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Increased total flexibility by 3D Servo Presses

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ABSTRACT

It is widely accepted that uncertainties influencing product costs and quality can be overcome by an increased manufacturing flexibility. Several approaches for flexible manufacturing machines and processes are known from literature. So far forming machines which enable high process flexibility have not been discussed thoroughly. In this paper, recent developments in the field of servo press technology are described and discussed under this aspect. Special attention is paid to the recent development of a 3D Servo Press concept which opens new horizons for flexible forming machines.

1. Introduction

Planning and selection of manufacturing systems are accompanied by uncertainties. This is caused by the limited validity of assumptions concerning future events which are made during the development and selection of manufacturing technologies and equipment. Uncertainties can occur either if the relevance of a future event for the manufacturing system under consideration is unknown or the occurrence of a relevant future event is probabilistic.

According to Gerwin [1], manufacturers have to deal with four main uncertainties: market acceptance of kinds of products, length of product life cycles, specific product characteristics and aggregate product demand.

One approach to encounter unavoidable uncertainties in the field of manufacturing is an increased flexibility of the applied systems and processes. Flexibility is classified, according to Slack [2], into two aspects: time and range. One solution to handle the uncertainties is called "bank" flexibility, i.e., a financial cushion is built to handle future needs. This investment opens up the possibility for several options, for example a dramatic change in market conditions can be intercepted rapidly. The second solution to deal with uncertainties is to work with flexible manufacturing systems. One manufacturing system is more flexible than another, if it can handle a wider range of possibilities [1]. Wiendahl and Heger [3] show the differentiation of production systems among each other according to their flexibility.

According to Son and Park [4], total flexibility consists of four different kinds of flexibility:

- Equipment flexibility
- Product flexibility
- Process flexibility
- Demand flexibility.

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Equipment flexibility is the capability of a system to integrate new products and variants of existing products. Product flexibility is determined as the adaptability of a production system to variances in the product mix. Process flexibility is defined as the adaptability of the system to changes in part processing, for example caused by changes of technology. Last, demand flexibility, describes the ability of a manufacturing system to respond to changes in market demand. Flexible manufacturing systems anticipate variations and built-in flexibility a priori [5].

Different concepts for flexible assembly and cutting machines have been investigated intensively in the past. Uncertainties can also heavily affect the future value of a selected forming machine. But so far, forming machines are either designed for large batch productions with fixed selected forming methods or for small batch productions with predetermined specialised tool movements. Consequently, their flexibility in terms of adaptation to changing market conditions is very limited [6]. The development of servo technologies for forming presses creates new possibilities for flexible forming machines [7]. This paper shows basic design principles for forming presses capable of fulfilling requirements resulting from large batch and specialised small batch forming processes simultaneously.

2. Measure of flexibility

Forming processes and associated machines vary in their number and types of driven degrees of freedom (DoF) necessary for the relative movement of tool and workpiece. Equipment, product and process flexibility can be increased by additional driven DoFs. Therefore the various processes and machines are analysed in Fig. 1 regarding the number of driven DoFs. On the other hand, demand flexibility is becoming poorer if the number of driven DoFs is increased. Especially high volume production is based on forming technologies with only one driven DoF for the tool–workpiece relative movement. These kinds of movement allow minimized tool path lengths and times of tool–workpiece contact. In the

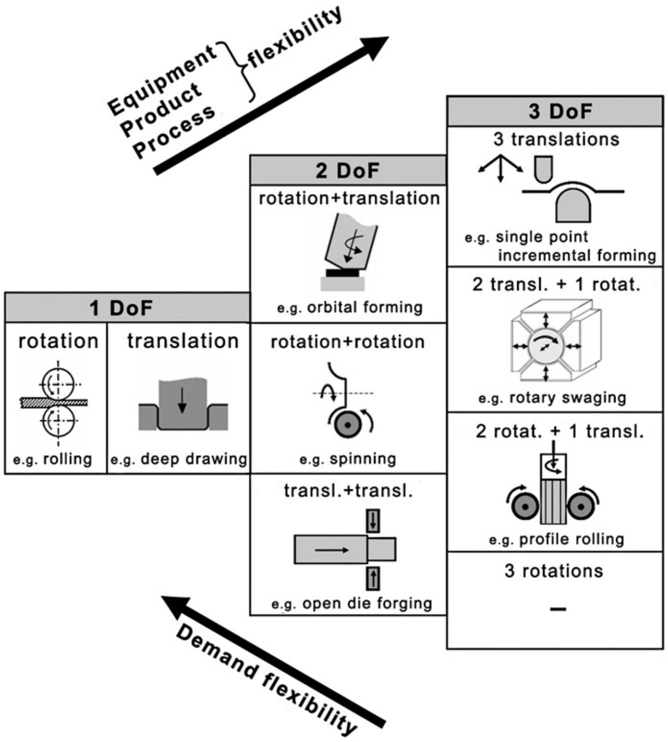

Fig. 1. Forming process classification by degrees of freedom (DoF).

following, processes and machines with different numbers of driven DoFs are discussed under the aspect of total flexibility.

The most elementary type of movement is given by a movement with one driven DoF like a rotation or a translation. These movements require one drive and control system for the tool or workpiece. Because of the short tool path length and contact time of tool and workpiece, the productivity is rated on a high level. According to the above-mentioned definition of flexibility, processes with one driven DoF for the workpiece or tool motion possess small equipment flexibility because the shape of cross sections is predefined and only changeable in a narrow bandwidth. Product flexibility is moderate because set-up times are usually long and high efforts are required for tool modifications. Process flexibility is poor due to the restricted usability of existing tools for the pre-planned production route. Demand flexibility is large if high numbers of parts are required. Due to the huge efforts for set-up demand flexibility is limited in the range of small batch production. Conventional mechanical presses provide a translational movement of tools or workpieces like it is required for a deep drawing operation of a sheet metal blank. New servo presses allow for translational movements with more flexible velocity time characteristics. This feature can be used for an improved material flow, a shorter set-up time or a higher accuracy of the produced parts. In consequence, total flexibility is slightly increased.

The second kind of forming processes are those with two DoFs. The forming flexibility of these processes is higher than those of processes with a single DoF. It is possible to produce new products or variants of existing ones not only by modified tools but also by changing the velocity–time curves of the two driven movements. In the same way modifications in part processing can be realised more easily. With the usage of an increased number of driven DoFs the tool path length and the time of tool contact is increased compared to a movement with only one DoF. Additionally, the effort to adjust the two motion axes to each other is higher and requires a more complex control. These facts result in a decreased productivity of forming processes with two DoFs and therefore a reduced demand flexibility if it comes to large batch production. Several examples for this type of operation can be found in the group of incremental bulk forming processes [8].

The highest level of process, product and process flexibility is achieved by forming processes with three DoFs in the tool–workpiece relative motion. This results from the possibility to form products with three-dimensional geometry by using a simple tool and a specific tool movement. Because of that, new products or variants can be integrated into the product mix in principal without a long set-up time. On the other hand, demand flexibility is small, if large numbers of a product are required. Compared to processes with one driven DoF the productivity of processes with three driven DoFs is low, because the tool path length is drastically elongated and the time of the tool in contact with the workpiece is longer. Therefore processes with three driven DoFs like single point incremental forming [9] are used for parts with complex geometries in small quantities. Efforts to plan and synchronise the movements in the three different DoFs are even higher than those for the processes with two DoFs.

The scheme in Fig. 1 with the given examples for forming processes shows the correlation between total flexibility and the amount of the used DoFs.

Processes with a single DoF offer high demand flexibility, especially if large numbers of products are required, at the expense of a large set-up and maintenance effort. In case of a decrease in demand and a lower lot size, these production processes are not efficient any more because of their high fixed costs. Forming operations with two or three DoFs are usually designed in order to realise special processes and not to create a high output of work pieces. An increase in demand could only be realised by additional machines which perform the same operations. Based on these findings, a forming process or a forming machine shows up to now either a high product, process or equipment flexibility or a high productivity.

3. Transformation of degrees of freedom

Conventional presses drive a translational relative movement of tool and workpiece. The analysis of forming processes shows that flexible forming machines should enable driven tool movements with several DoFs. Nevertheless, in order to reach a high productivity the drive system of a press should also be usable for simple linear motions without any reduction of production rate compared to conventional presses. Investments could be kept low, if all implemented drive systems are used for all kinds of movements. Consequently, also conventional translational relative movements of tool and workpiece should be driven by all drive systems of a press. Therefore, it seems attractive to use a multiple DoF forming press and transform the movement of the drives into different movement patterns of the ram. In order to build up a press with an isostatic, freely moveable ram, three points of translational actuations combined with suitable bearings are adequate. If the direction of the actuation for these three points is parallel, one DoF movement can be realised easily by synchronous movements. Other movements can be gained by transformations.

An example of such a transformation is shown in Fig. 2. On the left side a conventional movement of a ram with a single driven DoF is shown. The tool centre point (TCP) of the ram is moved in vertical direction z. Tilting around the axes perpendicular to the direction of movement, φ_1 and φ_2, does not occur. This kind of movement is accomplished by a synchronous movement in z-direction of the points 1, 2 and 3 according to the graphs shown. If crank mechanisms are used for the drive of these points, the displacement–time curves typically show a sinusoidal shape. Then the productivity is comparable to conventional presses with multiple pivot points between crank mechanisms and ram.

With the same drive systems also other types of ram movements are possible. One example is shown on the right side of Fig. 2. The drive systems are running with a phase shift and some smaller oscillations as magnified. Such kinds of movements are possible with servomotors linked to the drives which act on the points 1–3. The movements provoke a translational movement of

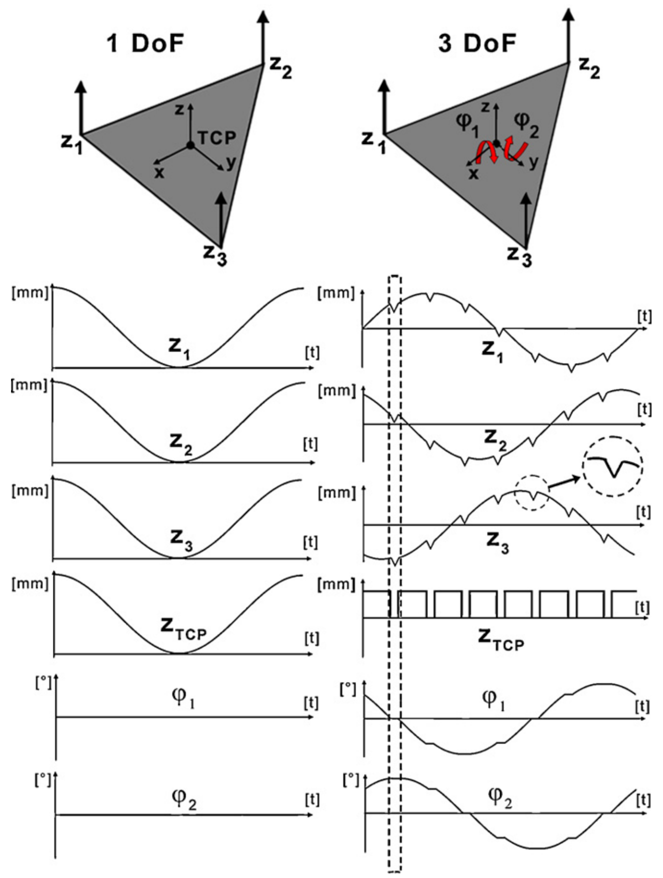

Fig. 2. Example for the transformation of degrees of freedom.

the TCP with a higher frequency as the sinusoidal movement of the points 1–3 and a tilting of the ram with some stationary intervals. An application of this kind of movement will be shown in Section 5. The displayed movement needs bearings at the points 1, 2 and 3 that allow rotations and axial movements around and in the directions of the axes from the points to the TCP as well as rotations around the axes in the ram plane perpendicular to these lines.

Many other patterns of movements are possible. The following equations describe the movements of the tool centre point of the ram in *z*-direction and around the *x*- and *y*-axes according to Fig. 2. They are based on the assumption that points 1, 2 and 3 are positioned at the corners of an equilateral triangle.

$$z_{\mathrm{TCP}} = \frac{1}{3}(z_1 + z_2 + z_3), \quad \varphi_1 = \arctan\frac{|z_1 - z_3|}{|y_1 - y_3|}, \quad \varphi_2 = \arctan\frac{(z_1 + z_3/2) - z_2}{|x_1 - x_2|}$$

Thereby, z_{TCP} describes the *z* position of the TCP. The variables x_i, y_i as well z_i define the positions of the different junctions *i*, $i = 1, 2, 3$ in the shown coordinate system. The angles φ_1 and φ_2 specify the tilting of the ram around the *x*- and *y*-axis as shown in Fig. 2.

Based on these equations different types of ram movements can be traced back to movements of the three different drive systems. Additionally, gears can be used to transform the movements of the ram into other movement patterns. These options expand the spectrum of possible forming operations from 1 DoF to 2 and 3 DoF ram movements. Hence total flexibility of presses is drastically increased.

4. 3D Servo Press

Servo presses are presses, in which servo drives control the motion of the ram. Servo motors are electrical actuators that operate with servo controllers in closed loops. The actuation can be torque-, velocity- or position controlled [10,11]. These presses allow flexible punch motions and a high accuracy.

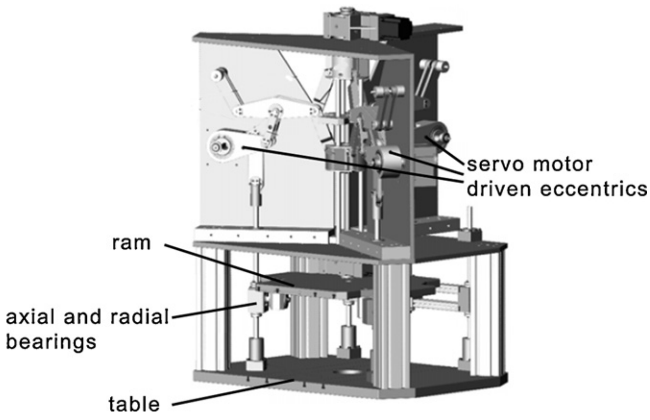

Fig. 3. Layout of the 3D Servo Press.

The afore mentioned considerations have been transferred to a new type of servo press, called 3D Servo Press, which provides a flexible ram motion with various numbers of DoFs. A sketch of this press is shown in Fig. 3. In the following a short description of the design is given.

Three drive systems, each consisting of a servo motor and a crank mechanism, are used for the movement of the ram at the three points 1, 2 and 3. These drive mechanisms are able to perform high stroke rates as already known from conventional mechanical presses. Since they can be controlled independently the translation of the TCP in *z*-direction and the rotations around the *x*- and *y*-axis can be realized freely as exemplarily shown in Fig. 2. The drive systems are arranged star-shaped with an offset of 120° as presented in Fig. 3. The crank mechanisms are linked to the ram by a connection rod and a bearing with the above described free rotational and translational movements.

The layout of the 3D Servo Press enables fast processes with one DoF movements of the ram like in blanking, stamping, deep drawing as well as processes with more than one DoF in tool movement like in orbital forming. Additionally, it can be used for the realisation of process chains in one clamping. An example for this kind of application is given in the following chapter.

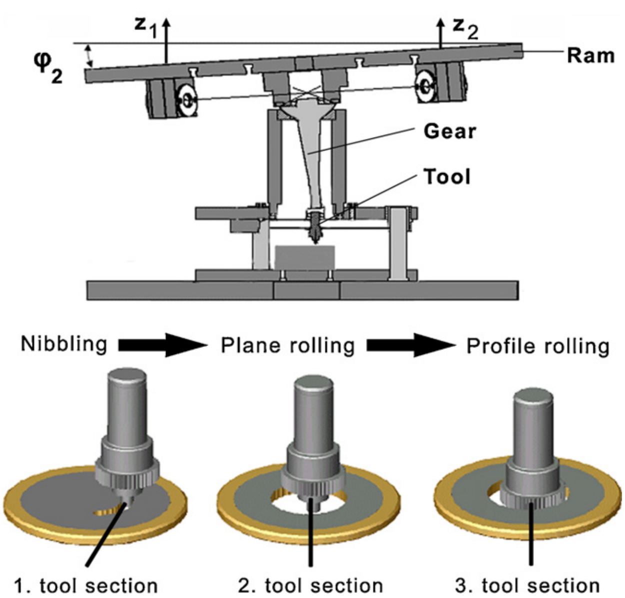

Fig. 4. Layout of the tool and the production sequence.

5. Application

To show the flexibility of the press system, a combined flexible blanking and rolling process for internal geared wheels is examined. The used tool, as shown in Fig. 4, is subdivided into three sections. During the different manufacturing processes, each of the tool sections are in use subsequently. The orbital motion of the ram, a rotation around the x- and y-axes like shown in Fig. 2 on the right side, is transferred by a gear into a translation in the x–y-plane. The ram motion in z-direction is also realised by the three drives of the 3D Servo Press. The motion pattern in this direction can also be seen in Fig. 2.

In the first stage of the manufacturing sequence a hole is nibbled into the workpiece as the first tool section moves along a defined path on the x–y-plane. While the stroke motion in z-direction is executed the movement in the x–y-plane stops. Before the second step, the tool moves downwards whereby the second section of the tool is brought into the correct vertical position. This tool section is used to plane the surface of the nibbled contour. The roll movement is realised in the x–y-plane during this process. In this case, there is no additional movement in vertical direction required. Thereafter, the third tool section is brought into contact with the workpiece by moving it downwards. This tool section performs the profile rolling procedure of the internal teeth. With the shown tool concept it is possible to create internal teeth with different diameters by changing the control parameters.

According to the definition of flexibility, this manufacturing sequence demonstrates a high product, process and equipment flexibility of the proposed 3D Servo Press. In addition to this, it is possible to shut down the degrees of freedom needed for the tilting movements and use specific tools for conventional blanking of internal gears with a predefined fixed geometry. By this, also large batch productions with production rates similar to conventional mechanical presses are achievable. Consequently, a high demand flexibility of the press is given too.

6. Summary

In this paper flexibility requirements for forming machines in the manufacturing sector are described. Flexibility is especially needed to handle different uncertainties in manufacturing. A classification of flexibility in forming systems is presented. Based on the definitions of flexibility, a scheme is developed which shows that the more degrees of freedom a system offers, the more flexible it is. Servo presses already provide a high flexibility in one degree of freedom. Therefore they build a good basis for a new type of press which is called 3D Servo Press. This forming machine provides the possibility to use driven tool movements in three directions. With the aid of gears movements with the proposed degrees of freedom can be transformed into other movement patterns. The flexibility of the concept could be demonstrated by a manufacturing sequence for the forming of internal geared wheels.

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