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Corresponding Author: Prof. Kozo Osakada, D.,

Corresponding Author's Institution: Osaka University

First Author: Kozo Osakada, D.,

Order of Authors: Kozo Osakada, D.; Ken-ichiro Mori, Dr.; Taylan Altan, Dr.; Peter Groche, Dr.
Mechanical servo press technology for metal forming

K. Osakada (1)a, K. Mori (2)b, T. Altan (1)c, P. Groche (1)d

School of Engineering Science, Osaka University, Toyonaka, Osaka, Japan
Department of Mechanical Engineering, Toyohashi University of Technology, Toyohashi, Aichi, Japan
Center for Precision Forming, Ohio State University, Columbus, OH, USA
Technische Universität Darmstadt, Darmstadt, Germany

Abstract
Recently several press builders developed gap and straight-sided metal forming presses that utilise the mechanical servo-drive technology. The mechanical servo-drive press offers the flexibility of a hydraulic press (infinite slide (ram) speed and position control, availability of press force at any slide position) with the speed, accuracy and reliability of a mechanical press. Servo drive presses have capabilities to improve process conditions and productivity in metal forming. This paper reviews the servo press designs, servo-motor and the related technologies, and introduces major applications in sheet metal forming and bulk metal forming.

Keywords: forging, stamping, servo press

1. Introduction
1.1. Characteristic features of mechanical servo press

Electro-mechanical servo-drives have been used in machine tools for several decades. Recently, several press builders, mainly in Japan [7,46] and Germany [1], developed metal forming presses that utilise the mechanical servo-drive technology. The mechanical servo-drive press offers the flexibility of a hydraulic press (infinite slide (ram) speed and position control, availability of press force at any slide position) with the speed, accuracy and reliability of a mechanical press [102].

Figure 1 shows two types of servo presses developed at early stages [80]. In the design of Figure 1a, the rotational motion of the servo-motor is transmitted to the slide using a timing belt and ball screw. The press slide is moved up and down by the reciprocating motion of the motor and ball screw. The tilting of the press slide is detected by linear sensors and corrected by adjusting the motion of each individual motor as needed. Thus, it is possible to maintain slide/bolster parallelism under off-centre loading of the press. In the linkage design, seen in Figure 1b [62,63], the knuckle-joint mechanism is activated by the ball screw.

Due to the feed-back control of slide position of the servo press, scatter of the bottom dead centre is kept very small as shown in Figure 2, in which the result for the press of Figure 1a is given, and the product accuracy is kept high irrespective of working time or temperature change [12].

Because all the press motions such as starting, velocity change and stopping, are done only by the servo-motor, the mechanical servo press has a simple driving chain without flywheel, clutch and brake that are essential for a conventional
mechanical press, and thus the maintenance of the servo press is simplified.

Compared with the hydraulic servo press which has been used for many years, the mechanical servo press has higher productivity, better product accuracy and better machine reliability without noise of hydraulic pump and complicated piping.

The most important feature of the servo press is flexible slide movement. Figure 3 presents the typical motions used with the servo presses [3]. Since a servo press can realize almost all the motions, the following merits are considered to be brought about by choosing a motion suitable for each purpose.

![Figure 3: Typical slide motions of servo-press [3].](image)

1) The accumulated know-how with the existing presses can be inherited because the motions such as crank press and linkage press can be duplicated by a servo press.
2) Impact loading is avoided and the tool life is extended by reducing the touching speed of the tool to the work piece.
3) Lubrication is often improved and the working limit can be extended by using a pulsating or oscillating slide motion.
4) Touching and break-through noise is reduced by stopping the slide for a short time or reducing the slide speed.
5) Vibration of sheet metal can be reduced by an optimised slide motion and the shape of sheet metal product is stabilised.
6) The accuracy of the product can be improved by controlling the slide parallelism and choosing an optimum slide motion.
7) Higher productivity is possible by shortening of a forming cycle with a partial short stroke around bottom dead centre as well as a high speed return motion as shown in Figure 4.

![Figure 4: Decrease in cycle time as well as in impact speed using a servo press (150% increase in output) [15].](image)

The digital control of the servo press enables harmonic movements of various devices such as hydraulic, air and servo-motor controlled cushions with the main slide. By utilizing this function, servo presses are often employed to extend the forming limit and to improve product accuracy. On a multi-axis servo press, two or more processes may be completed in a stroke by moving the driving axes cooperatively.

Since a servo-motor can recover kinetic energy during deceleration, some servo presses store the energy during dynamic braking in the capacitor or in the independent flywheel. The stored energy is taken out and used during short energy peak demands of the next stroke, which results in a decrease of the voltage in the intermediate circuit [17].

1.2. Historical background

Although the servo-motors were used in metal cutting machine tools as early as in the 1950s, they were not mounted on the metal forming presses for a long time because their power was not strong enough for the large force required in metal forming. High powered AC servo-motors were realised in the 1980s with the development of the strong magnets. Together with the development of transistor controllers, they were applied to injection moulding machines in the late 1980s, and the production of servo-motor driven injection moulding machines increased rapidly in the 1990s [89].

High powered servo-motors were also applied to CNC powder compacting machines. In powder compaction, many axes should be driven independently to achieve uniform density in a product with non-uniform heights. Tsuru et al. [134,135] and Kishi et al. [53] developed a 6 axis CNC powder compacting machine on the basis of servo-motor driven injection moulding machine.

Since some metal forming processes, such as enclosed die forging, necessitated complicated motions of multiple slides, hydraulic servo-presses were built in the 1970s, but only a small number of presses was constructed because the areas of their application were limited.

In 1987 a 100kN press brake (bending machine) driven by an AC servo motor, shown in Figure 5, was developed by Toyokoki to carry out accurate bending [20] by measuring the stroke with the taco-generator of the motor and the load with the motor torque. Similarly to later servo presses, the force was transmitted through a ball screw. This press is considered to be the first commercial servo press, and since then press brakes driven by electro-hydraulic [2] and purely mechanical [38,44] servo systems have been manufactured by increasing the maximum load as the power of servo motor has been raised.

![Figure 5: 100kN press brake driven by servo motor built in 1987 [20].](image)
Because the power of servo motor was not large enough, a general purpose servo press was not built until 1997 when Komatsu HCP3000, shown in Figure 6, appeared. The driving mechanism of this press is given in Figure 1a. In this press, the maximum load of 800kN was transmitted through two ball screws. Since then various types of servo presses have been developed in Japan, Germany, Taiwan, Spain [27] and China.

In presses, servo-motors can be used in two different ways. Either they are used as high speed motors or as low speed and high torque motors. To provide high forces needed for forming, high speed motors require timing belt, linkage and gears to transform the high speed rotational motion into the low speed motion. The low speed and high torque servo-motors allow direct drive of the eccentric or crank mechanism and thus there is no need for belt, linkage or ball screw drives [14].

From around year 2000, linear motors began to be used for small servo presses. The motion of the linear motor press is fast and is controlled accurately, but the power of the press is limited. The linear motor driven presses are mainly used for high speed punching of polymer tapes and metallic foils [97,121], and are also applied in micro-forming and precision coining [32,138].

2. Designs of servo-motor driven press

2.1. Types of mechanical press

Conventional presses are classified into stroke controlled presses (crank press, knuckle-joint press, linkage press), energy controlled presses (screw press, hammer) and force controlled presses (hydraulic press) [64]. The common feature of stroke controlled presses and the screw press is that the rotational movement of motor is mechanically converted into the linear slide movement. To convert the movement, various mechanisms with crank, knuckle-joint, linkage and screw, shown in Figure 7, are used. The crank press is the most commonly used model, and the knuckle-joint and the linkage presses are used to modify the shortcomings of the crank press, i.e. to reduce the slide velocity around the bottom dead centre and to extend the slide travel of large available force.

Since the power of a conventional motor is not large enough to carry out a metal forming operation directly, the energy supplied by the motor is stored into the fly wheel as the rotating kinetic energy as shown in Figure 7 and is released in a short time when forming is carried out. In the cases of crank, knuckle-

![Figure 6: 800kN servo-motor driven press developed in 1997 [80].](image)

Joint and linkage presses, the positions of top and bottom dead centres and the velocity characteristics are determined by the driving mechanism. In the energy controlled screw press, the rotational movement of the flywheel is changed to the linear motion with a screw, and the slide stops when the energy stored in the flywheel is consumed completely, and thus the bottom dead centre cannot be pre-determined.

Figure 8 shows the time-stroke curves of the mechanical presses. The slide velocity of the screw press is kept almost constant, but once forming starts the slide is decelerated very rapidly. The crank press moves with a sinusoidal motion due to the simple crank system. In the knuckle-joint and linkage presses, the velocities near the bottom dead centre are lowered compared to the crank press [22]. Since the torque applied to the driving axis is limited by the twisting strength of the axis, high maximum working load is possible when the slide position is low.

In the case of the hydraulic press, the pressure of the working oil is raised by the motor, and the slide is driven by the oil pressure. Due to the limit of the motor power, the slide movement is usually slow. By using the flow control servo valves and air accumulators, it is possible to control the velocity and position of the slide, as used in the hydraulic servo presses.

![Figure 7: Conventional mechanical presses (S: Slide, B: Bolster).](image)

The high powered servo-motor enabled direct driving of the mechanical press without using a flywheel and clutch, but the fundamental driving mechanisms remain the same as conventional presses. In the following, the presses driven by servo-motors are reviewed.

2.2. Servo-motor and ball screw driven presses

The first servo presses illustrated in Figures 5 and 6 employed ball screws to reduce the friction of the screws. Differently from the traditional screw press, this press does not require a flywheel and clutch, and the slide velocity can be controlled during forming. Later, the screw press that simply
replaced the motor with a servo-motor keeping the flywheel was
developed [22].

An important feature of the ball screw type servo press is
that the maximum force and the maximum slide speed are
available at any slide position, and thus it can be applied to
almost all the forming methods. This feature is especially useful
for forming with a long working stroke such as extrusion, and for
forming that needs a high speed motion at the end of forming. As
will be introduced later, the majority of the present servo presses,
such as the crank, knuckle-joint, and linkage presses, use crank
mechanisms to achieve large press forces, and the slide velocity
is slowed down around the bottom dead centre although it is
controllable to some extent.

The maximum load is limited by the torque capacity of the
servo motor, the reduction of the belt drive and the load carrying
capacity of the ball screw. One of the solutions to increase the
power of the ball screw type servo press is to increase the number
of motors and driving axes (spindles). Figure 9 shows the
500kN ball screw type servo press with four spindles build by
Hoden Seimitsu Kako (HSK) [144]. In this press, the four
spindles are moved independently, and thus the inclination of the
slide to any direction can be corrected [43, 91]. Further, as shown
in Figure 10, it is possible to drive multiple axes by several
servo-motors in order to carry out multiple processes in a single
stroke [90, 92] as will be explained in section 4.5 [39].

Servo presses with four spindles were developed also in
Germany. Figure 11 shows the presses from Heitkamp and
Tumann [41] as well as Synchropress [126]. They use servo
motors positioned above (Figure 11a) or below (Figure 11b) the
slide for each planetary roller thread spindle. The slide is guided
by linear bearings. Sensors recognize a tilting of the slide due to
eccentric loading. Since the spindles are not linked mechanically,
the position of the slide can be kept parallel to the table of the
press by an appropriate control of the servo motors. Press forces
from 630kN up to 2500kN are used for both transfer and
progressive tools.

2.3. Servo-motor driven crank presses

Since the ball screw type presses were expensive, crank
presses driven by servo-motors began to be manufactured. Figure
12 shows the crank type driving mechanism [40]. In this case, a
high torque servo-motor is attached directly to the press drive
shaft.

By combining the servo driving mechanism and the existing
press structure, gap (C-frame) presses shown in Figure 13 were
developed by Aida Engineering [127,128] and Amada [118,119].
The structural stiffness and the gear-eccentric drive were the
same as the conventional crank presses while only the flywheel,
clutch and main motor were replaced with the servo-motor.
When the main shaft rotates at a constant speed, the stroke-time
curve is the same as the conventional press (see Figure 8).
To increase the power and to keep parallelism of the slide under off-centre loading, crank presses with two connecting rods were produced as shown in Figure 14 [21, 57].

For crank presses with larger forming forces, many servo-motors can be attached to one driving gear shown in Figure 15. By utilizing this motor arrangement, a 50000kN hot forging press is under construction.

2.4. Servo-motor driven linkage presses

Linkage mechanisms are often used for presses to reduce the slide velocity and to increase the load capacity of a given motor torque around the bottom dead centre as shown in Figure 8, and they are often applied to cold forging presses. For servo-motor driven presses, linkage mechanisms are considered to be advantageous in increasing the approaching and returning speeds by slowing down the slide speed in the working region in a stroke, and having large available load over a relatively long working stroke. Yossifon et al. investigated various linkage [146] and double knuckle [147,148] mechanisms suitable for metal forming processes on servo presses.

Figure 16 shows a 6300kN servo press for cold forging driven by two servo-motors and the linkage mechanism [8].

Groche et al. [30,31] proposed a three degree of freedom servo press which enables three dimensional movement of the slide, which can be rotated during a stroke as shown in Figure 17. By tilting the slide, a product which necessitates plural tool actions from different directions can be produced.

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Meng et al. [78] proposed a link mechanism using a conventional constant speed motor and a servo-motor. In this mechanism, the main function of forming is carried out by the conventional motor, and a servo-motor is used to vary the velocity of the slide during a stroke depending on the purpose of forming. Using this concept of combining a conventional motor and a servo-motor, Du et al. [18] and Li et al. [65] examined some other linkage mechanisms.
2.5. Hybrid servo press with ball screw and knuckle-joint

As shown in Figure 8, the knuckle joint and the linkage mechanisms are used to increase the press power with the crank shaft mechanism, and they can be combined with the ball screw mechanism for servo presses. The servo press shown in Figure 1b is a 5000kN hybrid press with ball screw drives and knuckle-joint mechanisms [61]. Figure 18 shows a 25000kN servo press driven by a different type of combination of a ball screw and knuckle-joint mechanisms [4,131].

2.6. Servo-motor driven hydraulic press

By the direct drive volume control (DDVC) of hydraulic system (Figure 19a) with the AC servo-motor, the flow rate and direction of oil flow are controlled without using flow control valves. Some hydraulic presses driven by servo-motors have been developed [143] because the high power servo-motors realised higher slide speed compared with the conventional servo press with flow control valves. Figure 19b shows the hydraulic servo press made by Kawasaki hydromechanics.

![Figure 18: 25000kN Hybrid type servo press (Amino) [6].](image)

![Figure 19: CCVD hydraulic servo press (Kawasaki Hydromechanics) [51].](image)

3. Control and systems of servo presses

3.1. Servo-motor

Servo-motors are available as AC or DC motors. In the 1980’s servo-motors were mainly DC motors because their large currents could only be controlled by silicon-controlled rectifiers. As transistors became capable of controlling and switching larger currents at higher frequencies, the AC servo-motor became common. Early servo-motors were specifically designed for servo amplifiers [24]. Today most motor manufacturers offer a wide range of motors, which are designed for applications that use a servo amplifier or a variable-frequency controller. That means that a motor may be used in a servo system in one application, and used in a variable-frequency drive in another application. Various manufacturers define any closed-loop system that does not use a stepper motor without feedback system as a servo system. Hence any simple AC induction motor connected to a velocity controller may be denoted as a servo-motor [54].

Torque motors represent a type of servo-motors, which provide high torques. A torque motor is in principle a large scaled servo-motor with a hollow shaft and optimised torques. The layout of a torque motor is shown in Figure 20. It works like a regular synchronous motor. The moving part is a drum with fixed magnets on the inner surface. The stator consists of a large number of magnetic coils integrated in an iron stack. These coils are star-connected and provided with three-phase current. The required velocity is controlled by the frequency. Due to the large number of poles a high torque at a very low speed can be achieved. To reduce cogging to a minimum the permanent magnets inside the rotor are fixed. There is no need for gearboxes, worm-gear drives, and other mechanical transmission elements since the rotor is directly connected to the shaft.

This combination is, in connection with pre-loaded ball bearings, absolutely free of play. Depending on the used control system the rigidity of the drive can be increased. Further higher power, precision, angular speed and acceleration can be realised [133].

![Figure 20: Layout of a torque motor [133].](image)

The advantage of torque motors (broken line) compared to conventional asynchronous motors without control (solid line) is explained in Figure 21. Characteristic torque curves and the operating area for both motor types are shown. The asynchronous motor is reaching its maximum torque with an increasing number of revolutions while the torque motor directly provides the maximum torque. This is possible because the torque motor has no slip. This is the major of the reason why servo presses are primarily driven by torque motors. Furthermore the characteristic curve of a linear motor is identical to the shown torque curve. Linear motors are employed as well in several types of servo presses [33,42].
3.2. Servo control

The control of a servo press can be divided between the control of the motor position and the control of the motor moment. To control the slide movement usually an internal control loop is employed. Therefore the motor position is monitored and fed into the controller. A force limiter or a default force function is used to perform defined forming operations and to avoid overshooting of the slide [23]. Figure 22 displays an internal control loop for a single input single output system.

This scheme can also be employed for the control of more than one motor as multiple input multiple output system. In that case the variables represent vectors instead of scalars. Further linear sensors can be used to measure the current position of slide (Figure 23). This can be used to detect and compensate slide tilting in multi drive presses. Therefore the measured tilting is fed back into the controller [1].

To further improve the press accuracy for unpredicted changes an iterative learning control (ILC) can be used for repetitive movements. Therefore an additional external control loop is employed [97]. Figure 24 displays the scheme of an iterative learning control [65]. The slide position is measured and fed back to the controller. The determined deflection is used to adjust the following stroke. Hence environmental fluctuations, machine deformations or changes in load, such as the break through during blanking, can be counterbalanced.

Conventional presses usually employ a flywheel that is connected to the main gear via a clutch brake. Therefore most attention has been paid to the on/off operation of the clutch brake [37]. For most servo presses the energy is directly transmitted. Hence an overrun of the servo-motor directly leads to an overrun of the slide’s motion. Thus additional digital control becomes necessary also for safety reasons. To avoid errors in position sensing, multiple position measuring is employed, combining absolute slide position sensors, pulse coders and, if applicable, angle sensors in the gear. Further redundant control loops are employed to avoid incorrect outputs [37].

3.3. Energy storage

In generating a full press load by using servo motors, a large amount of energy is taken from the electric circuit. An analysis of different operating press modes shows, that most energy is required during the forming and acceleration processes. Furthermore it is detected, that a large amount of energy is produced during the deceleration of the slide. Conventional mechanical presses store this energy in a flywheel. In hydraulic presses the energy is lost. Currently there are two options to store energy in servo presses. Either the energy is stored in a flywheel or fed back to the electricity network by using capacitors. By storing the energy inside the press, the size of the main line connection can be reduced by 30% to 70% [59]. Figure 25 shows the modification possibilities of a press with flywheel to a press with capacitor.
The example in Figure 26 illustrates power storage and output in a servo-mechanical press system over the course of a cycle. Operating with two main motors, each with a maximum output of 175 kW, the excess energy is stored in an energy-storage device during deceleration and is drawn upon when the press requires more than 175 kW. Because the stored energy is used during peak power requirements, the load on the facility network remains at approximately 50 kW. Two available methods to save the energy generated resulting from the deceleration of the slide are capacitor storage or motor/generator connected to a rotating mass. The more reliable and longer-lasting method is a motor/generator, but on-going developments in capacitor capabilities will likely make capacitors the preferred storage option of the future [111].

Currently capacitor banks with a capacity of $132 \mu F$ are used for presses of the mid-range engine-power class. Up to three capacitor banks can be connected to increase the storage capacity. The application of capacitors is also possible for already existing presses by retrofitting them.

3.4. Manufacturing information system

A manufacturing information system supports manufacturing functions such as production scheduling, plant design and inventory management [125]. Therefore, information from different sources is required and consolidated in this system. Material and personnel data, inventory and vendor information as well as engineering specifications are processed in a manufacturing information system [125]. This information is defined as an intangible object, which flows value-carrying through the product development process and the manufacturing sequence using software tools like CAD/CAM or data sheets [26]. The possibility to exchange information between different production systems, departments or even production sites is one of the most important advantages of a manufacturing information system. The control system of a servo press represents a part of a manufacturing information system. Data can be transferred between different presses and production sites. The knowledge of experienced operators is combined in the manufacturing information system and is accessible to all operators in the company. Hereby a prototyping process can be easily reproduced and checked at different production sites even overseas. Using this control possibility the conventional evaluation method of different machine parameters is simplified. This leads to a reduction in time and effort for the setup from prototyping to high volume production (Figure 27).

3.5. Internal connections

In the following the connections of servo presses with other elements of the production system are differentiated in internal and external connections. Internal connections are located inside the system boundary defined around the press itself. Here applications of die cushions, ejector and multi-slide systems will be presented. External connections are referred to elements outside of the system boundary such as handling system, press feeder and the arrangement of multiple presses.

A servo-motor supplier [1] shows the possibility to apply the servo-motor drive principle to the design and control of a die cushion. In Figure 28 the schematic configuration of a servo die cushion is shown [9]. The servo-motor underneath the working surface of the press is connected to a bolt. The bolt is then connected to the working surface of the press. The pressure sensor is mounted on the bolt. The servomotor is controlled by a control unit which is connected to the press control system. The control unit receives signals from the pressure sensor and adjusts the speed of the servomotor accordingly. This ensures that the force applied by the press is constant and does not fluctuate. The control unit also receives signals from the position sensor which measures the position of the bolt. This information is used to adjust the speed of the servomotor so that the bolt moves at the correct speed to achieve the desired force.

Figure 25: Servo press with energy storage [59].

Figure 26: Power storage and output in a servo mechanical press system [111].

Figure 27: Effect of visualisation and exchange of machine data [36].

Figure 28: Schematic of servo drive die cushion [9].
space is linked to a screw by a timing belt. By powering the motor and turning the screw the movement of the die cushion is realised. The pressure sensor between the elements of the die cushion controls the position of the assembly. The application area of this cushion is similar to hydraulic cushions, which are used in conventional mechanical and hydraulic presses. To optimize the metal flow in the flange, between the die and the blank holder multiple point die cushions are required. With the shown servo-motor an enlarged number of cushion pins can be implemented. The most important advantage of the servo die cushion is the possibility to regenerate energy when it is pushed down by the upper die. Hereby the servo-motor act as a generator which recuperates the energy back into the system and provides it for the next stroke.

For die cushions for deep drawing air and hydraulic ones have been used. Since the die holding force of the air die cushion cannot be controlled, and the response of hydraulic die cushion with a servo valve is slow, a servo motor controlled hydraulic die cushion was developed. Figure 29 shows the NC control hydraulic die cushion attached to a servo press [77]. It is reported that the die cushion can reduce the impact loading at the time of contact and 70% of the energy used for die cushion is recovered.

3.6. External connections

3.6.1 Servo feeders

To allow transfer systems to be synchronized to the press motion servo feeders are used. The feeding function can be integrated into the press control, avoiding collision with the slide during the feeding motion [19]. Due to the absence of a mechanical drive coupling wear and maintenance effort are reduced [49]. Especially, for forging applications servo-motor actuated transfer fingers are applied. These allow carrying out changes in their opening and closing movement as well as traverse movement without mechanical adjustment. Further the correct gripping can be monitored by the position and force information of the servo system. Hence no additional sensors become necessary [49].

3.6.2 Connection of presses

For the production of more complex parts, multiple servo presses are combined with press lines. Hence productivity is increased and problems regarding eccentric loads can be limited. In a transfer press line one transfer is employed for the part’s handling between all presses. In a tandem line each press is fed from an external device. Hence the feeder can be easily matched to the press movement (Figure 31) [96,128].

To optimize cycle times of press lines a phase shift between the motions of successive presses is employed (Figure 32). Therefore the influence of the transport time on the cycle time is limited. Furthermore employing a phase shift allows smoothening peaks in energy consumption.
While a mechanical transfer press usually provides a high productivity, a transfer press line provides a high flexibility. Since each press in a tandem line is fed by an individual device, the height of the dies does not have to be matched [13]. Furthermore each press can be used independently from the others, allowing shortening the line or production on single presses as shown in Figure 33.

3.6.3 Large press lines

By extending the idea of connecting presses, large presses can be connected to transfer press lines for plate forging and sheet drawing of auto body panels. The gaps between the presses are set to be small only to accommodate the transfer devices and robots.

For plate forging, seven 6300 N forging presses, explained in Figure 16, are connected to each other without gaps as shown in Figure 34. The total press force is 42,000kN [8].

Tandem servo press lines for draw-forming of automobile body panels have been built by Toyota (with Komatsu), Honda (with Aida Engineering [132]) and BMW (with Schuler [115, 123]). Figure 35 shows the servo press line in Suzuka plant of Honda [77]. This tandem line is composed of 4 servo presses (23000kN drawing press force) and 4 servo feeders for conveying panels from one process to the next. It is reported that more complicated shapes of body panels can be formed by this line with faster speeds than conventional press lines because the motions of die cushion and transferring equipment can be optimised for each product.

Figure 36 shows a layout of a servo press line of the BMW factory in Leipzig [115]. The total press force is 103,000kN, the drawing press force is 25,000kN, the length of the press line is 34 m (total length is 98m), and the stroke per minute is 17.

Figure 33: Individual forming motions of presses in a transfer line [13].

Figure 34: 42000kN servo press line with seven 6300kN presses for plate forging (Komatsu) [8].

Figure 35: Servo press line for automobile panels (Honda-Aida) [77, 132].

Tandem servo press lines are believed to increase the efficiency of small quantity production and to reduce the time for preparation of production and to stabilize the product quality and to increase the yield of material usage. Because of large freedom of slide motions and related equipment such as servo die cushion, process simulation is essential.

Figure 36: Layout of servo press line in BMW Leipzig [115].
4. Application of servo press to sheet metal forming

Press forming of sheet metal, often called ‘stamping’, includes bending, deep drawing, stretching and shearing. Sheet metal forming is usually carried out at room temperature, but to form high strength steel sheets hot stamping began to be used in the last decade.

4.1. Bending

To reduce the weight of car, high strength steel sheets are more and more employed as the material of body panels. In bending of high strength steels, spring-back is extremely large, and the dimensional accuracy of the formed products deteriorates. To decrease the amount of spring-back in V-bending of various steel parts, Mori et al. [82,83] used a servo press and examined the slide motions: holding and bottoming shown in Figure 37a. The angle of spring-back in the 980 MPa level ultra-high strength steel sheet was considerably reduced by the bottoming motion, which gives a small amount of excessive deformation at the bent corner, whereas spring-back was not improved by the holding motion without giving excessive deformation as shown in Figure 37b. Kaewtatip et al. [50] used the bottoming motion to reduce spring-back in U-bending of high strength steel sheets.

At the final stage of the bottoming motion, the bent corner is indented by the punch tip and the stress state may be changed from pure bending to compression, and the spring-back associated with the bending stress may be reduced.

(a) Sliding motions
(b) Effect of slide motion and forming speed

Figure 37: Reduction in spring-back by bottoming in V-bending of 980 MPa level ultra-high strength steel sheet [83].

In U-bending, Suganuma [128] used the re-striking motion (Figure 37c) with a servo press by compressing the side wall to the height direction in the second strike as shown in Figure 38a. The re-striking process was realized by installing a device to change the tool distance between the bottom surface and the flange surface after the first strike. From the Figure 38b it is clear that spring-back is suppressed by re-striking. In the re-striking, the stress state of the sheet becomes compressive in the height direction of the sheet and the stress gradient in the thickness direction, which is the main reason of spring-back in bending, may be reduced.

In bending of sheet metal, the bent parts often undergo stretch flanging, which causes large tensile stress, and fracture tends to take place. Fracturing strain of the flange made in bending of an ultra-high strength steel sheet was increased by improving the sheared surface of the blank and using forming a servo press [81]. To improve the quality of the sheared surface, the clearance between the punch and the die in shearing before the stretch flanging process was optimised, and the sheared edge was smoothed with a conical punch.

4.2. Deep drawing

4.2.1 Deep drawing with various slide motions

In deep drawing, the occurrence of wrinkling is the most important defect that should be avoided and a blank holding force is applied to suppress the occurrence of wrinkling. But a large blank holding force increases the frictional force which tends to cause fracture of the sheet. Thus it is important to reduce the friction to achieve a successful deep drawing operation.

Tamai et al. [130] tried to improve the formability of high strength steel parts in deep drawing by detaching the tools from the die cushion periodically from the sheet as shown in Figure 39a. It was found that the sheet was automatically re-lubricated when the tool was detached. A 590 MPa level high strength steel sheet was successfully drawn by using the detaching motion as Figure 39b.
Komatsu et al. [58] reported a case where wrinkling in deep drawing was prevented by applying the stepwise drawing motion shown in Figure 40a on a servo press with a constant clamping force. As shown in Figure 40b, the occurrence of wrinkling was eliminated by applying a smaller (about 1/3) flange clamping force than the conventional motion with the stepwise motion. No clear reason is given why wrinkling disappears by the stepwise motion. Although wrinkling would start with the low clamping force in the downward movement of the stepwise motion, the initiated small wrinkle may be suppressed or released by the clamping force during the upward movement of the main slide. A similar effect for preventing the occurrence of wrinkling by the pulsating internal pressure was reported for hydroforming of tubes [85].

Hagino et al. showed that a stainless steel sheet was successfully stamped into a fuel cell separator with a servo press, and the dimensional accuracy was improved by striking two times at the bottom dead centre [34]. Since rupture of stainless steel sheet in deep drawing tends to be caused by local temperature rise at a high stamping speed, low forming speed is desirable. By reducing the slide speed just before the contact of the punch and the work piece on a servo press, deep drawing of a stainless steel sheet was successfully carried out with a high productivity without causing rupture [122].

4.2.2 Deep drawing with variable blank holder force

By combining a servo press and a hydraulic or servo motor driven die cushions (see Figure 28), it is possible to vary the blank holder force (BHF) during a process, as is done in the large servo press lines of automobile body panels. Figure 42 shows an example of the motion of a servo die cushion when applied to deep drawing [9]. The position controlling and force controlling can be switched during a process. The blank holder force is changed to prevent wrinkling of flange while moving the cushion with the same speed as the slide.

Figure 40: Prevention of wrinkling in deep drawing by stepwise slide motion [58].

A sheet product, which ruptures with the conventional crank motion, is successfully formed by optimizing the slide motion of a servo press as shown in Figure 41 [95]. In this motion, the punch touches the sheet with a slow speed, and the slide movement is once reversed before the pre-forming stage of the top portion and the drawing stage of the rectangular portion. Since a complicated motion is used, the most influential motion for preventing fracture is not clear.

Figure 41: Prevention of rupture in stamping by controlled slide motion [95].

To achieve large deformation in deep drawing by avoiding wrinkling and fracture, optimum BHF was searched for with a servo press by keeping the BHF at different constant levels [145]. Since the optimum BHF varies during an operation, variable BHF began to be studied by Manabe et al. [69] and many researches [100] have been carried out to determine the BHF history for drawing of deep cups without fracture and wrinkling. Since the BHF history cannot be decided easily with experiment, some methods using the FEM simulation were carried out for a round cup [142] and a square cup [55]. Koyama et al. optimized the process by combining FEM simulation and a data base [60]. Figure 43 shows a concept of determining BHF history by including logic of control in the finite element simulation [106].

Figure 42: Motion of servo die cushion used for blank holding in deep drawing [9].

Figure 43: Concept of determining optimum history of blank holding force [106].
4.2.3 Deep drawing with heated tool

Magnesium alloy sheets exhibit poor ductility at room temperature but when they are heated to a temperature between 200 and 300 °C, they become ductile and deep drawing is possible. To avoid cooling of the heated Mg blank by contacting with the cold tools before deep drawing starts, heated tools are used. Oyamada et al. [114] adjusted the contacting time of the blank with the heated tools. Kaya et al. [52] included a heating process in the slide motion of a servo press, i.e. the sheet was sandwiched between the die and the blank-holder having inside heaters just before drawing operation as shown in Figure 44.

![Figure 44: Warm deep drawing of magnesium alloy sheet with heated dies. The numbers given in the lower part of the figure denote the stages of the process [52].](image)

4.3. Ironing

Koga et al. [56] applied a stepwise motion to the ironing of cups, by calling this “vibratory ironing”. As shown in Figure 45, a larger reduction in thickness was attained with the vibratory ironing method.

![Figure 45: Large reduction in thickness in ironing of aluminium cup by stepwise motion [56].](image)

4.4. Shearing

Murata et al. [93, 94] proposed a “progressive stair die” in which shearing of a sheet is done at multiple slide strokes by using a punches with different lengths as shown in Figure 46. Since the available press force is not changed by the slide position in the case of the ball screw type servo press, it is not necessary to carry out shearing near the bottom dead centre, differently from the conventional mechanical press. By shearing at different slide positions, the maximum shearing force is kept low. Together with the good parallelism of slide of the servo press, Figure 46a, the low sharing force leads to accurate shearing of products with complicated shape such as Figure 46b.

![Figure 46: Shearing by progressive stair die [94].](image)

Otsu et al. [113] proposed a slide motion to reduce the noise in shearing by calling it “variable punch speed”. As shown in Figure 47a, the punch is stopped midway during shearing and then accelerated to finish shearing. Figure 47b shows the change of noise level by the stopping position in the variable punch speed motion. The noise level is lowered especially when the punch is stopped at the late stage of shearing because the load before breakthrough is reduced, and the horizontal vibration is restricted during intermediate stopping by holding the punch in the half-made hole. Junlapen et al. [47] also examined the reduction in blanking noise with various motions.

![Figure 47: Reduce in noise of shearing by two-step punch motion on servo press [113].](image)
In the shearing of plates and sheets, it is known that burr formation is prevented if the shearing direction is reversed twice as shown in Figure 48 [66]. Julapen et al. [48] used a servo press to realize this process and showed that burr-free shearing was possible if the working condition is carefully chosen.

![Figure 48: Burr-free shearing of aluminium alloy sheet [48].](image)

**4.5. Sheet forming with multiple driving axes**

In the progressive and transfer dies mounted on a press, as in the general cases employed in sheet metal forming, a product is completed by changing the dies as Figure 49a. To complete a product without transferring the forming position, a one shot stamping process with a servo press having some driving slides was proposed by HSK as shown in Figure 49b [92]. The process is composed of several stages which are realised by using multiple slides on a servo press explained in Figure 10. For the one shot stamping, the process design and die structure are critically important but they are not disclosed for this case.

![Figure 49: One shot stamping process having some slides for controlling motion in one press [92].](image)

**4.6. Hot stamping**

Hot stamping of quenchable steel sheets is effective in solving the problems encountered in forming of the high strength steel sheets. By heating the sheets, the forming load is lowered, spring-back is prevented and formability is greatly improved. In addition, the hot stamped parts can be hardened by contacting with the cold dies just after forming (die quenching), and ultra-high strength steel parts having a tensile strength of approximately 1.5GPa are obtained with a low forming load.

To attain the slide motion for die quenching process, which holds the dies at the bottom dead centre for a while by sandwiching the sheet, servo presses are suitable [84]. In addition, a high slide speed of the mechanical servo press is advantageous to prevent temperature drop during stamping although the hydraulic presses having a slow slide speed are mainly employed in the present hot stamping operation.

In conventional hot stamping, the steel sheets are heated in a furnace and oxidation of the formed sheets is unavoidable. To prevent oxidation in hot stamping, Mori et al. [86] developed a heating process using rapid resistance heating as shown in Figure 50. The resistance heating equipment is synchronised with a servo press, and the sheet is stamped after only 0.2s of the end of heating. It is reported that oxidation is considerably reduced by stamping the sheet on a servo press just after heating by the resistance heating process.

![Figure 50: Hot stamping process using rapid resistance heating [86].](image)

A warm and hot punching method [88] was developed by combining the resistance heating method with a servo press to reduce the punching load of ultra-high strength steel sheets as shown in Figure 51. The resistance heating equipment is synchronised with the servo press. As the heating temperature increases, not only the punching load decreases but also the shiny burnished surface increases.

![Figure 51: Hot punching of 980 MPa level ultra-high strength steel sheet using resistance heating [88].](image)
When a sheet heated at 900 °C is drawn at a low slide speed, the sheet is ruptured due to local temperature drop. The formability in the hot stamping is improved by increasing the slide speed as demonstrated in Figure 52.

![Figure 52: Improvement of formability in hot stamping by increase in slide speed in deep drawing at 900 °C](image)

The combination of servo press and resistance heating was also applied to hot spline forming of high strength gear drums used in automobile transmissions [136]. At first a sheet is drawn into a deep cup, and then a spline is formed on the side wall of the cup by a gear drum die. As shown in Figure 53, the side wall of the cup was heated by resistance heating to decrease the forming load and to increase the formability. Since the cross-sectional area of the side wall of the ironed cup is uniform in the electrification direction, the temperature of the side wall is uniformly distributed and this helps to form the can with gear drum easily.

![Figure 53: Hot spline forming having resistance heating of side wall of 980MPa level high strength steel cup](image)

A die quenching method for producing ultra-high strength steel parts having strength distributions was developed [87]. Since the quenchable sheets are not hardened by air cooling, the strength distribution is controlled by limiting the contacting area with the tools to the portions requiring a high strength as shown in Figure 54. The contacting parts were locally quenched by the grooved tools when the slide is kept at the bottom dead centre for a given time, while the non-contact portions were left without quenching. A servo press was employed to control the holding time at the bottom dead centre.

![Figure 54: Tailor die quenching in hot stamping for producing ultra high strength steel formed parts having strength distribution](image)

5. Application of servo press to bulk metal forming

Since the early servo presses had low loading capacities, they were employed mainly for cold forging that requires low forging force due to the small product size [10,12]. Recent development of strong servo motors enabled construction of large servo press for hot forging of large product size [104].

5.1. Free forging

Free forging is frequently carried out as the first process of die forging under the name of “upsetting”, and has been used in incremental bulk forming because various shapes could be flexibly formed with a small number of tools [29]. In free forging, deformation is not strongly restricted by the tool shape and the forming pressure is low, but the forming pressure in upsetting of thin plate is extremely high due to the restriction by friction.

Maeno et al. applied the oscillating or pulsating motion of a servo press to plate upsetting [68]. In the unloading stage of the oscillating motion, the periphery of the work-piece leaves from the tool surfaces as shown in Figure 55a and liquid lubricant is sucked into the gaps reducing the friction in the next loading stage. Figure 55b illustrates the load-stroke curve in upsetting of an aluminium plate of 2 mm in thickness and 20 mm in diameter. By the oscillating motion, the load is lowered especially at large reductions.

![Figure 55: Mechanism of lubrication in upsetting with oscillating load and change of load in upsetting of thin plate](image)
Traditionally incremental forging has been performed as hammer forging, and is used now to forge very large products such as rotors of electric generators by using large hydraulic presses with capacities of 50MN - 200MN. Manipulators are combined with the presses to handle large work-pieces.

By combining a servo-press with a robot, this process may be used as an efficient method for small batch production of smaller parts by using robots to handle the work-piece in positioning and posturing. Wang et al. [141] demonstrated the case of the robot in combination with a servo press for incremental forging as shown in Figure 56.

![Figure 56: Free forging with robot and servo-press [141].](image)

### 5.2. Closed die forging

Die forging is used to change the shape of a bulk metal to the shape of die cavity by compressing between the upper and lower dies. In closed die forging, the product shape is the same as the shape of die cavity, and the pressure tends to be increased excessively. Since the servo press can detect the working load and stop the slide motion before the bottom dead centre in case of excessive loading, it is advantageous for close die forging.

For close die forging of a magnesium plate, it is necessary to heat the plate up to 200 - 300 °C to deform it without causing brittle fracture [98], but the heated plate is easily cooled down during transferring from the furnace to the die. To carry out heating and forming of a Mg plate with heated tools, the process shown in Figure 57 [73] was developed. The Mg plate is sandwiched between the high temperature dies for a while, and then forming is carried out with the same dies [74]. For this movement of the upper die in this process, the servo press was effectively used. Since the Mg alloy exhibits significant work softening at 200 - 300 °C, it is desirable to deform the work-piece without restriction at the beginning of forming until the flow stress drops sufficiently [70,75].

![Figure 57: Forging of Mg alloy with heated tools [73].](image)

By using heated dies, Shiraiishi et al. [124] proposed a plate forging method for magnesium covers with ribs and flanges as shown in Figure 58a. By applying a back pressure to the central part of the work-piece on a servo press, the ribs are formed successfully without contraction defect as shown in Figure 58b.

![Figure 58: Forging of magnesium cover with rib and flange [124].](image)

Coining is a die forging method in which a thin plate is compressed between closed dies with shallow cavities at room temperature. Because the work piece is thin, very high pressures are necessary.

By using a servo press, coining of a thrust bearing shown in Figure 59a which has shallow grooves formed by the hammering motion in which the tool hit the work-piece repeatedly without changing the slide position [20]. When the hammering pressure is high (392kN) as shown in Figure 59b, the grooves are completely shaped, but the groove depth is incomplete when the pressure is not high enough.

![Figure 59: Coining of thrust bearing by hammering motion [20].](image)

### 5.3. Forward extrusion

Free extrusion is a method used to reduce the cross-sectional area of rod shaped work-piece by pushing through the die hole without restricting by container. This method can be successfully applied when the compressive pushing stress is lower than the yield stress and the elastic buckling limit of the rod.
In “FM forming” or “Axial Forming” patented by Felss [25], the die or the billet is oscillated during extrusion, i.e. the die or the billet moves forward about 2 mm and then back 1 mm in each step (Figure 60a). The work-piece is re-lubricated with liquid lubricant when the tool retreats. By using the oscillating motion, the forming load in free extrusion of a spline shaft was reduced by about 40% as shown in Figure 60b [101], and the load drop extended the forming limit set by buckling of the shaft. Although this result was obtained with the specially designed machine, the oscillation mode can be realised by a servo press.

![Slide motion](image1)

(a) Slide motion

![Load history](image2)

(b) Load history

Figure 60: FM Forming with oscillating motion [101].

Pinion gear shown in Figure 61a is often manufactured by forward extrusion. An important technical problem of this process is that the temperature of the deforming area gradually changes as extrusion progresses and the dimensional error of the teeth is varied along the axis as shown in Figure 61. Ando showed that it was possible to keep the error to a minimum extent in the whole length by varying the extrusion speed during an extrusion process on a servo-press [11].

![Pinion gear](image3)

(a) Pinion gear

![Distribution of dimensional error](image4)

(b) Distribution of dimensional error of teeth

Figure 61: Dimensional error of helical gear extruded with mechanical and servo-presses under different forming speeds [11].

5.4. Backward extrusion

Backward extrusion is used to produce cup shaped products, and is often combined with forward extrusion for making backward cup and forward cup, or backward cup and forward rod. One of the problems of this process is that the extrusion pressure becomes too high when the extrusion ratio is large.

The accuracy of an extruded product is influenced by the history of deformation speed during forming because different final temperature distributions, which is affected by the speed history, causes different amounts of heat contraction in cooling after forming. Ishiguro et al. examined the punch motions shown in Figure 62a in backward extrusion and investigated the variation of outer diameter of the extruded cup [45]. As shown in Figure 62b, a high-speed stroke condition without multiple strikes caused the minimum diametric error because the heat contraction balanced with the elastic spring-back.

![Punch motions](image5)

(a) Slide motions

![Variation of outer diameter](image6)

(b) Variation of outer diameter to height direction

Figure 62: Variation of outer diameter of extruded product by slide motion [45].

5.5. Cold forging with multiple driving axes

5.5.1 Enclosed die forging

In enclosed die forging, the billet is enclosed in the die cavity between the upper and lower dies, and then it is squeezed out by the upper and lower punches sideways. As shown in Figure 63, an enclosed die forging operation consists of: (a) supplying of a billet into the cavity, (b) closing of the upper and lower dies, and (c) pushing of punches to fill the billet material in the cavity. To realize this process, multi-axial hydraulic servo press was developed by Mitsubishi Heavy Industries in 1970s [79]. Because the contacting areas of the punches do not change during an operation, the forming load does not increase sharply, differently from die forging with flash formation. When the pressure in the die cavity exceeds a certain limit, the upper die floats up to relieve the pressure.

![Enclosed die forging](image7)

(a) Billet supply  (b) Die closing  (c) Forging

Figure 63: Method of enclosed die forging process and product.
Recently, an AC servo-motor driven mechanical press was used for cold enclosed forging of bevel gears as shown in Figure 64. It was reported that the die life was extended by 3 times and the energy consumption decreased to a half [5] by substituting a hydraulic press to a mechanical servo press.

5.5.2 Cold forging with axially driven container

In many closed die forging processes, the product corners cannot be filled well. To fill the corners in closed die forging with a straight cylindrical container, a method to drive the container in parallel to the punch as shown in Figure 65a was proposed [108,109]. In this process, the second slide drives the container while the main slide compresses the billet. The frictional force between the work-piece and the container helps to push the material into the corners with the movement of the container, and the punch pressure to fill the cavity is reduced almost to a half when the oscillation mode is used as shown in Figure 65b.

In extrusion of a double cup product with the usual fixed container, one of the cup walls reaches the objective length first and is stopped by the stopper tool, and then only the other wall is extruded. The punch pressure is raised extremely when the flow is changed to one side extrusion. When the container is moved to the axial direction as Figure 66, the extruding velocities to both sides can be controlled in such a way that both walls reach the objective lengths at the same time, and the extrusion pressure is kept low during the whole process [108]. This idea was extended to using a moving container with tapered inside surface, where the extruded cup is elongated by ironing [139].

5.5.3 Piercing against counter pressure

Piercing is often employed to make a hole in the ring shaped billet for cold forging. When a long billet is pierced, the volume of the discarded slab cannot be neglected and the surface quality of the pierced surface is poor.

Nishiyama et al. [99] applied a counter pressure from the die exit to the slug (part to be thrown away) as shown in Figure 67a. By the slide motions of a servo press shown in Figure 67b, the counter pressure is applied to the slug and the deformation mode is changed from simple shear to extrusion of a forward bar-backward cup, and the length of the slug is shortened.
Matsumoto et al. applied this method to piercing of a magnesium alloy at room temperature [72] with a servo press. By applying a counter pressure, brittle fracture is prevented and a long smooth shear surface is obtained, and the length of the slug is shortened as shown in Figure 68.

Figure 68: Effect of pressure on smooth shear surface and slug length in piercing of Mg alloy against counter pressure [72].

5.5.4 Extrusion against counter pressure

Because a servo press can be operated with synchronization of air and hydraulic cylinders, and moving the secondary slide axis with a controlled force, it is convenient to use it for the processes that apply a force to the tools during forming.

In forward extrusion, the shape defects shown in Figure 69a tend to occur. When the billet height is short, the cavity defect is caused on the rear surface of the product. If a counter force is applied to the extruded end by a retreating counter punch driven by a servo cushion as Figure 69b, the rear cavity may be suppressed and the front surface may be flattened.

As shown in Figure 69c, the rear cavity disappears when the pressure is about 0.3 times as high as the flow stress, and the front end becomes completely flat when the counter pressure exceeds the flow stress [35,105].

Figure 69: Prevention of extrusion defects by using pressure supported punch [105].

When a work-piece is extruded through multiple exit holes, the extruded lengths are different from each other. By using a counter tool supported by a proper pressure, it is possible to obtain the same extruded lengths as shown in Figure 70 [103]. It was found that the extruded lengths could be equalised with an average counter pressure less than 5 % of the flow stress.

Figure 70: Forward extrusion against pressure supported tool [103].

Otsu et al. proposed an extrusion method of a forward rod and a backward cup by driving the two punches using a double axis servo press [112]. The speed of the counter punch was controlled to form the length of the forward rod accurately. As an extension of this method, reversed slide extrusion shown in Figure 71 was proposed, in which the extruded forward rod is pushed back while the main punch was kept at the final position. By employing this motion after combined extrusion, the dimensional accuracy and the flatness of the front end were improved.

Figure 71: Extrusion with reversed slide motion [112].

5.6. Hot die forging

In hot die forging, it is generally believed that high slide speed is desirable to avoid cooling of the billet and heating of the dies due to the direct contact of the hot billet and the cold dies. On the other hand, it is known that the flow stress is strain rate sensitive at high temperatures, and a low speed deformation brings about a low forming force as is utilised in isothermal forging with the dies kept at a high temperature. Thus the appropriate forging speed may be determined by the temperature and heat conductivity of the dies. Maeno et al. examined the effect of the slide speed in spike forging by using a servo press for an aluminium alloy. As shown in Figure 72, the spike height is the largest for \( \nu = 15 \text{ mm/s} \) becomes the largest because the
equivalent stresses near the corner of the spike portion for \( v = 6 \) and 75 mm/s are larger than those in the flash portion, and thus the flow into the spike portion becomes small [67].

In this way, servo presses may be used at an optimum speed depending on the balance of cooling by the dies and heat generation by plastic deformation.

In this way, servo presses may be used at an optimum speed depending on the balance of cooling by the dies and heat generation by plastic deformation.

Figure 72: Effect of slide speed on spike height for spike forging obtained from experiment with Al-Si alloy [67].

5.7. Combination of forging and joining

The new plastic joining method for fixing a cold bar with a hot forged plate shown in Figure 73a was studied by using a servo-press. During indentation of the cold bar into the hot plate, a high speed movement of the bar prevented cooling of the hot plate and resulted in a low indentation pressure and high bonding strength as shown in Figure 73b [71].

Figure 73: Effect of indentation velocity on forming pressure and bonding stress in joining of cold bar with hot forged plate [71].

5.8. Improvement of workability in forging

In upsetting tests of a magnesium alloy AZ31B at 473K, the effect of the strain rate change during an operation shown in Figure 74a was studied. Slide motion (A) was the natural motion of the link type servo press (Komatsu) without speed modification. Motion (B) accelerated the speed at a reduction of 20%, and motion (C) decelerated the strain rate. As shown in Figure 74b, it was found that slide motion (C) caused a higher ductility than (A) and (B) by about 30% [76].

By utilizing the function of the servo-press that the forming velocity can be freely changed, the best working condition to give a large working limit was searched for Ti by Venugopal et al. [137]. The deformation mode was plotted on the map of temperature and strain rate and the optimum temperature and strain rate avoiding instable deformation was found for commercially pure titanium.

6. Concluding remarks

6.1 Advantages of mechanical servo press

In this review, various servo press designs and their applications are introduced. The apparent advantages of the servo press can be summarised as follows:

1. Because all the press motions such as starting, velocity change and stopping, are done only by the servo-motor, the mechanical servo press has a simple drive chain without a flywheel, clutch and brake that are essential for a conventional mechanical press.

2. The flexible slide movement enables the most suitable motion for each forming method or product. The optimised motion can extend the forming limits, enhance the productivity, and improve the product accuracy.

3. Due to the reduction of friction loss by clutch and brake, reuse of the stored kinetic energy during deceleration and the optimised slide motion, the energy consumption in forming is reduced.

4. A servo press with multiple driving axes enables to incorporate in-die operations that can reduce the number of forming steps and to form more complex and accurate parts in one press.
(5) Due to the computer control of servo-motors, many servo presses can be connected by driving with different motions in order to maximize the production efficiency.

6.2 Industrial trend

At present, the servo presses are used mainly in the fields of sheet metal forming to extend the productivity and the forming limit, and also to improve the dimensional accuracy of the products. Some auto makers have built tandem press lines for stamping of automobile bodies to attain greater formability and better productivity. The industrial trends of mechanical servo-drive presses indicate as follows:

(1) In the last decade, more than three thousands of servo presses with relatively small capacities, up to 400 ton, have been built in both C frame and straight side frame designs.

(2) Several press lines with large straight side sheet metal forming presses up to 3000 ton capacity have been built and used in automotive production. They offer considerably larger stroking rate than the conventional transfer presses for stamping of large body components.

(3) It can be expected that the application of servo presses will increase rapidly since these presses realize higher productivity as well as quality improvements.

6.3 Future prospect

Due to the rapid changes in information technology and progress of global production, servo presses will be integrated into the large scale manufacturing systems. Although the future prediction may be easily differed by various factors, the followings are the present prospects of the authors:

(1) New and innovative forming methods will be developed by using the flexible slide motion and multiple driving axes.

(2) To optimize the complicated slide motion of servo presses, computer simulation of forming processes will become essentially important.

(3) Similarly to the cutting machine tools, majority of the present presses will be replaced by servo presses, and the number of driving axes of each servo press will be increased.

(4) Servo presses will be used on the same floor as the cutting machine tools to make smooth production lines because they do not cause strong vibration and impact noise.

(5) Servo presses will form integration platforms for the combination of several different manufacturing processes.

(6) Servo presses will be preferably used for global production because the same slide motions can be realised irrespective of the location of production without depending on the skill of the operators.

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References

[23] EP 1917564 B1, 2009, Method and Apparatus for Controlling and Regulation of the Ram Movement on Servo-Electric Presses, Müller Weingarten


