# Analysis of the Energy Efficiency of Hydraulic Deep Drawing Presses

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#### Abstract

Hydraulic deep drawing presses are widely used for industrial sheet metal forming today. Small manufacturers of drawn parts and suppliers of the automotive industry especially appreciate these machines because of their flexibility in process design.

Despite their high energy consumption, the energy efficiency of modern hydraulic presses is nearly unknown due to a lack of experimental investigations as well as suited simulation models.

The authors' objective is to reduce this gap by analyzing the energy efficiency using measurement and simulation. This is the prerequisite for systematic technical improvement.

KEYWORDS: hydraulic press, energy efficiency

#### 1. Introduction

Hydraulic deep drawing presses are multi-purpose machines that are widely used for many tasks in sheet metal forming. The main application is the production of parts for the automotive and domestic appliance industry.

Nowadays, pollution is becoming a bigger concern in public discussion. There are plans to supervise the energy efficiency of machine tools through legal regulation or standardization. The international standard series ISO 14955 "Machine tools – Environmental evaluation of machine tools" is under development for this purpose. Additionally, the costs of electricity are rising. The effect that this will have on the overall production costs is small at present. However, the future trend is hardly predictable. Because of this reason, it is necessary to know the energy efficiency of presses and to have a concept for further technical improvement.

In contrast to these demands, the actual knowledge about the energy efficiency is poor. Research activities dealing with this topic have already been carried out /1/. However, the machine design has been developed further since then. For example, the electrohydraulics has mostly substituted classical hydro-mechanical control in presses.

The objective now is to determine the energy efficiency of modern hydraulic deep drawing presses with measurement and simulation in order to generate and to evaluate concepts for technical improvement.

# 2. Machines and forming processes

# 2.1. Demonstration machines

Currently, two machines are being analyzed. The first one is part of a line with a total of six presses and produces sheet metal parts for the automotive industry, see **Figure 1**.



Туре	Single action	
Year of manufacture	2004	
Slide (force, stroke)	6300 kN, 1300 mm	
Pressing speed	139 mm/s	
Fast forward speed	700 mm/s	
Die cushion	1500 kN, 250 mm	
Slide cushion	1000 kN, 200 mm	

Source: MA Automotive Dtl. GmbH

## Figure 1: Production machine

As the sixth follow-on press, it is used for cutting and calibration operations. Handling robots do the part transfer automatically. Apart from this, the press can be decoupled from the rest of the line for being able to do the tryout procedure of new forming tools.

The second machine is used within research only. It is a relatively small press with closed frame and a maximum slide force of 1600 kN, see **Figure 2**. It is not utilized in

industrial production making its availability for experiments and parameter studies very good. It has no transfer unit. Blanks and drawn parts must be handled manually.

FORMATESTER HPY 160	F

Туре	Single action
Year of manufacture	1992
Slide (force, stroke)	1600 kN, 200 mm
Pressing speed	36 mm/s
Fast forward speed	150 mm/s
Table dimensions	800 x 780 mm
Die cushion	400 kN, 100 mm

#### Figure 2: Research machine

Commonly, the slide hydraulics of production presses is pump controlled and the die cushion is valve controlled. Apart from that, the design of the hydraulics varies because the machines are customized and built according to the user's demands. Here, the structure of the research machine shall be explained exemplarily, see **Figure 3**.

The head piece (1), table (2), which carries the forming tool, and frame (3) are the nonmoving mechanical parts. The slide (4) holds the upper tool and generates the vertical forming motion. In single action machines the die cushion (5) is necessary for drawing processes. It generates a variable clamping force, which is put on the flange of the sheet metal blank and controls the material flow.

The slide drive is actuated by a pump (6) with a load sensing system. The pilot pressure valve (10) decides if valve (8) or valve (9) will work as a measuring throttle. The proportional pressure relief valve (7) limits the maximum slide pressure. The safety valve block (11) ensures that the slide cannot fall down because of its own weight. The decompression valve (12) inhibits the rise of the pump pressure when the machine is in idle. The prefill valve (13) connects the pressing cylinder (14) with the tank when inactive. Fast motion down is realized with two plunger cylinders (15) while two other cylinders (16) are responsible for the fast motion up.

The die cushion is equipped with a fixed displacement pump (17). The pressure relief valve (18) limits the pump pressure to about 20 bar. Using the directional control valve (19), the die cushion can be moved independently from the slide. The cylinder (20) is the interface between hydraulics and mechanics. A proportional pressure relief valve (21) is responsible for pressure control.

Two fixed displacement pumps for high pressure and low pressure (22) supply the auxiliary circuits with oil. These circuits are necessary for functions like the adjustable end stop of the slide, the cutting damper system and the pilot actuation of valves. The accumulators (23) store energy and satisfy peaks in demand. The pressure relief valves (24) limit the maximum pressure level.



Figure 3: Simplified structure of the research machine

The cooling circuit has a fixed displacement pump (25) and a cooler with an electrical fan (26). All pumps and the fan are driven by asynchronous motors, which are supplied from the three-phase electricity network with 400 V and 50 Hz.

## 2.2. Forming tools

Typical processes that run on the regarded machines are deep drawing, stretch drawing and cutting. They have completely varying force-stroke-characteristics. In industrial production a forming part is normally produced in steps; the initial drawing process is followed by several cutting and calibration operations. Each one is done with a single tool in one press. Typically, a tool set consists of up to six tools.

The experiments with the production machine were done with five different forming tools during serial production: a drawing tool, three cutting / calibration tools and a transfer tool containing four single forming operations.



Figure 4: Drawing tool (left) and cutting tool (right), mounted in research machine

The research machine was tested with two different tools, see **Figure 4**. The drawing tool produces a rectangular tub with a maximum height of 100 mm. The cutting tool performs a circular cut. Both are symmetrical. The blank material was the dual phase steel HCT500X (1.0939) with a thickness of 1 mm.

# 3. Experimental investigations

## 3.1. Methodology

In order to be able to systematically analyze the energy efficiency of a press, the definition of appropriate system boundaries is necessary. **Figure 5** shows the energy flow chart exemplarily for the research machine.

Motor-pump-units, which represent the generatoric section, are responsible for the conversion of electric energy into hydraulic energy. Additional components with electrical supply are the cooling fan and the electrical equipment, e.g. the PLC. The hydraulic energy is conducted through valves, tubes and blocks. During that process, it

is partially dissipated into heat. The cylinders are responsible for the conversion of hydraulic energy into mechanical work. Between mechanical parts, which are in relative motion to each other, friction occurs and causes heat losses. To sum this up, it can be said that the electric energy is converted by the machine into forming work  $W_U$  and heat Q. Stored energy occurs temporarily, but can be neglected when regarding complete working cycles.



Figure 5: Energetic system boundaries for the research machine

In general, power is the mathematical product of potential variable and flow variable. Hence, it is not possible to directly measure electric, hydraulic and mechanical power. The electric power of polyphase systems can be determined according to DIN 40110-2. The active power  $P_{\Sigma}(t)$  in a system with *n* wires is calculated using phase currents  $i_{\mu}$ and virtual star voltages  $u_{\mu0}$  /2/:

$$P_{\Sigma}(t) = \sum_{\mu=1}^{n} u_{\mu 0} \cdot i_{\mu} .$$
<sup>(1)</sup>

Instead of the latter, it is possible to use the voltages measured against any neutral point. Electric power  $P_{eh}$  which is equivalent to the collective active power  $P_{\Sigma}$ , is defined as the arithmetic average:

$$P_{el} = \overline{P_{\Sigma}(t)}.$$
 (2)

The hydraulic power  $P_{hyd}$  is calculated using pressure p and flow rate Q:

$$P_{hvd} = \rho \cdot Q. \tag{3}$$

The mechanical power  $P_{mech}$  can be determined with velocity v and force F:

$$P_{mech} = v \cdot F \,. \tag{4}$$

The velocity v is the derivative of the measurable position z. While the forming force can be measured directly when the tool is equipped with a force sensor, hydraulic cylinder forces are calculated based on chamber pressure and piston area.

The energy *E* respectively the work *W* is the time-based integral of power *P*:

$$E = \int_{t_1}^{t_2} P \, dt \,. \tag{6}$$

The efficiency  $\eta$ , which is the quotient of outgoing power  $P_{out}$  and incoming power  $P_{in}$ , is used to evaluate components and systems in stationary operation:

$$\eta = \frac{P_{out}}{P_{in}} \,. \tag{7}$$

During a press cycle the machine passes many different operating points. This fact causes the efficiency to fluctuate permanently. Because of this reason, it is better to look at outgoing energy  $E_{out}$  and incoming energy  $E_{in}$  over a certain time interval, e. g. a complete press cycle. This is done by the energy efficiency  $\varepsilon$ :

$$\varepsilon = \frac{E_{out}}{E_{in}} \,. \tag{8}$$

#### 3.2. Results

Following /3/, machine operation consists of non-processing time and main time. Standby, idle, tool changing, workpiece changing, tool closing and tool opening belong to the non-processing time, while the main time is the forming time. For both machines, measurements of the energy efficiency took place, covering all operation modes.

**Figure 6** shows exemplarily some results for the research machine working in semiautomatic mode with the built-in drawing tool. The first row contains the power and the energy as well as the mechanical work for the whole machine, beginning with the electrical supply and ending at the forming process. While the process has a power demand during pressing mode only, electric energy is consumed at all times. When regarding the whole press cycle, which consists of fast motion down, pressing, force relief and fast motion up, the energy efficiency is  $\varepsilon = 11.8$  %.

The second and the third row show the position, force and power of the slide and die cushion drive. During forming, the mechanical power of the die cushion reaches negative values because the die cushion is displaced, generating a counterforce that



acts against the slide motion. The slide has to overcome the forming force as well as the die cushion force. The fourth row shows the power of the auxiliary circuits.

Figure 6: Experimental results for research machine with drawing tool

**Figure 7** shows the extent of forming work and heat losses for the production machine. The automatic mode with four different forming tools and the idle are compared. For each tool, at least ten single measurements were averaged.

In idle, the losses of the slide pump units are dominant. During production the conductive sections of the hydraulic circuits, which transport and control hydraulic energy, cause the biggest losses. The slide circuit is the most powerful and also generates the highest loss. The die cushion, which is normally said to be one of the most important sinks of energy because of its valve control, is only active for tool 1 and causes 7 % of losses. In this typical industrial configuration real slide forces were with

10...43 % much lower than the available press capacity. Additionally, forming strokes were small compared to the overall tool motion. These big reserves in machine design reduce the energy efficiency significantly.



Figure 7: Forming work and heat losses for the production machine

**Figure 8** illustrates the production machine's consumption of electric energy. For fully automatic operation, the break is part of the press cycle because of its certain length. This definition differs from the semiautomatic mode. As the picture shows, the most energy is needed during fast motion up to bring the slide back to its starting position against gravitational forces, and not, as expected, during press mode.



Figure 8: Electric energy consumption of the production machine

**Figure 9** shows the results of a similar investigation for the research machine. Here, the deep drawing and cutting processes in semiautomatic mode as well as in idle are compared. The distribution of heat losses varies strongly. During production the conductive section of slide hydraulics causes big losses. The deep drawing process has the highest energy efficiency, as about 50 % of the nominal slide force and the maximum forming stroke are used. That combination of machine and tool harmonizes

well. In idle, both the die cushion drive and auxiliary circuits with their constant pumps cause more losses than the slide hydraulics, because the latter has a variable displacement pump which can be adjusted to zero. The energy consumption in idle is about one third of the consumption in production.



#### Figure 9: Forming work and heat losses for the research machine

Summarizing the machine analysis, the following recommendations can be given. If possible, force and stroke should match well when combining tool and machine. Tool closing and tool opening strokes should be kept as small as possible. Electrical motors should, if possible, stop in breaks. Subsystems which are not necessary for the current forming task should be switched off during production.

## 4. Simulation model

A system simulation model of the research machine was built in order to be able to analyze the energy efficiency in more detail. At first, the model should be able to calculate the static and dynamic properties of relevance. The second step is the integration of electric, hydraulic and mechanical efficiencies.

Besides mechanics, hydraulic systems and PLC, the model also contains the process in a simplified way. The software tool which is used provides predefined model objects for all physical domains of relevance /4/.

The mechanical parts were statically and dynamically analyzed with an FE tool. The aim was to decide which effects are important for the system model. The estimated minimum stiffness is at least four times higher and the lowest natural frequency more than three times larger than that of hydraulics. Based on that result, the press frame is modeled rigidly. Slide and die cushion are represented by discrete mass elements.

**Figure 10** exemplarily compares the measurement and simulation of slide hydraulics, using slide position, pump pressure and hydraulic power. As one can see, the simulation is in sufficient accordance with reality so far.

In the following steps, the model will help to generate and to evaluate concepts for technical improvement of press hydraulics.



Figure 10: Model check for slide drive

## 5. Summary

Although the importance of the energy efficiency of modern hydraulic deep drawing presses is growing, only little information is available from past research. Hence, systematic technical improvement was previously very difficult. This is the motivation for the presented research activities.

The basic step was the experimental analysis of machines under the conditions of industrial production. So far, a medium sized press and a small press were used for this analysis. This article has explained the methodology used and has presented selected results.

The next step will be to develop technical concepts for improving the energy efficiency. For this, the system simulation is the appropriate tool. The modeling concept has been outlined in this paper.

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#### 7. Nomenclature

E	energy	kWs
F	force	kN
$i_{\mu}$	phase current	А
n	number of phases	-
Ρ	electric power	kW
p	pressure	bar
Q	heat, volume flow	kJ, l/min
t	time	S
$U_{\mu 0}$	virtual star voltage	V
V	velocity	mm/s
W <sub>U</sub>	forming work	kNm
Ζ	position	mm
ε	energy efficiency	-
η	efficiency	-

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