Deep drawing with superimposed low-frequency vibrations on servo-screw presses

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Abstract

The power train of a modern servo-screw press with low rotational moment of inertia provides higher dynamics and a new kind of flexibility in forming and stamping processes compared to conventional servo presses. In this paper a new technology for deep drawing on servo-screw presses called cushion-ram pulsation is described. It uses superimposed low-frequency vibrations between 10 Hz and 50 Hz at the cushion and the press ram. For deep drawing operations, the high tensile stresses in the frame of cylindrical cup usually lead to a reduction of material thickness. Thus, and due to the lack of work hardening, fractures frequently occur in the punch radius. The process developed here shifts critical loads to higher drawing ratios by decoupling the drawing operation and the prevention of wrinkles. A high frequency of the cushion-ram pulsation is necessary to allow high productivity. Technological results will be increasingly determined by the machine.

1. Introduction

The targeted utilisation of the dynamics of electromechanical servo presses without flywheel opens up new opportunities in sheet metal forming (Altan, 2007; Nakano, 2010; Osakada et al., 2011). Previously, increases in...
servo crank presses’ productivity have been achieved for the most part by increasing speed in the stroke without load, i.e. beginning from bottom dead center to touching down. Angular velocity of a crank shaft is on the one hand reduced to prevent e. g. impact shocks and on the other hand increased to maximise productivity (Altan and Tekkaya, 2012). In the future flexible servo press kinematics during the work piece contact would lead to new advantages. Servo presses with crank shaft (SEYI-AMERICA, INC. Online http://youtu.be/HPrMzQm1z4o 2014) or roller screw drives as shown in Fig. 1 (Gruner and Mauermann, 2009; Kuhn, 2011) or hydraulic servo pump (Rüger and Kraus, 2012) can be flexibly programmed with computer numerical controlled (abbr.: CNC) systems.

A new servo-screw press running at Fraunhofer IWU is equipped with 5 servo-screw drives at the ram and 8 additional ones at the cushion (see Fig. 1). Servo-screw presses are characterised by low rotational moment of inertia and high drive stiffness as a result of the axial powertrain arrangement. With this equipment, rapid changes of direction are also feasible in the cushion. To provide higher forces the vibrations can be superimposed by a hydraulic pulsator, which applies to the main press cylinder of a servo pump press (Rüger and Kraus, 2012). Further research projects deal with special hydraulic cylinders with small strokes directly attached to the forming tools.

![Servo-screw press diagram](image)

Examples showing the new technological opportunities are summarized in different papers (Landowski, 2004; Nakano, 2010; Osakada et al., 2011; Neugebauer and Drossel et al., 2012). Today, the design of highly dynamic processes is only supported by empirical methods. However, the effects of flexible kinematics have to be investigated in a systematic manner and optimal process parameters need to be reliably predicted in order to fulfil the ever increasing requirements in sheet metal forming.

Previously, the effects arising from highly dynamic processes have only been interpreted in an almost exclusively phenomenological way. Predictability by forming simulations is limited due to the complex, mainly non-linear relationships between the influencing parameters and gross simplifications in modelling. Newly developed advanced simulation models consider, for instance, quasi-static ram displacements and kinematics (Großmann et al., 2010; Großmann et al., 2013; Neugebauer and Großmann, 2013). However, in deep drawing techniques with vibration superposition, it is also necessary to map the machine-dynamic conditions, as well as material- and frictional models, as a function of time. Stand-alone approaches describing speed-dependent phenomena in highly dynamic forming processes have already been developed in the past (Neugebauer and Drossel et al., 2012; Neugebauer and Großmann, 2013).

In the following paper an overview of deep drawing techniques with flexible path-time curves will be presented, especially a servo-screw press for deep drawing processes with superimposed vibrations. At last the paper describes some remarks on process simulation. Due to the empirical character of the results the paper shows qualitative comparisons between conventional deep drawing processes and the new technique to demonstrate the positive effects.
2. Deep drawing with superposition of vibrations

The limit drawing ratio is influenced both by the part properties and friction. In a large-sized die, friction force is up to three times greater than the force necessary for forming without losses (ideal forming force) (Altan and Tekkaya, 2012). Friction between sheet and die is minimised when superimposing vibrations. In previous technical implementations using conventional presses, the vibrations in the die were created either in a magnetostrictive, piezoelectric electro-mechanic, or hydraulic way. With the introduction of advanced servo presses, new opportunities to dynamically affect the forming procedure are available in work piece contact. The term “highly dynamic process” here indicates quick load cycles, with high jerk values (for instance j > 300 m/s³) and great accelerations (for example a > 3 m/s²) at the press’ drive axes. Low- as well as high-frequency exciting mechanisms are in use for sheet metal forming. Amplitudes are in the micron range (Jimma et al., 1998; Siegert and Ulmer, 2001) at high-frequency excitation in the kHz range. At low frequencies in the range up to 50 Hz, vibration amplitudes of a few (sub) millimetres are technically feasible due to the machine-dynamic conditions (Klose and Bräunlich, 2000; Siegert, 2003; Neugebauer and Drossel et al., 2012).

In terms of classification, vibrations at cushion only and cushion-ram pulsation are principally located between deep drawing with static and without any blank holder. Despite provable positive effects, forming techniques supported by vibrations have only been able to position themselves in small industrial applications. Fig. 2 shows different forming kinematics. The varying path-time curves are composed of various speed portions, acceleration and jerk.

![Fig. 2. Summary of drawing techniques with variable kinematic profiles and superimposed by vibrations – schematic view.](image-url)

The kinematic sequence, including start and stop modes, is shown schematically in Fig. 2a). Some projects are focused on the speed-dependency of the coefficient of friction (Mori et al., 2007; Majidi et al., 2012), on material behaviour when interrupting stroke (Yamashita, 2010; Nakano, 2010) or deformation by plastic tension and compression (Kaya, 2008; Hayashi and Nishimura, 2009; Osakada et al., 2011). For high strength steel, an increase of up to a maximum of 20% in drawing depth can be achieved by means of a defined interruption of stroke (Yamashita 2010). The results demonstrate a stress relieve of the material as a function of time, independently of load speed and pre-stretch. The positive effects achieved on the real part are assumed to be caused by holding times, which were determined in an empirical manner. Longer holding times cause another drop in productivity (Komatsu and Murakami, 2009; Osakada et al., 2011). In this arrangement, a fracture in the high-strength steel sheet bottom is avoided using an unloading stage with return stroke (Tamai et al., 2010).

Other studies highlight differences when using a servo press instead of a conventional one, making it possible to form a square-shaped cup of low-alloy stainless steel with no fractures on the servo press (Landowski, 2004). The positive effects are assumed to be caused by the more suitable draw-in behaviour of the steel sheet near the bottom dead center. Current explorations are aimed at favourably utilising the tribologic conditions’ dependency on speed in deep drawing with special path-time curves for the forming procedure. Fig. 2b) outlines a schematic view of the kinematic sequence with a clear change of direction. We succeeded in fabricating an example of a deep drawn panel with irregular geometry with no failures due to a decreasing touch-down impact and modified process kinematics after pre-drawing and sub sequential final drawing (Nakano, 2010). If the part is deep drawn on a press with standard kinematics, the part fails in the drawn panel bottom area.
Deep drawing with pulsating punch, shown in Fig. 2c), can be found in different research papers (Klose and Bräunlich, 2000; Siegert, 2003; Wagner and Felde, 2005). The results demonstrate that high frequencies and low path amplitudes are useful for process design. In another variant (see Fig. 2d), the hydraulic cushion is made to pulse in a controlled manner (Fiat, 1994). The process result is constant above a certain cut-off frequency which depends on the specific material parameters. Two other technologies with several pulsating axes on servo-screw presses, which are currently under investigation at Fraunhofer IWU, are highlighted in Fig. 2e) and Fig. 2f) (Großmann and Neugebauer, 2010; Neugebauer and Drossel et al., 2012). The special drawing technique called cushion-ram pulsation (Mauermann, 2004) (see Fig. 2e) shows an example of a highly dynamic deep drawing process and is described in detail in the following chapter. The technique is a contribution to extend the process limitations, on the one hand. On the other hand, it takes more time to conduct the position-controlled process than the pulsating method, since additional holding times in the ram movement have to be addressed (Neugebauer and Drossel et al., 2012). The kinematic sequence of bi-directional deep drawing shown in Fig. 2f) (Mauermann, 2008) is carried out before starting the intrinsic deep drawing procedure. Focus is put on the area at the punch radius, which is critical for crack formation. There local strain hardening and wall thickness are minimal. The full drawing force must be transmitted through this bottleneck. Strain hardening in this zone increases due to alternating bending of the blank in bi-directional deep drawing. The sheet is thickened in the deformation zone by additional compression, since the material is pulled out of the flange in radial direction to the inside by means of customised kinematics before the drawing procedure itself. Fig. 2g) elucidates a strategy implementing one or more calibration strokes at the end of the drawing process. Stroke return deep drawing was engineered to reduce springback (in this case: distortion) of a profile. Before reaching the bottom dead center, the punch is run back one or two times (two step stroke return deep drawing), whereby a counter-punch arrests the drawn panel’s bottom and the blank holder fastens the flange. Material at the edge (the wall of the deep drawn part) is compressed. High cushion force means that the edge is stressed at the bend, because the material is jammed in the flange as a result of friction. Material can flow at a lower cushion force value, so that the different states of stress are superimposed by compression stresses after deformation at the edge, which is the wall of the deep drawn part. This way, curvature of edge due to springback is reduced. (Geka et al., 2013)

3. Description of cushion-ram pulsation

During standard deep drawing, the force transmitted directly to the edge increases to a critical maximum. The cushion-ram pulsation is superimposed just before the process point, at which increasing stresses at the edge would result in local drawing instability in the bottom curvature zone (minimal strain hardening) (see Fig. 2e). This means e.g. 20% of the drawing depth and with e.g. 50 cycles. During pulsation the maximum drawing force is reduced, therefor larger drawing ratios can be manufactured. Ram and cushion pulsate in a synchronised way, and pulsation is position controlled (Mauermann 2004). In Fig. 3, the process parameters (path- and time variables) for an individual cycle are elucidated.

![Fig. 3. Process parameters for cushion-ram pulsation (Neugebauer and Drossel et al. 2012).](image)

A cycle consists of two process steps, which starts with a ram dwell time. In step 1) the distance between sheet blank and die (flange gap) grows as the cushion moves away from the ram. Then the ram moves to draw the part in
a small step. At this time, the flange gap remains open and we obtain low friction and compression forces both in the drawing radius and in the flange, which is the technical benefit of the cushion-ram pulsation. Ram amplitude in step 1) is limited due to the formation of wrinkles in the open flange gap, similar to that in deep drawing without blank holder. Consequently, in the following step 2) the ram is stopped during the holding time. This is the relevant distinction from the procedure introduced in Fig. 2d) (Fiat, 1994). The ram stop means that no tensile stress relevant for breakdown affects the edge. In step 2) the cushion moves against the stationary ram, which results in an increase in surface pressure, wrinkles in the flange will be reduced. Elastic deformations of press machine and tool systems have to be compensated by specific parameter settings, e. g. a negative offset (see Fig. 3) or die closing force (Neugebauer and Drossel et al., 2012). All process parameters are usually varying from cycle to cycle. Ram and cushion amplitudes are inversely proportional to wrinkling. Amplitudes have to be decreased and frequency is adequately increased to achieve high productivity. Usual amplitudes can be found in the sub millimetre range. During a typical process on the servo-screw press (see Fig. 1), for instance, a maximum speed of approximately 23 mm/s is temporarily achieved for the ram, and approximately 42 mm/s is reached for the cushion, assuming a ram movement at an amplitude of 0.5 mm and a cushion movement at a value of 0.8 mm. For this setup one pulsation cycle is 0.068 sec long, which corresponds to a frequency of 15 Hz. In contrast the average drawing speed is approximately 7.3 mm/s.

A comparison between conventional deep drawing and cushion-ram-pulsation of the cylindrical cup shows the increase of drawing depth within a sequence of increasing drawing ratios (see Fig. 4). Using the example of steel DC04 with an initial blank thickness of 1 mm drawing ratios of \( \beta_{\text{max}} = 2.1 \) and \( \beta = 2.4 \) could be reached, respectively (Neugebauer and Drossel et al., 2012). During deep drawing there are cracks caused by local tension instability near to the punch curvature of the cup. Due to the technological separation of drawing progress (process step 1) and wrinkle reduction (step 2) critical loads are avoided with cushion-ram-pulsation in the frame.

Less local thinning in the zone of bottom curvature is characteristic for cushion-ram pulsation. The surface of a selected drawn panel was scanned on both sides by means of the optical measurement system GOM ATOS (Online http://www.gom.com 2014). Based on these scans, sheet thickness distribution was calculated from the orthogonal distance to the surfaces scanned and scaled by colours as indicated in Fig. 5. Strong tangential compression at the part’s margin causes particularly thick areas, which, in turn, can cause wrinkles and fractures in
the event of inappropriate process parameters and high drawing ratios. For this reason, dies for cushion-ram pulsation have to be designed with a greater drawing gap in order to avoid draw and wall ironing if the sheet is thickened too much. The analysis of the maximal punch forces as a function of the drawing ratio evidences lower part stresses when using cushion-ram pulsation. During progression in drawing, the total force is composed of the force value necessary for forming without losses (ideal forming force), the force for bending back and the frictional force at the draw ring curvature. In deep drawing, the friction between die and blank holder must also be considered. Consequently, in cushion-ram pulsation, the total force introduced via the punch is always lower than in deep drawing.

Further examples of the experimental comparison between various materials and parts were introduced in different research projects (Neugebauer and Drossel et al., 2012). The parts made by cushion-ram pulsation show small wrinkles in the flange area (see Fig. 6a), thus reducing part quality. The technique is aimed at expanding the forming limits for structural parts, as well as exploring a new product range for application. Part quality can be significantly enhanced by optimizing process parameters (see Fig. 6b) (Neugebauer and Drossel et al., 2012). In structural parts, for instance, it is possible to cut off the flange so that this quality feature is no longer critical. Profitability of the technique arises from the manufacturing of products that cannot be made by conventional deep drawing. The part shown in Fig. 6b) is out of steel DC04 with an initial thickness of 1 mm. The initial blank outline for standard deep drawing and cushion-ram-pulsation has the same size 680 mm by 430 mm. The conventional deep drawing ends up with a crack at the bottom corner after 46 mm depth. A much larger drawing depth can be reached by applying cushion-ram pulsation with 30 Hz and amplitudes of 0.2 mm (ram) and 0.8 mm (cushion). The tests were performed at the servo-screw press shown in Fig. 1.

4. Process simulation methods

The previous results show the complexity of deep drawing processes with superimposed vibrations. Further work goes on understanding the elementary relationship between forming processes and influence of machinery to enable planning and controlling dynamic processes. Therefor application of finite-element analysis for simulation of deep drawing processes, simulation of machinery with multibody systems or digital block simulation for environmental systems has already become an integral part in the planning and engineering stage of production processes (Großmann and Neugebauer, 2010; Denkena and Hollmann, 2013).

Hitherto simplified and stand-alone partial models have been employed for the process simulation. Since predictability is limited, making it necessary, as a rule, to manually spot the dies before manufacturing any good parts (Roll, 2012; Großmann et al., 2013). These shortcomings are exacerbated in the case of large-sized parts and materials of higher strength. For instance, surface defects and wrinkling cannot be simulated without modelling the elastic constraints in the flange clearance between sheet and die. Nevertheless shell elements provide a good representation of the anisotropic plastic material behaviour in the planar stress state. Anisotropic material behaviour results in the development of scallops or earing at the part margin. In simulation, the whole process is scaled in time, taking into account the quasi-static assumptions in order to reduce calculation time.
Fig. 7. Comparison of sheet thickness (steel DC01, initial blank thickness 1 mm, $\beta=2.2$) between simulated and measured values (see Fig. 5) (Neugebauer and Drossel et al., 2012): (a) conventional deep drawing, (b) schematic view of simulation model, (c) cushion-ram pulsation.

The blank holder in deep drawing is pressed against the die with a constant force contrary to the drawing direction, and the die is given a speed constraint. For simulation of position controlled cushion-ram pulsation, it is necessary to predefine a path constraint both for the blank holder and the die. However, once the sheet in the flange becomes much thicker, the contact partners penetrate more and more each other every time when the blank holder touches down onto the sheet. Numerical errors in the explicit calculation method add up and cause instabilities. In the real process, thickening of sheet are compensated by clearances and elastic deformations of machine and tool parts. In addition, the vertical press stiffness was envisaged as spring elements with clearance (Großmann et al., 2013). This was done in order to simulate the dynamic behaviour of sheet thickening and blank holder offset in the uniaxial simulation model of the circular cup (see Fig. 7).

Compared with the sheet thickness values measured by GOM ATOS (see Fig. 5), the deviation between the surveyed part and mid surface is negligible (see Fig. 7). In cushion-ram pulsation the sheet is thicker than in deep drawing at critical punch radius. The necking measured in the area of bottom curvature on the real part cannot be represented in simulation. Here, however, improvements are to be expected when using a much finer mesh and suitable failure models. Surface pressure at scallops strongly increases at the moment of drawing the sheet completely through the die, so that sheet thickness is reduced mostly in the area of the small scallops. Scanning by means of GOM ATOS provides sheet thickness values at the margin that are much lower than those obtained in simulation, which, in turn, can be explained by the neglect of the normal stress component in the planar stress state. In Fig. 7b) simulation and measurement mostly deviates at bottom of the drawn part for the cushion-ram pulsation. This effect can be traced back to varying characteristic material parameters or different friction parameters. Stress in the drawn part’s bottom is diminished with lower friction and a lower flow point, and thus material is less starkly thinned.

Fig. 8. Numerical deformation analysis with forming limit diagram calculated on x-shaped cup (steel DC01, initial blank thickness 1 mm) (Neugebauer and Drossel et al., 2012): (a) deep drawing, (b) cushion-ram pulsation.
With an x-shaped cup, deformation was also analyzed additionally in order to evaluate the opportunities for failure description in simulation (see Fig. 8). In the forming limit diagram, the principal strains at the edge exceed the failure limit along the y-coordinate first for deep drawing, whereas all elongations remain uncritical in cushion-ram pulsation. As a matter of fact, the principal strains are shifted into the region that is characteristic for compression states and indicates possible wrinkling.

5. Summary

Vibration superposition in part contact during deep drawing will enable the manufacturing of parts that either cannot be fabricated at present by means of standard procedures at all or can only be made with great effort. This potential is opened up by advanced servo presses with highly dynamic axes and flexible controlling options. In process engineering, results must be provided that make possible reliable predictions in order to cope with ever-greater requirements, such as for dimensional accuracy, part quality or costs preceding series launch. Reasonable forecasting results even in dynamic forming processes on servo presses can only be achieved by a continuous qualification of the simulation methods. Once speed-dependent effects appear, such as the impact at touch down after an increase in stroke number or superposition of vibrations in the deep drawing process, the interactions have to be represented by a complete model comprising both process and machine. As a result, calculation time increases, and, in consequence, simplified modelling of influencing variables is sought.

Development of deep drawing techniques supported by vibrations is in general just beginning. Hence additional research projects are required to enable production engineering of complex 3D parts for users, as well as to provide guidelines on design and machine life for machine and die manufacturers. The focus of future work is on evaluating simulation strategies to understand forming processes with superimposed vibrations. Sensitivity based methods help to identify significant process parameters and allow development of specific meta-modells which approximate the behaviour and improves the simulation of complex processes.

Acknowledgements

The presented results of this paper are part of a public research project at Fraunhofer IWU. The project (17058BR) of the research association “Europäische Forschungsvereinigung für Blechverarbeitung e. V.” (EFB) was financed by the “Arbeitgmeinschaft industrieller Forschungsvereinigungen – Otto von Guericke e. V.” (AiF) as part of the programme to support “Industrial Community Research and Development” (IGF) with funds from the “Federal Ministry of Economics and Technology” (BMWi) following an order by the German federal parliament. The financial support is gratefully acknowledged by the authors.

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