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ANALYSIS OF ENERGY CONSUMPTION OF SPINDLE PRESSES

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Preliminary notes

Almost all working effects are accompanied by energy losses in machine operations. It is necessary to minimize the losses, because they increase the costs of these operations. The research is concerned with the analysis of energy consumption of mechanical presses. This paper presents part of research dealing with spindle presses. Analysis of energy consumption was carried out on the real 4 MN spindle press. In this paper, an analysis of influences on this energy consumption is also shown.

***Key words**: energy consumption, spindle press*

Analiza potrošnje energije vretenaste preše

Prethodno priopćenje

Skoro svi radni efekti su popraćeni gubicima energije u strojnim pogonima. Neophodno je minimizirati gubitke, jer su oni uzrok porasta troškova ovih pogona. U istraživanju se bavilo analizom potrošnje energije mehaničkih preša. Ovaj članak prikazuje dio istraživanja koji se bavi vretenastim prešama. Analiza potrošnje energije je bila izvršena na stvarnoj 4 MN vretenastoj preši. U ovom članku je također pokazana analiza utjecaja na ovu potrošnju energije.

***Ključne riječi:** potrošnja energije, vretenasta preša*

1 Introduction
Uvod

One of the tasks of our Department of Machine Design is the problem of energy consumption of production machines. We are also concerned with the analysis of energy consumption of presses.

Emphasis should be laid on economic parameters, ecology and operational performances in modern factories. Main product parameter is its market price. It is possible to reduce the price of machines products both by changing of the product (mostly impossible) and by decreasing of costs for machine functions. We deal with the second way of cost savings.

Almost all working effects are accompanied by energy losses in presses operations. It is necessary to minimize the losses, because they increase the costs of these operations. Mechanical presses are machines, which work with high forces and energies. Each saving of energy noticeably improves economy of production.

This paper presents part of research dealing with mechanical spindle presses. Analysis of energy consumption was carried out on a real 4 MN spindle press.

2 Energy consumption of forming machines
Potrošnja energije strojeva za oblikovanje

2.1 Basic energy consumption equation
Osnovna jednadžba potrošnje energije

The energy consumption of forming machines is given by the basic energy consumption equation as follows:

$$A_C = A_U + A_Z \pm A_D \pm A_A \pm A_G \tag{1}$$

A_C – the total energy consumed by the machine (energy requirement)
A_U – the technological energy, which is spent in material forming (load).

The forging force and the work stroke describe the forging process. The chart of dependency of the forming force and work stroke is also called forming characteristic (example in Fig. 1). The area below the curve of forming force corresponds to technological energy. The following is a simpler equation for the calculation of technological energy:

$$A_U = \kappa \cdot F_{max} \cdot h_U \tag{2}$$

Where κ is the ratio between the ideal forming characteristic and the real forming characteristic (coefficient of filling the forming characteristic).
A_Z – the energy of friction forces for overcoming the motion resistance of the spindle presses, such as slide and tap friction forces

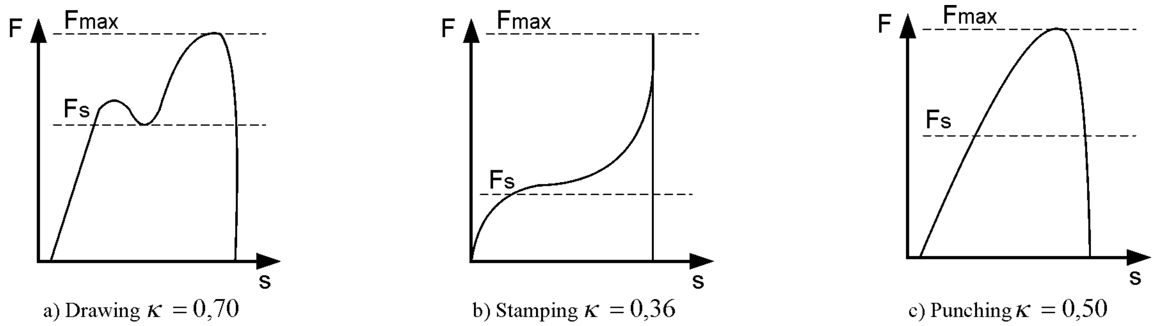

Figure 1. Example of forming characteristics
Slika 1. Primjer karakteristika oblikovanja

A_D – the energy consumed in the deformation of the machine elements; energy is accumulated into elastic deformations

Comment: Deformation (with the exception of strain energy) causes inaccuracy in forming machine production.

A_A – the dynamic forces energy (A_A is not considered in continuous operations)

A_G – the gravitational forces energy (A_G is not considered in continuous operations).

One way for comparing of the press energy consumption is to find out its efficiency. We use total technological efficiency of the forming machine in this paper.

$$\eta_C = \frac{A_U}{A_C}. \tag{3}$$

2.2 Loading action on spindle press by computing

Numeričko simuliranje opterećenja vretenaste preše

The triangular characteristic which substituted the real stamping characteristic was considered in the computing of the spindle press. This characteristic is defined by the forming force and useful work stroke. The area below this triangular characteristic corresponds to the amount of technological energy A_U. The amount of the technological energy A_U must be lower than or equal to the amount of the nominal energy A_j which the press is able to deliver in the forming process. The nominal energy A_j is defined by the intensity of the nominal forming force F_j (this force depends on the stiffness and strength of the press) and by the delivered energy by a flywheel (flywheel, spindle and rotor of press drive are considered inertial masses).

Fig. 2, which is shown below, presents the whole load cycle of spindle presses (energy input and energy output distribution) with modified triangular forming characteristic (there are considered elastic deformations of machine elements).

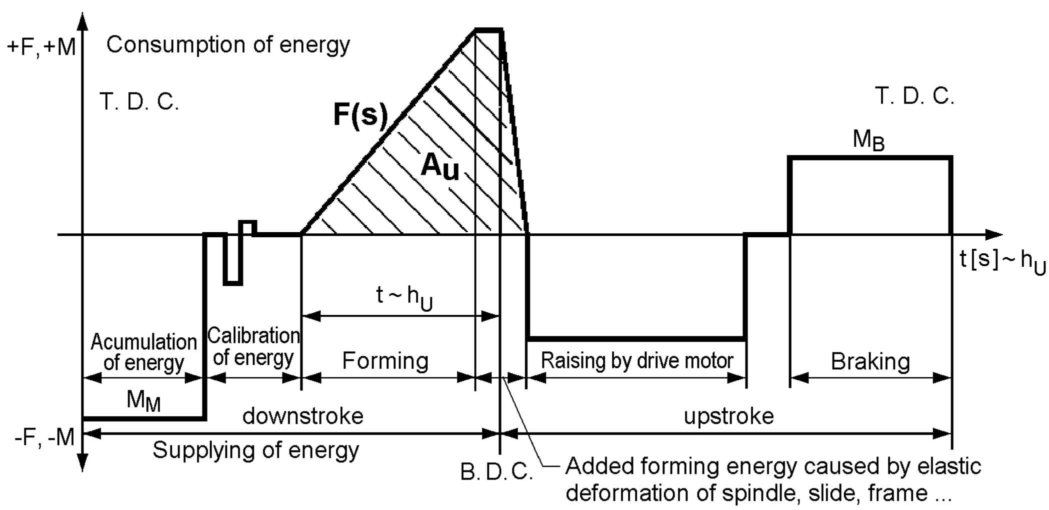

Figure 2. Forming characteristic for solution
Slika 2. Karakteristika oblikovanja za rješenje

3
Spindle press energy losses
Gubici energije vretenaste preše

3.1
Spindle 4 MN press
Vretenasta 4 MN preša

All research, presented in this paper was carried out on a 4 MN spindle press (example of such press is presented in Fig. 3), which provides in 4 MN nominal forming force ($F_j = 4 \cdot 10^6$ N). The press has a wide scope of application for hot and cold forming. It is suitable especially for precise die forging, straightening, sizing and other forming operations. The press, not equipped with driving disks, is provided with direct drive of the screw by a special motor. It is a modern press with a welded frame and its long guide of the ram allows eccentric loading.

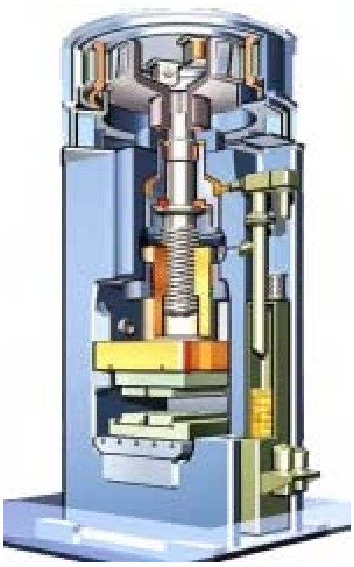

Figure 3. Spindle 4 MN press
Slika 3. Vretenasta 4 MN preša

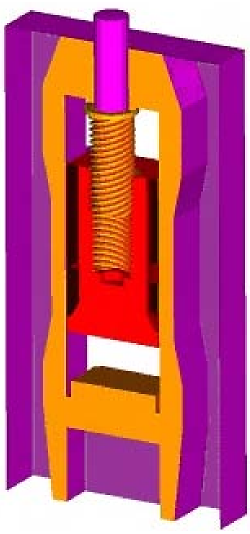

Figure 4. Section view of CAD model
Slika 4. Presjek CAD modela

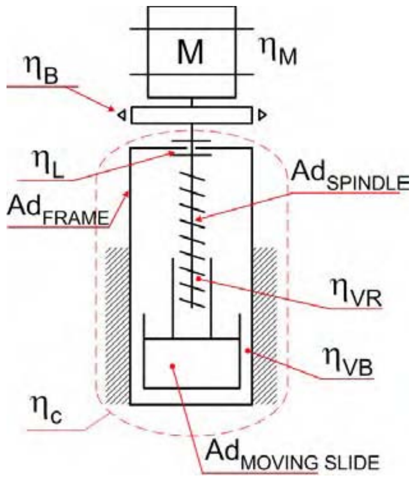

Figure 5. Main energy losses
Slika 5. Glavni gubici energije

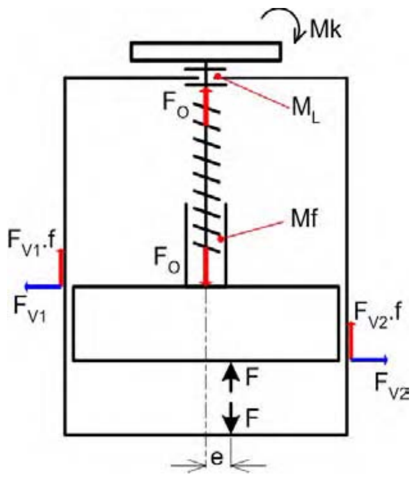

Figure 6. Forces and moments
Slika 6. Sile i momenti

3.2
Main influences on energy consumption
Glavni utjecaji na utrošak energije

Energy losses (Fig. 5):

Energy of deformation:

Ad_{FRAME} – strain energy of the frame

$Ad_{SPINDLE}$ – energy consumed in the deformation of the spindle

$Ad_{MOVING\ SLIDER}$ – energy consumed in the deformation of the ram (moving slider)

Energy of friction forces:

η_C – total technological efficiency of the press

η_B – efficiency of the brake

η_M – motor efficiency

η_{VR} – efficiency of the spindle thread

η_{VB} – efficiency of the slide of the ram

η_L – efficiency of the axial friction bearing.

Force influences (Fig. 6):

Influence energy of deformation:

F – forming force

F_{V1}, F_{V2} - forces produced by the eccentric forming force
F_0 - force which deforms the spindle and the frame
M_k - driving moment which twists spindle.

Influence energy of friction forces:
$F_{V1}\cdot f$, $F_{V2}\cdot f$ - friction between the ram and the slide induced by F_{V1}, F_{V2}
M_L - moment caused by friction in the spindle bearing
M_f - moment caused by friction in the thread.

3.3
Method of computing of strain energy
Metoda izračuna energije deformacije

Strain energy (energy of deformation) A_D is energy consumed in the deformation of the machine elements. Strain energy can be simply influenced by modification of the press structure and material change. Most of this energy is accumulated into the elastic deformations. A part of accumulated energy is wasted into the vibration and heating up of structure elements, a part returns to the forming process in the case of decreasing of forming force, and a part of accumulated energy helps with rising of the moving slider but most of the strain energy is lost.

The amount of strain energy of all components was computed both analytically and by means of FEM. It is necessary to know the rigidity of examined component or the value of component deformation (gained by FEM or manual computations) for analytical computation of the strain energy. Amount of strain energy was found out by the application of the following equations:

Linear deformations $A_D = \frac{1}{2}\cdot F\cdot y = \frac{1}{2}\cdot\frac{F^2}{k}$,

torsions $A_D = \frac{1}{2}\cdot M\cdot\varphi = \frac{1}{2}\cdot\frac{M^2}{k_\varphi}$ (4)

F - forces which deform component, y - displacement by deformation, k - linear stiffness, M - torque, φ - twisting angle, k_φ – torsional stiffness.

Besides, the values of displacements are significant parameters for machine designing.

3.4
Analytical computations
Analitički izračuni

Some simple press components (spindle, press frame) were computed analytically. Results of the frame deformations were obtained by the application of the Castiglian method. Example of the analytical computational model of spindle presses is shown in Fig. 6.

Final equations for computing of the vertical displacement are presented below (5).

Bending of the frame:

$$y_1 = \frac{2}{E\cdot J_1}\cdot\left(-M_0\cdot\frac{l_1^2}{8}+\frac{F\cdot l_1^3}{2\cdot 8\cdot 3}\right) = \frac{l_1^2}{4\cdot E\cdot J_1}\cdot\left(\frac{F\cdot l_1}{6}-M_0\right)$$

Columns stretch $y_2 = \frac{F\cdot l_2}{2\cdot E\cdot S_2}$

shear of traverses $y_3 = 2\cdot y_P = \frac{\beta\cdot F\cdot l_1}{2\cdot G\cdot S_1}$

$$\Delta y_R = y_1 + y_2 + y_3 . \quad (5)$$

3.5
FEM computations
FEM izračuni

FEM (application of the **F**inite **E**lement **M**ethod for mechanical engineering) is very useful for determination of the amount of energy consumed in the deformations of machine elements. It is possible to compute the amount of the strain energy A_D with the results of deformations computations – equation (5). FEM systems also allow determining A_D by the summation of the strain energy of all elements.

Several difficulties such as necessity of combination of different meshes and a large amount of mesh elements appeared during computations of press components. Therefore, for example, the frame was significantly simplified; centric loadings were taken into account thus it only one quarter of the press frame could be computed. The central part of the frame was modelled as a solid. A solid mesh was used. Outer wall of the frame was modelled by using surfaces and plane meshes for the model simplification. The same or analogous difficulties had to be overcome when computing of the moving slider and work spindle.

We also checked problematic places of the frame (corners, edges…) whether "von Mises reduced stress" exceeds the yield point of the material and what the safety against the yield point is.

Main point of our analysis was to find out the amount of the energy consumed in the deformations of the component.

Press frame

It was found out that the vertical displacement of the frame with the nominal forming force was 0,433 mm. The amount of strain energy (for stamping) of the press frame is

$$A_D = \frac{1}{2}\cdot F\cdot\Delta y = \frac{1}{2}\cdot 4\cdot 10^6\cdot 0{,}433\cdot 10^{-3} = 866 \text{ J}. \quad (6)$$

Stiffness of the press frame is:

$$k = \frac{F}{\Delta y} = \frac{4\cdot 10^6}{0{,}433} = 9237875 \text{ N/mm}. \quad (7)$$

That is more than a typical size (The typical stiffness of frame is $4\cdot 10^6 \div 6\cdot 10^6$ N/mm).

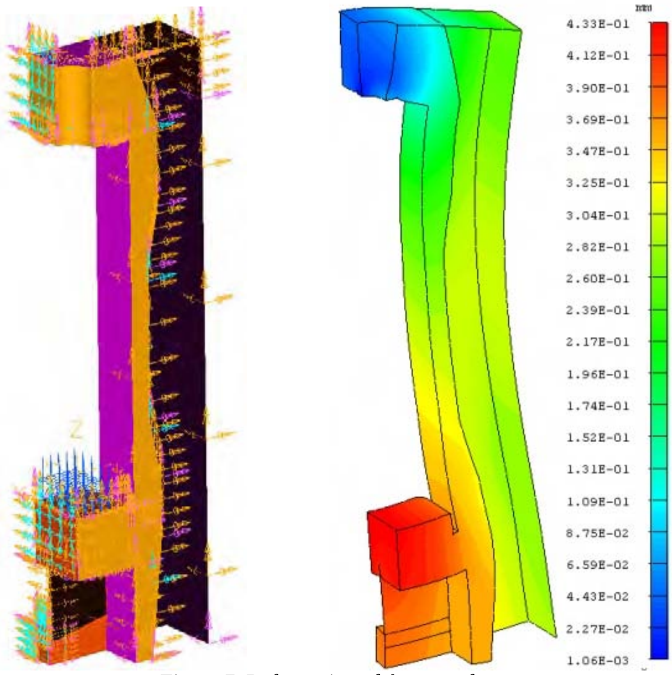

Figure 7. Deformation of the press frame
Slika 7. Deformacije okvira prese

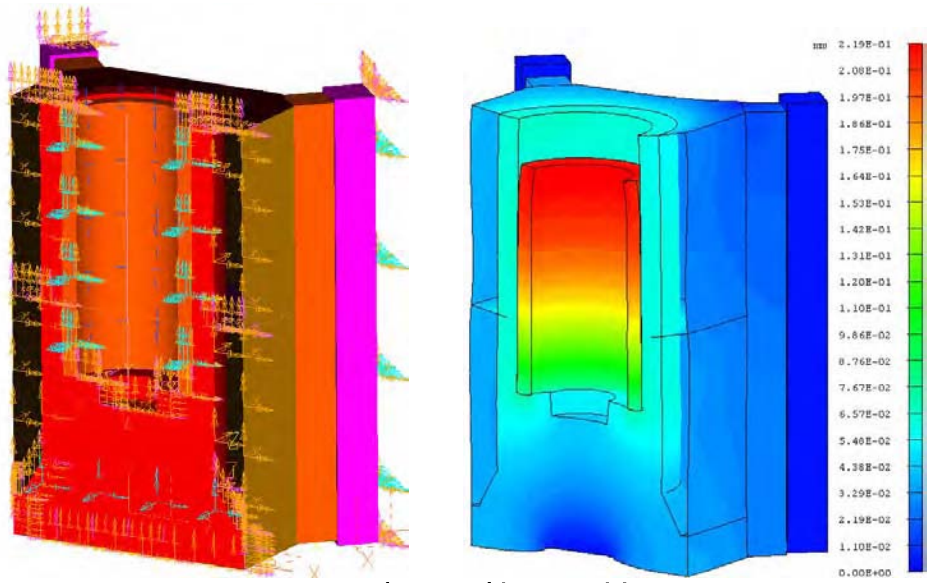

Figure 8. Deformation of the moving slider
Slika 8. Deformacija pokretnog klizača

Moving slider

Computed vertical displacement of the spindle nut towards bottom of the moving slider is 0,219 mm. The amount of strain energy (for stamping) of the moving slider is

$$A_\mathrm{D} = \frac{1}{2} \cdot F \cdot \Delta y = \frac{1}{2} \cdot 4 \cdot 10^6 \cdot 0{,}219 \cdot 10^{-3} = 438 \text{ J.} \qquad (8)$$

Stiffness of the moving slider is:

$$k = \frac{F}{\Delta y} = \frac{4 \cdot 10^6}{0{,}219} = 18264840 \text{ N/mm.} \qquad (9)$$

Spindle

Computing of the spindle deformation brings several difficulties with numbers of "normal" (which the law of elasticity is valid for) elements and contact elements placed on spindle thread. Also complexity of spindle geometry makes computing difficult on model preparing and computer performance. For these problems, only a few successful computations were done. Fig. 9 presents result of computation of "reduced von Mises stress".

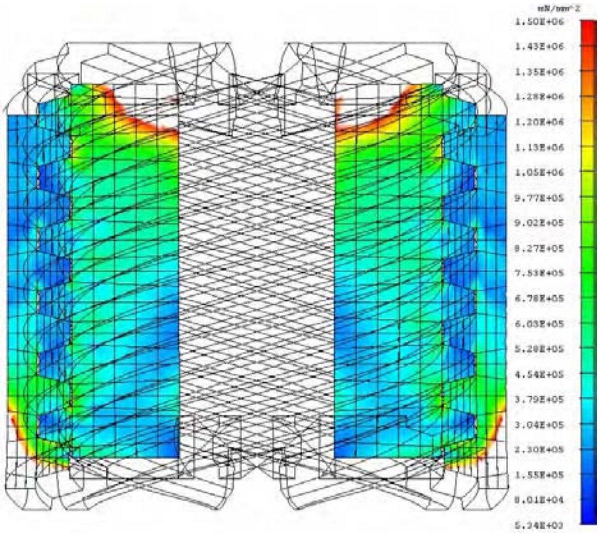

Figure 9. Spindle – von Mises stress
Slika 9. Vreteno – von Misesekvivalentno naprezanje

3.6
Method of computing of energy of friction forces and moments

Metoda izračuna energije sile i momenta trenja

Amount of energy of friction forces and moments is computed by energy equations below:

$$\text{Linear motions } A_Z = F_T \cdot S$$

$$\text{rotary motions } A_Z = M_T \cdot \psi \qquad (10)$$

F_T – friction force, S – friction force acting distance, M_T – friction moment, ψ [rad] – friction moment acting angle. Values of forces F_T and moments M_T are found out from computational model (Fig. 6).

4
Influence of press design on energy consumption

Utjecaj konstrukcije preše na energiju potrošnje

All further mentioned influences were computed for loading by stamping operation without eccentricity of forming force, if another initial condition is not mentioned.

4.1
Loss of energy in stamping

Gubitak energije u utiskivanju

The total technology efficiency of the spindle press is 63 %. The energy for deformation of all loaded machine parts is 5 % of the total energy (delivered energy to the press) and friction force losses constitute 32 % of the total energy.

The chart (Fig. 10) also shows percentages of main partial energy losses. Energy lost by friction in spindle thread consumes the biggest part of the total energy loss and seems to be the key for decreasing of energy consumption. Unfortunately it is very difficult maybe impossible to change this loss as it is presented in chapter 4.4. To influence other energy losses is much easier but their effect on energy consumption is not as considerable as the influence of change in friction coefficient on the thread.

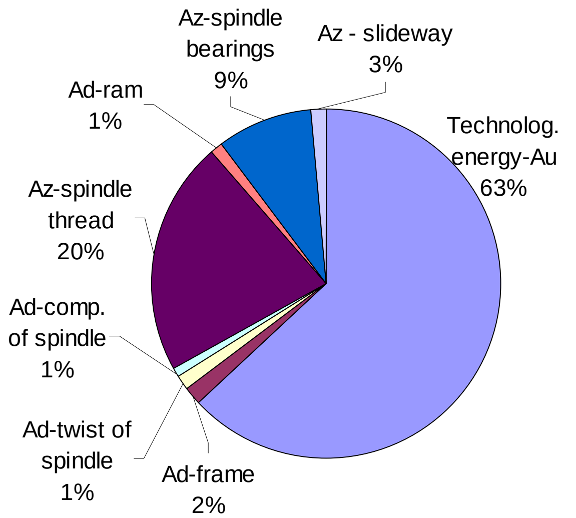

Figure 10. Percentage of different kinds of energy
Slika 10. Postotak različitih vrsta energije

4.2
Influence of change in frame stiffness

Utjecaj promjene krutosti okvira

Fig. 11 shows (a real press characteristic is shown) influence of change in frame stiffness. If the frame stiffness gets lower than 10^6 N/mm, the total technological efficiency η decreases rapidly. With the frame stiffness bigger than $3{\cdot}10^6$ N/mm, the improvement of efficiency is not noticeable and the next improvement is contrary to the request for low price of press.

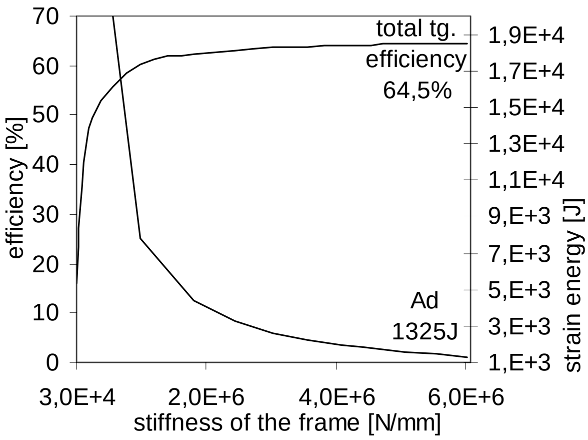

Figure 11. Influence of change in frame stiffness
Slika 11. Utjecaj promjene krutosti okvira

The stiffness growth positively affects the press efficiency (theoretic formula for this efficiency):

$$\eta_P = \frac{1}{1 + \frac{1}{2} \cdot \frac{c_0}{c}} \qquad (11)$$

Where c_0 is the stiffness of material to be formed and c is press stiffness.

4.3 Influence of spindle size

Utjecaj dimenzije vretena

Fig. 12 shows small influence of change in a spindle size on energy consumption (the press efficiency η_{TOTAL} decrease by 2,3 % - available screws types are considered). With the screw increasing the energy loss by friction gets heavier (the intensity of the drive moment grows together with increasing the screw mean diameter) and the strain energy of the spindle decreases.

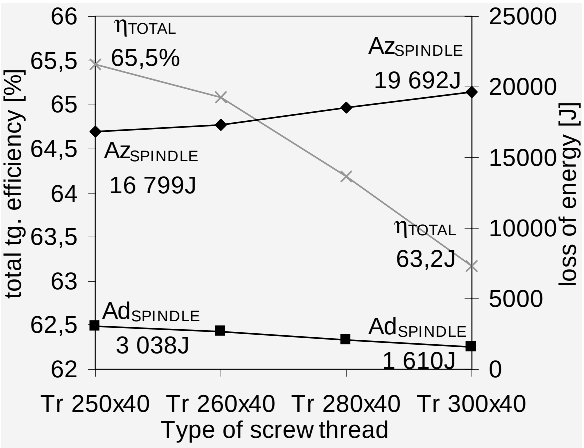

Figure 12. Influence of size of spindle on energy consumption
Slika 12. Utjecaj dimenzije vretena na potrošnju energije

4.4 Influence of friction coefficient

Utjecaj faktora trenja

Figure 13 shows influence of the friction coefficient (friction angle) in the screw thread on energy consumption. Reducing of the frictional angle (below 4,5° value) is very difficult. It means to find a new type of high-quality lubricant and new materials of the nut and spindle contact surfaces. When the frictional angle increases from φ = 4° (f = 0,0699) to φ = 6° (f = 0,1) the efficiency of the screw thread decreases by 8 % and total press efficiency decreases by 5,6 %. With high quality materials it is possible to reach 4,5° frictional angle (the total technological efficiency is 60,9 %).

The energy of friction forces in the slide way between the moving slider and the press frame consumes 3 % of total consumed energy. Arrangement and preservation of high quality slide way (with low friction coefficient) is complicated for it is exposed to high thermal stresses by stamping operation. Therefore the slides cannot be covered with a slick plastic and it is difficult to carry out sufficient lubrication.

The spindle bearing consists of radial rolling contact bearings and an axial friction bearing (necessary for the possibility of impact actions). A characteristic (Fig. 14) shows the influence of modification of the friction coefficient in the axial bearing on the total press efficiency. The total technological efficiency is 66 % for quality bearings (contact materials steel – bronze).

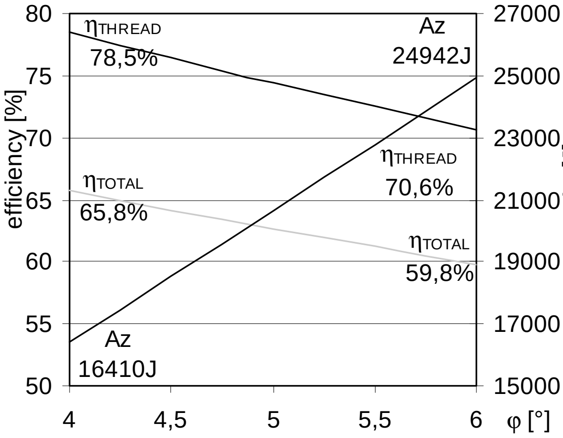

Figure 13. Influence of the friction coefficient of the spindle thread
Slika 13. Utjecaj faktora trenja navoja vretena

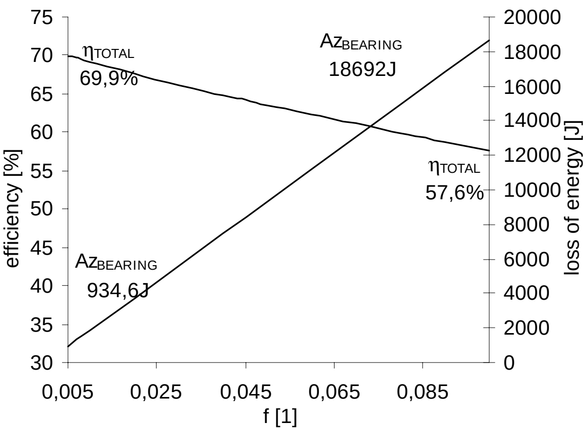

Figure 14. Influence of change of the bearing friction coefficient
Slika 14. Utjecaj promjene faktora trenja ležaja

Any change of the friction coefficients noticeably affects the press efficiency and any deterioration of the friction coefficients (caused by lack of lubrication or damage of the slide by a junk) leads to the worse energy consumption of the spindle press.

A rarely mentioned problem of friction-computations is uncertainty of the real friction coefficients by machine operations. Even machine producers take into account the friction coefficients in a range commonly published in technical literature.

4.5 Influence of forming force eccentricity

Utjecaj ekscentričnosti sile oblikovanja

Fig. 15 presents the relationships between energy waste by the slide friction and the forming force eccentricity. This characteristic is symmetrical.

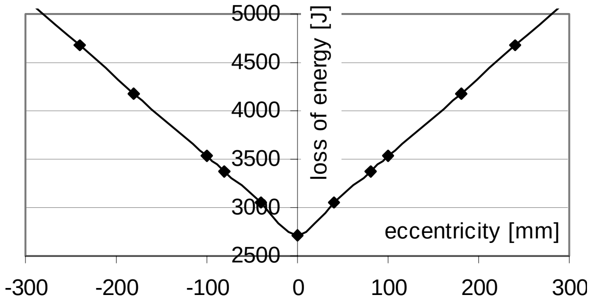

Figure 15. Influence of the force eccentricity
Slika 15. Utjecaj ekscentrične sile

Influence of the forming force eccentricity belongs to the technological influences and it is shown here as an example.

It is possible to increase the technological energy by repeating of a work stroke (total technological energy is equal to the sum of each of technological energies) at spindle presses. The influence of the forming force eccentricity was computed for only one stroke operation.

5
Conclusions
Zaključci

The aim of this work is to show main energy losses and influences of machine design on energy consumption of spindle presses. A frame structure, values of friction coefficients of spindle bearing and screw thread are most influential constructional parameters in solving of energy consumption (it is difficult to influence used technology and technological energy A_U).

Any constructional change should be reviewed with regard to the energy intensity (economy of machine operations) and expenses to set up the machine. Emphasis should also be laid on keeping machine parameters, suitable forming technology and suitable adjustment of the press (sufficient lubrication, appropriate maintenance).

Moreover, suitability of the press design was verified. All components had to meet safety conditions.

A lot of difficulties during press modelling and problems of the numerical model imperfections appeared during the computation of several components. Still unfinished computations of the spindle are the most difficult computations and it will be necessary to improve mesh, boundary conditions and other model parameters for obtaining right results.

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6
References
Reference

[1] Círek, M.; Čechura, M.: Vliv konstrukce stroje na energetickou bilanci technologického procesu, Sborník příspěvků konference FORM 2004, Conference Centre Brno Co, 2004.
[2] Círek, M.; Čechura, M.: The energy consumption of the producing on forming machines, Proceedings of MATAR Praha 2004, SMT – Society of machine tools, Praha, 2004.
[3] Círek, M.; Čechura, M.: Rozbor energetické náročnosti práce na mechanických lisech, Sborník příspěvků 9. mezinárodní konference Technológia 2005, Bratislava STU, 2005.
[4] Čechura, M.; Staněk, J.: Tvářecí stroje - Hydraulické lisy, Ediční středisko ZČU Plzeň, 1999.
[5] Hlaváč, J.; Čechura, M.: Předepnuté rámy v konstrukci tvářecích strojů, Sborník příspěvků 9. mezinárodní konference Technológia 2005. Bratislava STU, 2005.
[6] Rudolf, B.; Kopecký, M.: Tvářecí stroje – Základy výpočtů a konstrukce, SNTL Praha, 1982.
[7] Schuler, M.: Metal forming handbook, Springer-Verlag, Berlin Heidelberg 1998.
[8] Smith, D. A.: Fundamentals of Pressworking, Society of Manufacturing Engineers, 1994.
[9] Staněk, J.: Základy stavby výrobních strojů, Ediční středisko ZČU Plzeň, 2001.
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