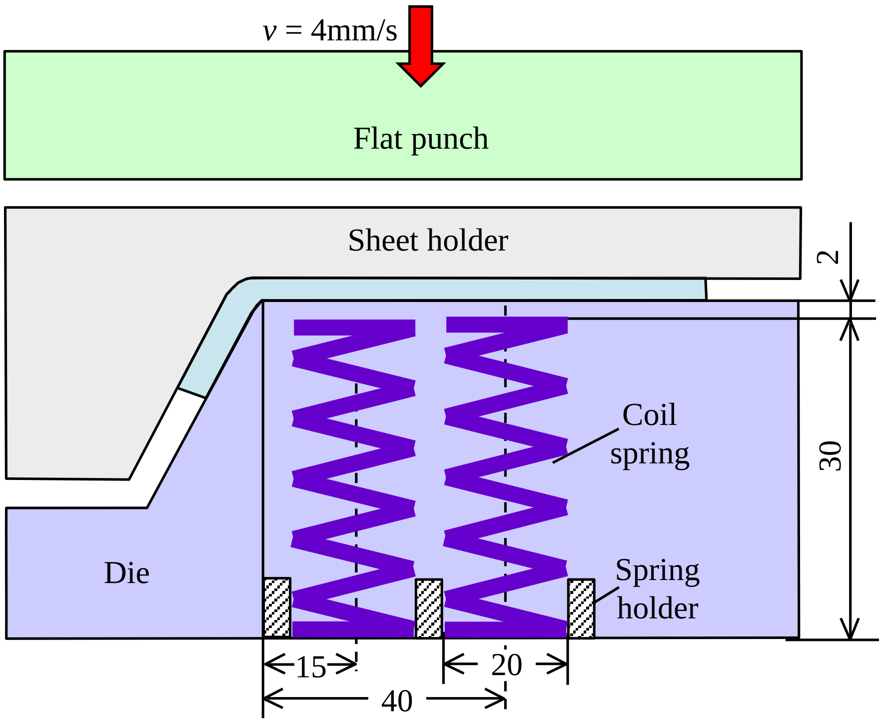


Fig. 6.9. Conditions of trimming L-shaped JSC1180YN steel sheet with coil springs for c = 10% and v = 4 mm/s.

The deformation behaviour for trimming the JSC1180YN sheets without and with the coil springs are shown in Fig. 6.10. As the punch stroke increased, the inclined zone was gradually trimmed. In case of without the coil springs, the deformation of the scrap was large at the inclined zone and therefore the scrap was bent. However, by utilizing the coil springs under the flat zone, bending of the scrap was greatly reduced as shown for s=6.0 and 8.6 mm.

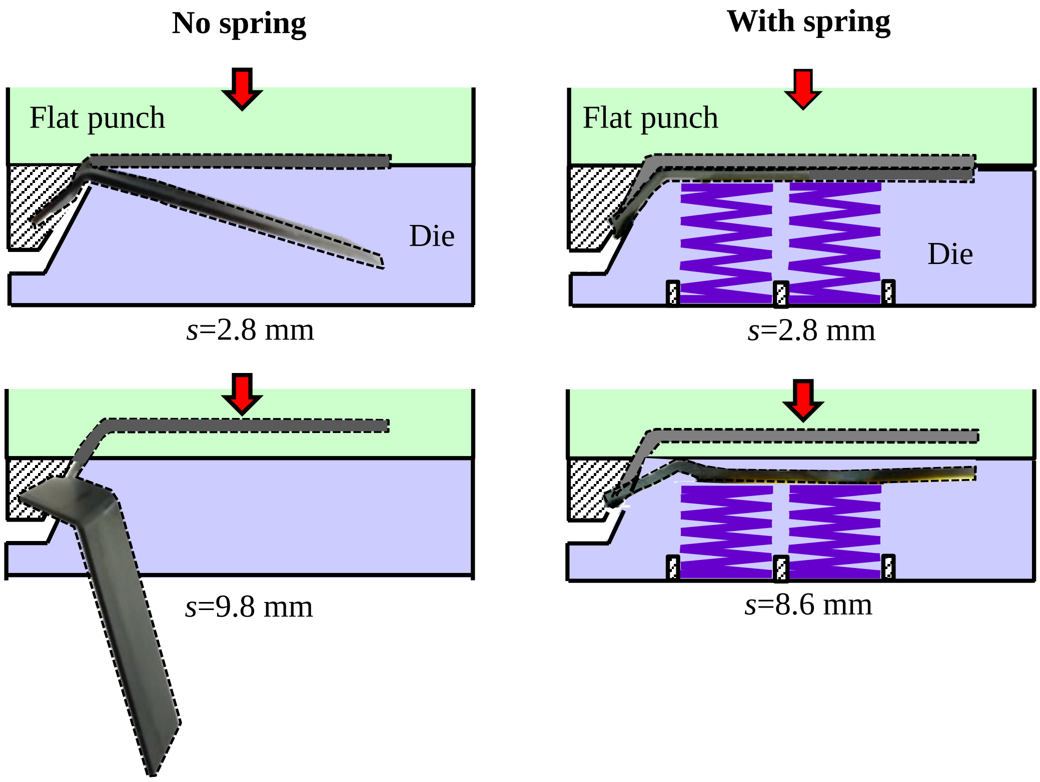


Fig. 6.10. Deformation behaviour for trimming the JSC1180YN sheets without and with the coil springs.

The trimming load-stroke curves for trimming the L-shaped JSC1180YN steel sheet with and without the coil springs are given in Fig. 6.11. The maximum trimming load was almost the same for both trimming conditions. However, for trimming with the coil springs, the sudden increases of the trimming load for *s* = 8 - 9 mm was eliminated. The inclined zone of the sheet was smoothly trimmed.

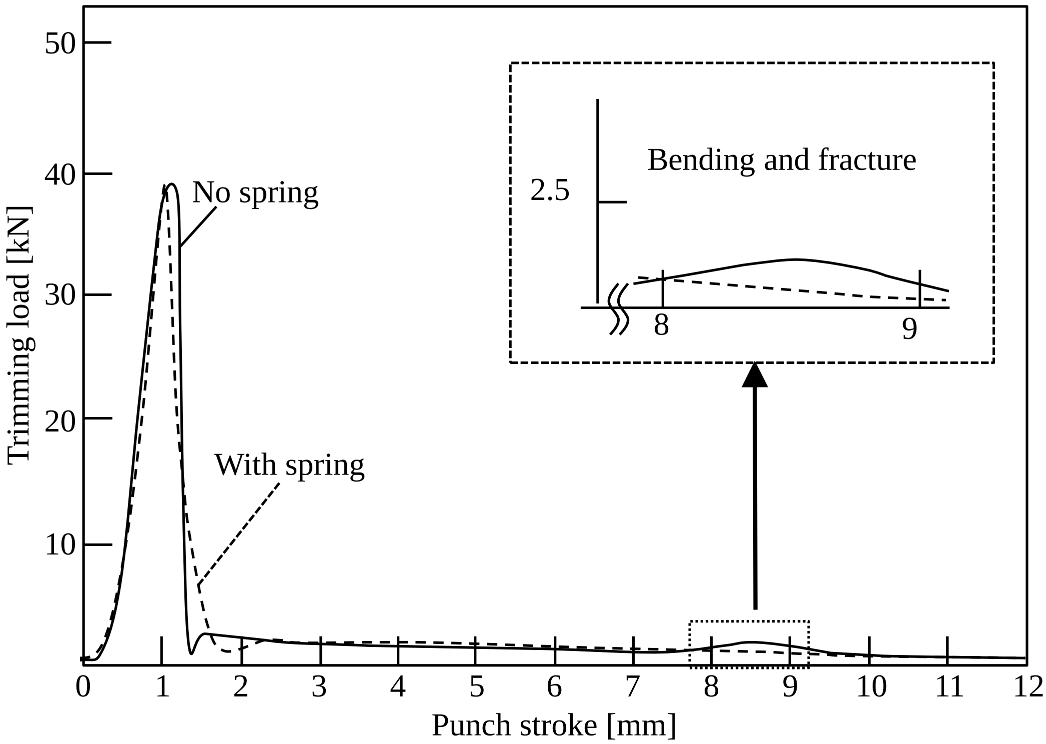


Fig. 6.11. Trimming load-stroke curves for trimming L-shaped JSC1180YN steel sheet with and without the coil springs.

The lower part of the inclined zone of JSC1180YN steel sheet after trimming with and without coil spring is shown in Fig. 6.12. No chipping was observed at the lower part of the inclined zone for trimming with the coil springs. The coil springs have reduced the bending of the scrap during the final stage of punch stroke and therefore chipping at the sheet was prevented.

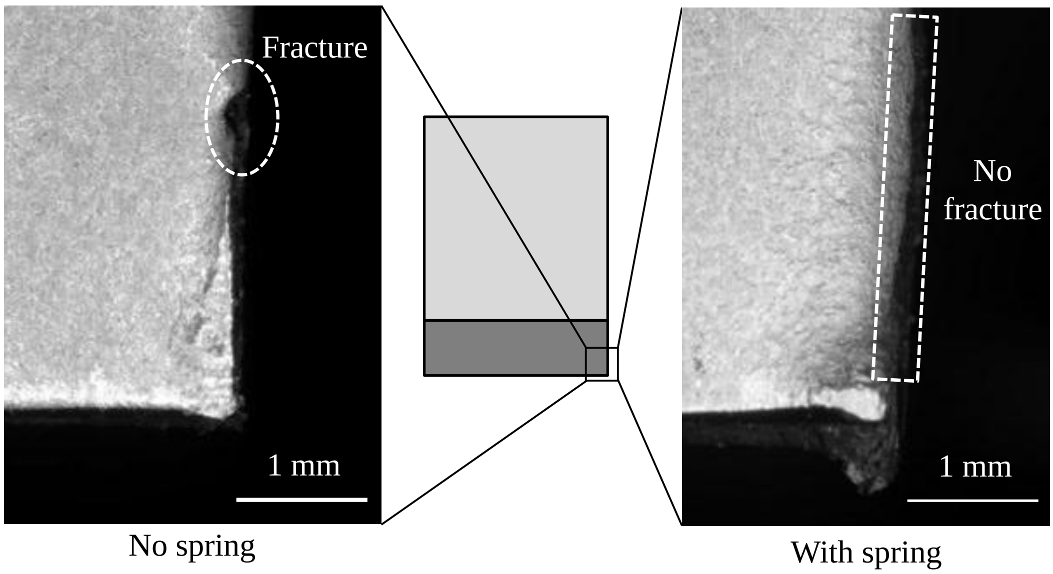


Fig. 6.12. Lower part of the inclined zone of JSC1180YN steel sheet after trimming with and without coil spring.

6.4.2. Prevention of chipping with L-shaped punch

Another approach to prevent chipping in trimming of the JSC1180YN steel sheet by trimming with the L-shaped punch was developed. The dimensions and trimming conditions for trimming with the L-shaped punch is given in Fig. 6.13. The trimming speed used was 4 mm/s and the clearance to the thickness ratio was 10 %. The radius of the curves zone *R* is 1 mm. The inclined angle *θ* of 0, 1, 3, 5 and 10° was used to investigate the trimming behaviour. In trimming of with L-shaped punch, the JSC1180YN steel sheet was used.

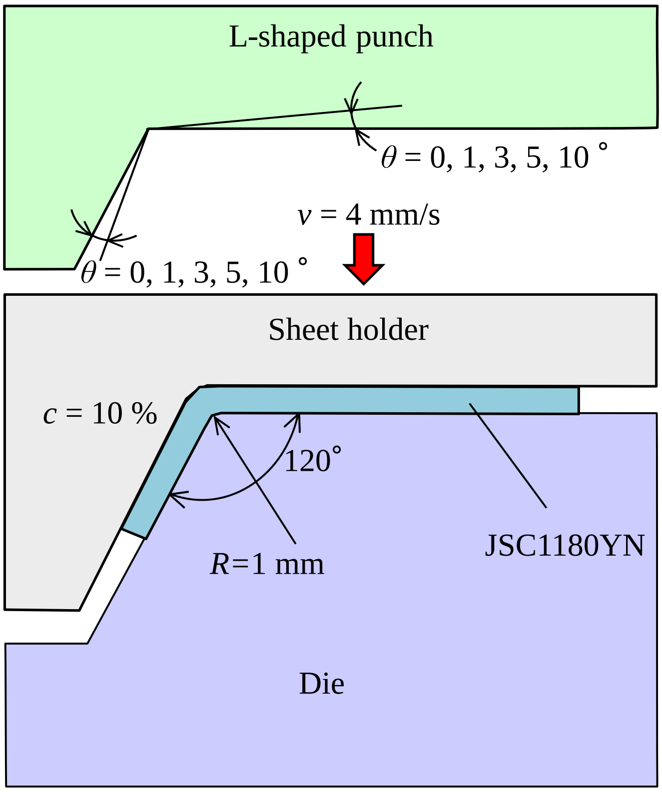


Fig. 6.13. Dimensions and trimming conditions for trimming with the L-shaped punch

The trimming load-stroke curves for trimming the L-shaped JSC1180YN steel sheet with L-shaped punch are given in Fig. 6.14. Since the all parts of the trimming zones of the L-shaped sheet was simultaneously trimmed by the L-shaped punch without inclined angle i.e. θ = 0, the trimming load was large. As the inclined angle increases, the trimming load decreases. However for the increases of the inclined angle, the punch stroke was increased.

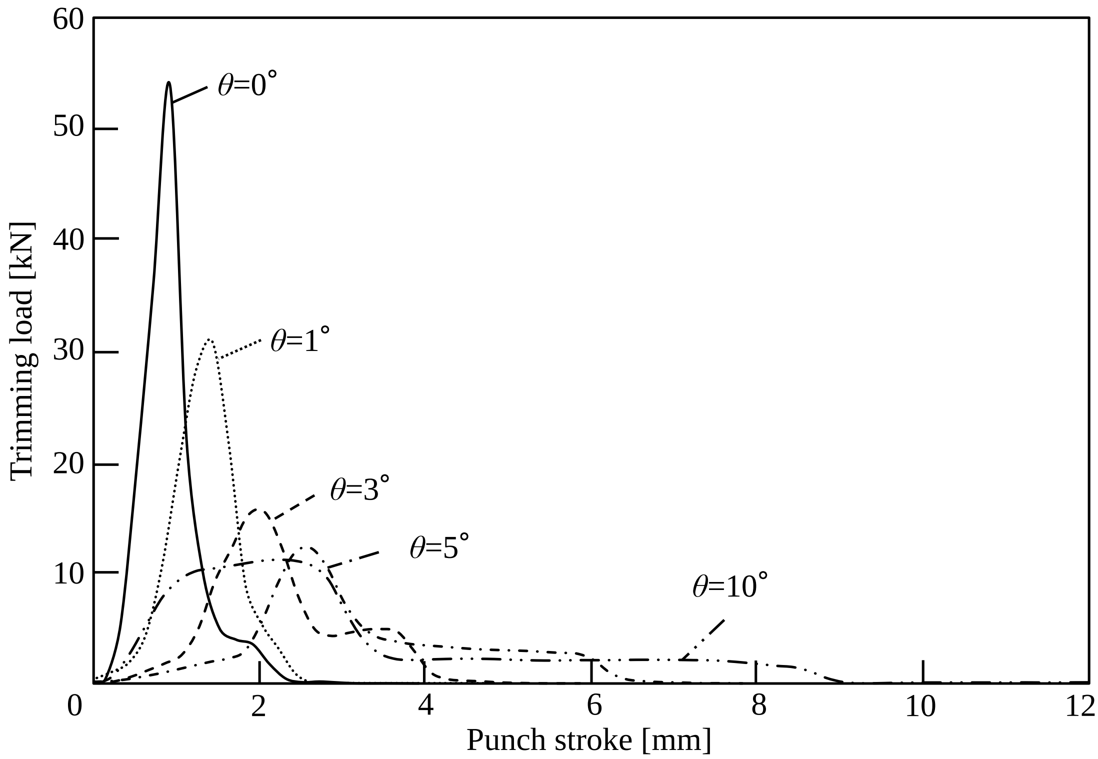


Fig. 6.14. Trimming load-stroke curves for trimming L-shaped JSC1180YN steel sheet with L-shaped punch.

The occurrence of chipping for trimming with different punch shapes is shown in Fig. 6.15. Chipping of the sheet occurred for trimming with the flat punch. However, for trimming with the L-shaped punch, no chipping occurred at the sheet for all inclined angle.

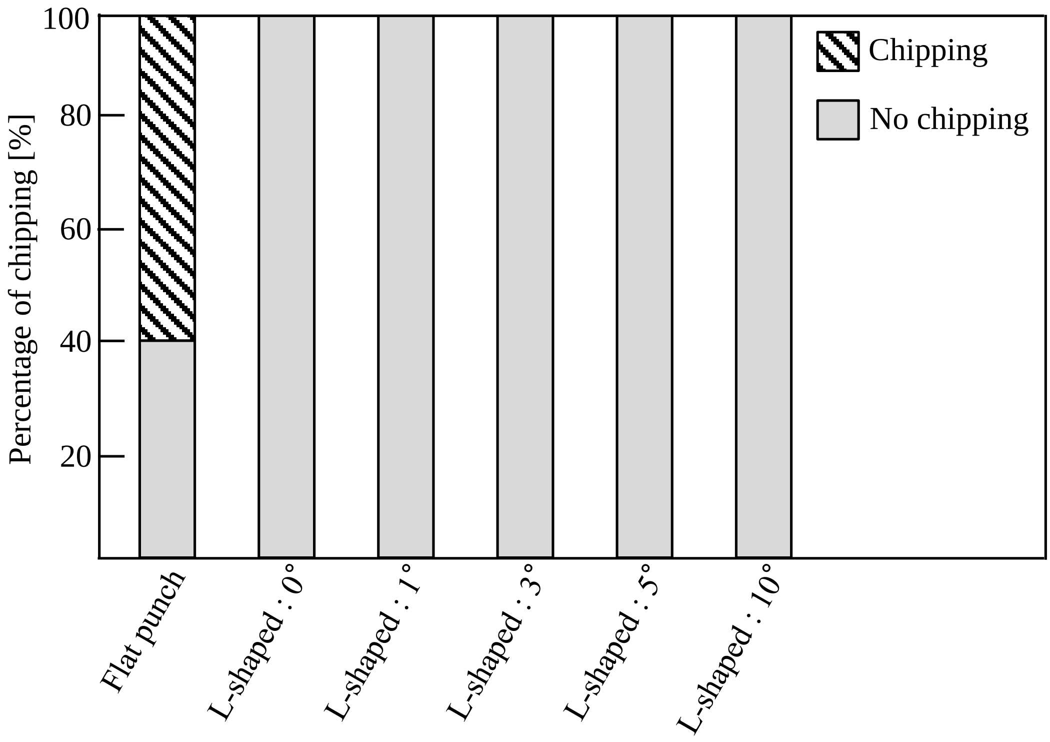
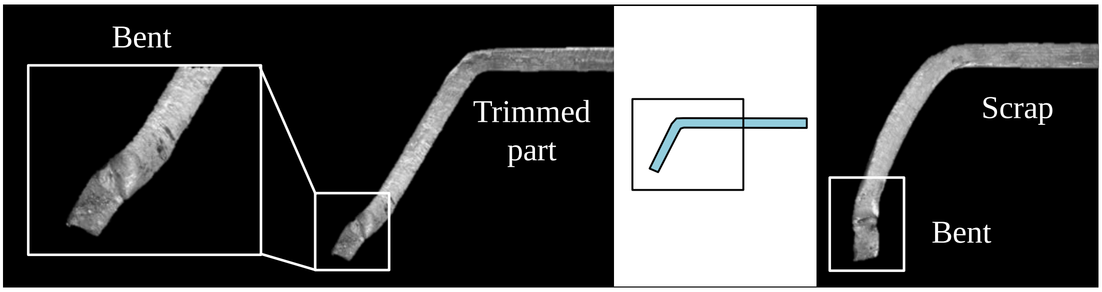
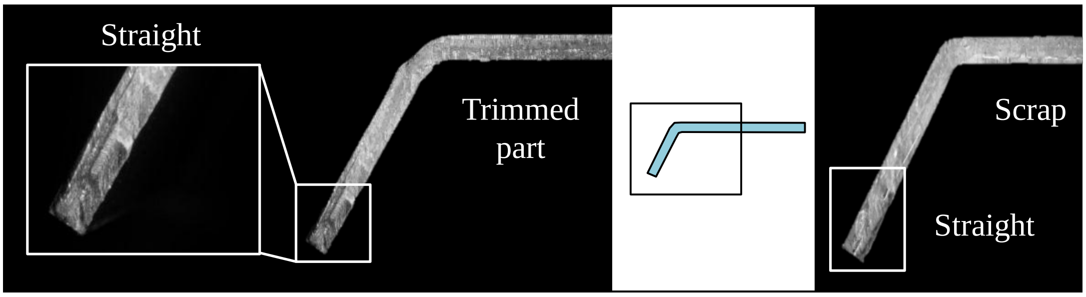


Fig. 6.15. Occurrence of chipping for trimming with different punch shapes.

The sheared edge surfaces of the trimmed and scrap parts of the JSC1180YN steel sheet for trimming with the flat and L-shaped punches are given in Fig. 6.16. The trimmed and scrap parts for trimming with flat punch were bent at the lower part of the inclined zones. For trimming with L-shaped punch, the lower part of the inclined zone for both trimmed and scrap parts were smoothly trimmed without any bent.



Trimming with flat punch



Trimming with L-shaped punch

Fig. 6.16. Sheared edge surfaces of trimmed and scrap parts of JSC1180YN steel sheet for trimming with flat and L-shaped punches.

The trimming energy for trimming with L-shaped punch for different inclined angle is shown in Fig. 6.17. The trimming energy was highest for inclined angle θ = 10° and lowest for θ = 3°. Therefore the L-shaped punch with an inclined angle of θ = 3° for an optimum results of low trimming load, low punch stroke and no chipping at the sheet.

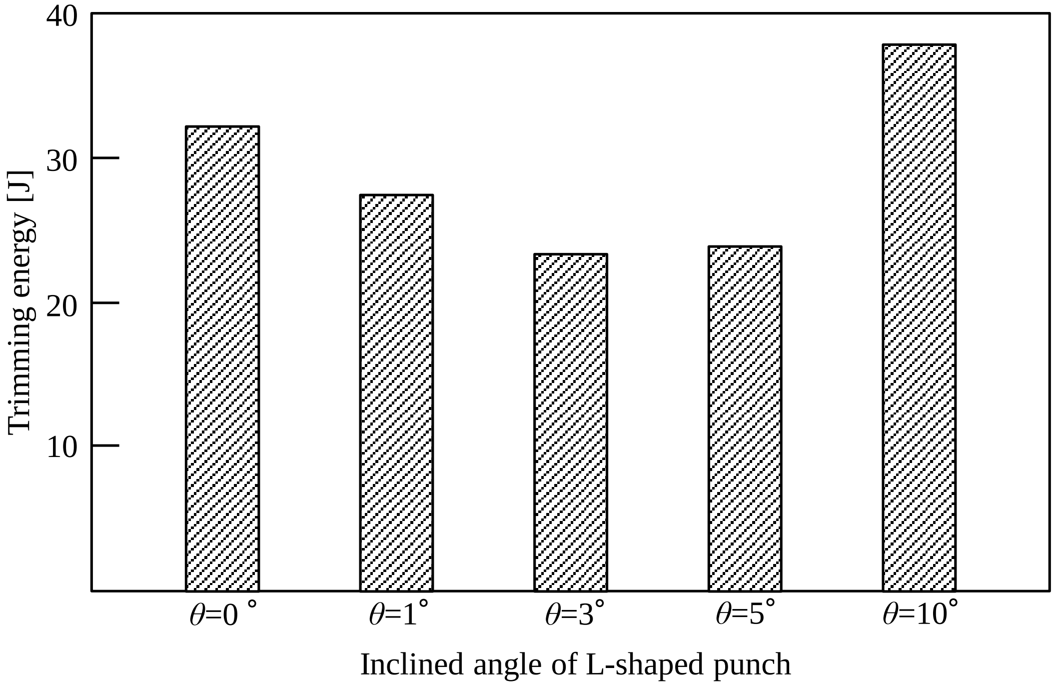


Fig. 6.17. Trimming energy for trimming with L-shaped punch for different inclined angle.

6.5. Conclusions

The trimming behaviour and observation of occurrence of chipping trimming of ultra-high strength steel sheets having curved shape were investigated. The method to prevent the occurrence chipping and defect at the sheet was proposed. The results are summarized as follows:

1) The possibility of fracture at the trimmed edge and chipping is increase with the increase of the strength of the steel sheet.
2) Since the JSC1180YN sheet is having higher strength, the fracture surface is large especially at the curved and inclined zones.
3) For trimming of the JSC1180YN steel sheet with the flat punch, the scrap was bent and twisted towards the die, and thus caused the fracture and chipping of the trimmed part edge.
4) In trimming of the JSC1180YN steel sheet with the flat punch, the application of the coil springs under the sheet reduce the bending of the scrap during the final stage of punch stroke and therefore the fracture at the sheet edge was prevented.
5) Chipping, bending and fracture of the sheet was prevented by trimming with the L-shaped punch, and the inclined angle was significantly reduced the trimming load.
6) The L-shaped punch with an inclined angle of $\theta = 3°$ give an optimum results for a low trimming load, low trimming energy, low punch stroke and no chipping at the sheet.

Chapter 7
Concluding remarks

7.1. Summary

7.1.1. Small clearance punching of die-quenched steel sheets by punch having small round edge

Although the hot stamping processes are attractive as a key technique for the reduction in weight of automobiles, finishing operations such as hole-making becomes difficult, and the application of laser cutting having high investment cost and low productivity is a barrier. The improvement of productivity and the low cost of the equipment and punching the sheets are requisite for increasing the use of hot stamped parts. The small clearance punching of hot-stamped parts by punch having small round edge has the advantages of high quality of the sheared edge. For the small round edge of the punch, the concentration of deformation around the edge of the punch was relaxed. Thus the onset of a crack from the edge of the punch was prevented. The combination of small clearance and small round edge of the punch produced a sheared edge surface with a large burnished surface. Therefore the delayed fracture was prevented due to large compressive stress around the sheared edge.

7.1.2. Automatic centring in small clearance punching of die-quenched steel sheets

The automatic centring in small clearance punching of die-quenched steel sheets with a moving die was developed to improve the quality of sheared edge. Although small clearance was effective for a high quality sheared edge in punching of die-quenched steel sheets, setting of tool was difficult due to small clearance between the punch and die and thus tends to make the punch and die eccentric. The automatic centring was developed for correcting the eccentricity between the punch and die and eliminate the problem of eccentricity. A moving die was utilised to automatically correcting the eccentricity of the die to the punch. By setting a gap between the moving die and holder, the die is shifted by imbalanced force, and the punch and die become concentric after several strikes. The combination of small clearance and automatic centring in cold punching of hot-stamped parts have the advantages of improvement of the sheared edge and fatigue strength and delayed fracture.

7.1.3. Repeated punching of die-quenched and ultra-high strength steel sheets by automatic centring

In the real industry application, the car parts are usually consist of many holes for joining, attaching, painting, etc. Since the small clearance punching process of die-quenched steel sheet having high specific strength was possible and produces a high quality of sheared edge, the repeated small clearance punching process was investigated for a much higher number of strikes. For repeated small punching of die-quenched steel sheet with the fixed die, this approach is found not effective. The punch was broken for the occurrence of eccentricity between the punch and die after several strikes.

The combination of small clearance and automatic centring using a moving die is effective for high number of strike in repeated punching of die-quenched steel and ultra-high strength steel sheets. This process has the advantage of not only for the improvement but also maintaining the high quality of the sheared edge even for high number of strikes particularly for the ultra-high strength steel sheets. The decrease in punching speeds in the initial strikes is effective to initiate the high quality of the sheared edge of the die-quenched steel sheets. Although the number of strike was high for die-quenched steel sheet, the high strength and hardness of the sheet deteriorate the punch life. By lubricating surface of punch, galling was reduced and tool life was increased.

7.1.4. Reductions of flying speed of scrap and noise in trimming of ultra-high strength steel sheets

Trimming of the ultra-high strength steel parts was a common process in the industry especially for the car makers. In trimming of ultra-high strength steel sheets, the flying speed is large due to the high strength, and thus the scraps jump out from a disposal box. The trimming operation also becomes noisy due to high trimming load. The deformation and shearing behaviour of the sheet during trimming with the flat punch was investigated. An attempt to reduce the fall velocity of the scrap and noise of level using a gradient trim punches was developed. By the bevel punch, only a local zone of the sheet is in contact with the punch during trimming. The sheet is gradually trimmed until the scrap is separated and therefore the trimming load and the flying speed of the scrap is reduced. Even the longer punch stroke is a drawback for a high inclined angle of the bevel punch, the 1 - 5° are because the flying speed of the scrap and the noise level were significantly reduce without compromising the length of the trimming stroke. The flat-bevel punch is also a promise for the reductions of the flying speed of the scrap and noise level. However the flat part of the punch generate high load during trimming, and thus is less effective to reduce the noise level than that of the bevel punch.

7.1.5. Prevention of chipping in trimming of ultra-high strength steel sheets

The car body made of ultra-high strength steel sheets usually consists of not only the flat but also curved and complex sections. Trimming of the ultra-high strength steel part having curved shapes has possibility of defect such as edge fracture, chipping and bent on the trimmed edge of the sheet which deteriorate quality and dimensional accuracy. Although the flat punch is commonly used in the industry, the shearing behaviour of the scrap was not so clear. For trimming with the flat punch, since the propagation of cracks from the upper and lower part of the inclined zones are not in the same line, the scrap at the curved and inclined zone of the sheet are bent which results in fracture and chipping of the sheet edge. The edge fracture and chipping on the trimmed edge of the sheet was prevented by applying spring coils under the sheet and also by using the L-shaped punch having an inclined angle. The L-shaped punch with an inclined angle of $\theta = 3°$ give an optimum results for a low trimming load, low trimming energy, low punch stroke and no chipping at the sheet.

7.2. Future perspectives

The stricter enforcement on the rules of the greenhouse-CO_2 emissions leads to the need of a much more reduction in weight of the vehicles. Given that the safety of the passengers is another issue need to be addressed, the car makers focusing on the high strength steel sheets as the car body materials for its cost advantage over the other lightweight materials. Since the strength of the sheet is higher, a thinner sheet can be used, and this will reduces the body weight. The high strength of the sheet is a gain; however leads to leads to the increase in forming loads, springback and tool wear and the decrease in formability.

Researchers has come out with a new approach so called hot stamping process, a much more advanced forming process where the sheet is form at an elevated temperature and quickly cool down by die-quenching between in the die to produce a much higher strength steel sheet than that of high strength steel with a tensile strength up to 1.5 GPa. As cold small clearance punching with automatic centring is a promising for making many holes at the die-quenched steel parts, the use of this method can be expanded.

Since the ultra-high strength and die-quenched steel parts are punch and trim in finishing operation, the durability and life of the tools are important (see Fig. 7.10. The new development in tools material, coating, and surface treatment process are needed to improve the performance of the tools. Common material for tool such as tool steels, powder metallurgy steels, cermets/cemented carbides and ceramics; material for coating such as titanium carbide (TiC), titanium carbonitride (TiCN), titanium nitride (TiN), titanium aluminum nitride (TiAlN), etc. need to be upgraded by a much advanced material in order to increase the tools life and improve the wear resistance.

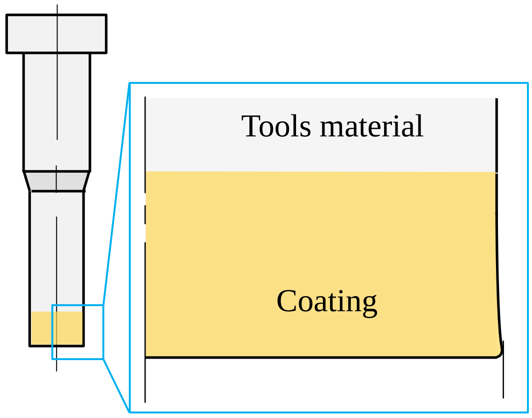


Fig. 7.1. New development for tools material and coating.

Although a single hole was successfully punched, the setting of tools becomes more accurate for punching of multiple holes. The ability of the automatic centring method to simultaneously punching multiple holes in a small clearance is a requisite to increase the productivity as shown in Fig. 7.2. This approach is desired to be expanded into punching of other high strength sheets such as titanium alloy, ultra-high strength steel and stainless steel.

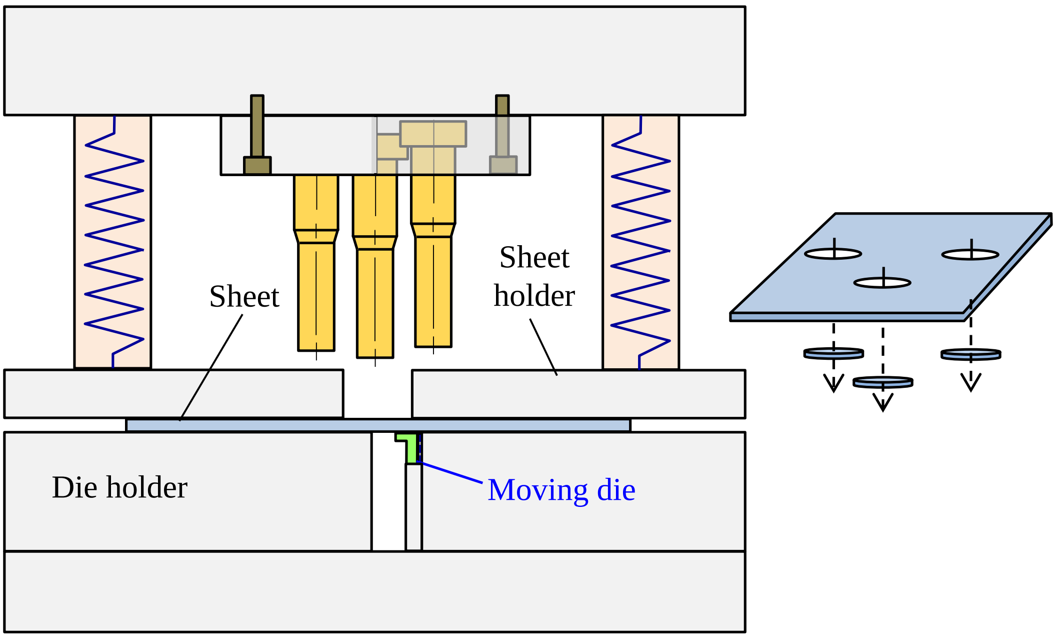


Fig. 7.2. Punching of multiple holes on die-quenched steel in single strike.

The reductions of trimming load, in trimming of ultra-high strength steel parts are important. Since the flying speed of scrap and noise are significantly depend on the maximum trimming load, the application relief angle θ_r at the punch is important to reduce the contact between the punch and scrap surface, and thus minimize the trimming load as shown in Fig. 7.3. Coating at tip of the punch is indispensable to avoid tools wear.

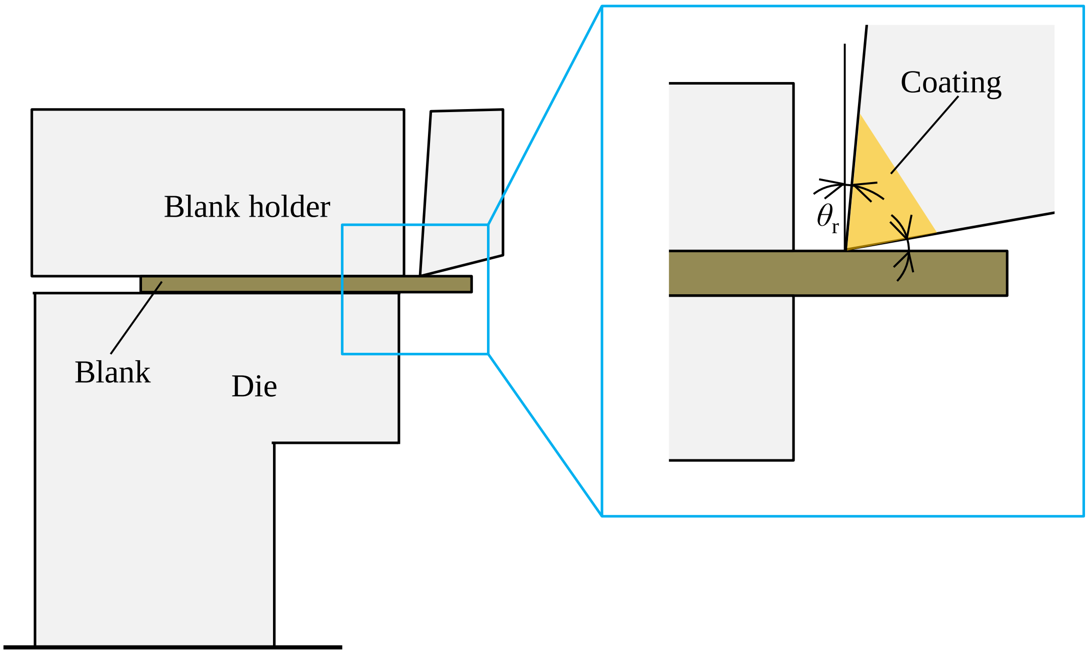


Fig. 7.3. Trimming using punch with relief angle and coated tips.

Although punching of the hot stamping part and trimming of ultra-high strength steel are important as a key technique for the reduction in weight of automobiles, this technique is hindered by the high cost of the operation and tools. The low cost of the equipment and stamping sheets and high productivity is desirable to extend the applicable range especially for making holes and trimming the undesired part.

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1. **Hasnulhadi Jaafar**, Ken-ichiro Mori, Yohei Abe, Keishiro Nakanishi, Automatic centring with moving die for cold small clearance punching of die-quenched steel sheets, Journal of Materials Processing Technology, 227 (2016), pp. 190–199.

2. 安部洋平, 岡本泰尚, 森謙一郎, **Hasnulhadi Jaafar**, “超高張力鋼板のトリミングにおける変形挙動とスクラップ速度の低減”, 塑性と加工, 57-661 (2016), pp. 146-152.

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1. **Hasnulhadi Jaafar**, Ken-ichiro Mori, Yohei Abe, Correction of eccentricity between punch and die in slight clearance punching of ultra-high strength steel sheets, *11th International Conference on Technology of Plasticity*, Nagoya, Japan, 19-24 October 2014.
2. **Hasnulhadi Jaafar,** Ken-ichiro Mori, Yohei Abe, Keishiro Nakanishi, Cold punching of high strength die-quenched steel sheets, *JSTP 7th International Seminar on Precision Forging*, Nagoya, Japan, 9-12 March 2015.

Local

1. **Hasnulhadi Jaafar**, Ken-ichiro Mori, Yohei Abe, Yasuhisa Okamoto, Automatic die centring for slight clearance punching of ultra-high strength steel sheets. *The 64th Japanese Joint Conference for the Technology of Plasticity,* Osaka, Japan, 1-3 November 2013.
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