Research Article

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Prediction of the parameters and the hot open die elongation forging process on an 80 MN hydraulic press

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Abstract: The main task of the study was to develop and implement predictive control in the hot open die forging process of heavy, large, and hard deformable steel forgings on an 80 MN hydraulic press at the Forged Products Department (FPD) of Celsa Huta Ostrowiec (CHO). The predicted hot flow stresses and the predicted deformation/forging forces as a function of the parameters of the elongation forging process were determined. The predicted parameters of the forging process were included in the dynamic model of the hydraulic forging press. Generalized predictive control (GPC) algorithm of the hot open-die forging process on the hydraulic press was developed. The use of predictive control solved the uncertainty of the hot open forging process, which depends on the dimensions, shapes, and material properties of the forgings, as well as the parameters of the hydraulic press and forging tools.

Keywords: hot open die forging process, hydraulic press, predicting parameters, predictive control

1 Introduction

High-pressure hydraulic forging presses with a force of up to 200 MN are used in the hot open die forging process of heavy, large steel components. It is constantly striving to constantly improve the quality and strength of the forged products, as well as to solve problems related to increasing the energy efficiency of the forging process. Over the years, the Forged Products Department (FPD) of Celsa Huta Ostrowiec (CHO), Celsa GrupTM steel plant in Poland, has identified the key research challenges related to the tech-

nological process of forging elements, as well as the need to improve the forging process. FPD uses hydraulic forging presses with forces of 20, 32, and 80 MN for the hot open die forging process. A view of the industrial 80 MN (8000 T) hydraulic press is shown in Figure 1. FPD is a leading European manufacturer of hot open die forgings for strategic industries: power generation, oil & gas, engine, tool steel, and metal processing. Forged components are made for the world's largest suppliers of wind turbines, high power plant turbines, and global corporations of the energy and mining sectors. In FDP, heavy components weighing from 1,000 kg to 80,000 kg, with a length of up to 22 m and a diameter of up to 2.4 m, made of carbon, low-alloy, and medium-alloy structural steel, are most often forged.

Figure 1: Industrial 80 MN (8000 T) hydraulic press for hot open die forging (photo source CHO)

The literature review of forging heavy and large forgings on high-pressure hydraulic presses was carried out. No research studies concerned the control of hydraulic presses in industrial conditions. The papers [1] and [2] present a predictive control strategy for the forging process on a 4000 T hydraulic press in laboratory conditions. Most of the papers concern material issues, such as ingot deformation, elimi-

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nation of non-metallic inclusions, and voids in forgings [3–6]. Similar problems related to the modelling of the hot open die forging process were considered in works [7–10]. Compared to the previous works [11] and [12], the authors developed a new hot open die forgings process control method, which includes Generalized Predictive Control (GPC), Predictive Forging Force Model (PFFM), Recursive Polynomial Model Estimator (RPME), and a nonlinear discrete-time state-space model of hydraulic control system (HCS).

2 Predicting the parameters of the forging process

Open die forging is a hot forming process in which the metal is shaped by pressing between two flat or simple contoured dies. The work concerns the hot open die forging process, during which the forgings are elongated. The geometry of the elongation forging process is shown in Figure 2.

Figure 2: The geometry of the forging during the elongation forging process: initial parameters: height h_0 , width w_0 , length l_0 , and bite length b_0 ; parameters for a single draft: height h_1 , width w_1 , length l_1 , and bite length b_1

During the lengthening of the forgings in one draft, the initial cross-section $S_0 = h_0 \cdot w_0$ is reduced to the cross-section $S_1 = h_1 \cdot w_1$. The deformation coefficient λ of the forging is determined by the ratio of S_0 to S_1 ,

$$\lambda = S_0/S_1 \quad (1)$$

The unit draft (relative forging height reduction) of the forging is determined as follows,

$$\varepsilon_h = (h_0 - h_1)/h_0 = \Delta h/h_0 \quad (2)$$

which for hydraulic presses is $\varepsilon_h = 0.2 - 0.3$.

The average forgings width w_1 for a single forging draft will be given as [13],

$$w_1 = w_0 \left(\frac{h_0}{h_1} \right)^a \quad (3)$$

while the average forgings length l_1 will be given as,

$$l_1 = l_0 \left(\frac{h_0}{h_1} \right)^{1-a} \quad (4)$$

where a is the value of the spreading coefficient experimentally determined by Tomlinson [14],

$$a = 0.14 + 0.36 \left(\frac{b_0}{w_0} \right) - 0.054 \left(\frac{b_0}{w_0} \right)^2 \quad (5)$$

where the value b_0 represents the initial bite, i.e. the length of the forging in contact with the dies.

The bite length b_1 of the forging in contact with the dies with a single draft is [15]:

$$b_1 = b_0 + \left(\frac{b_0(\lambda - 1)}{1.5} \right) \quad (6)$$

The predicted hot flow stress σ_p for a single draft of the forging, according to the simplified Hensel-Spittel model, was written in the following form [16],

$$\sigma_p = \sigma_0 m_0 \exp(m_1 T) \varphi^{m_2} \dot{\varphi}^{m_3} \exp(m_4 / \varphi) \quad (7)$$

where $\sigma_0, m_0, m_1, m_2, m_3, m_4$ are material constants resulting from nonlinear regression analysis of the experimental data using the FORGE software, T is the deformation temperature, $\varphi = \ln(h_0/h)$ is the true strain, $\dot{\varphi} = v/\Delta h$ is the strain rate, v is the deformation speed.

Material constants according to (7) for typical C45 40 carbon steel are: $\sigma_0 = 120$ MPa, $m_0 = 11$, $m_1 = -0.0025$, $m_2 = -0.0587$, $m_3 = 0.1165$, $m_4 = -0.0065$. The deformation temperature in the range $T = 850 - 1300^\circ\text{C}$ and the strain rate in the range $\dot{\varphi} = 0.01 - 10/\text{s}$ were selected.

Sample results of the forging process are presented for a single draft of the forgings with dimensions: $h_0 = 0.5$ m, $w_0 = 0.2$ m, $h_1 = 0.35$ m, $b_0 = 0.1$ m. For such dimensions, forging height reduction is $\Delta h = h_0 - h_1 = 0.15$ m, the unit draft is $\varepsilon_h = \Delta h/h_0 = 0.3$, and the deformation coefficient $\lambda = 1.59$.

Based on (7), the curves of hot flow stress σ_p as a function of true strain φ and strain rate $\dot{\varphi}$ for constant temperature are shown in Figure 3.

The curves of hot flow stress σ_p as a function of the unit draft ε_h for different deformation temperatures T are shown in Figure 4, and for different strain rates $\dot{\varphi}$ are shown in Figure 5.

The influence of friction and heat transfer on the contact surface of the die and the forging was described by Siebel using the dimensionless formula [17],

$$K_d = k \left(1 + \frac{\mu b_1}{2\Delta h} + \frac{\Delta h}{4b_1} \right) \quad (8)$$

Figure 3: Curves of the predicted hot flow stress σ_p as a function of true strain ϕ and strain rate $\dot{\phi}$ for constant deformation temperature $T = 900^\circ\text{C}$

Figure 4: Curves of the predicted hot flow stress σ_p as a function of the unit draft ε_h for different deformation temperatures T and constant strain rate $\dot{\phi} = 1 \text{ s}^{-1}$

Figure 5: Curves of the predicted hot flow stress σ_p as a function of the unit draft ε_h for different deformation strain rates $\dot{\phi}$ and constant deformation temperature $T = 900^\circ\text{C}$

where μ is the coefficient of friction stress on the die surface ($\mu = 0.3$), k is the deformation strengthening indicator ($k = 1.115$).

The contact surface A_d of the forging and the die for a single forging draft is determined as follows,

$$A_d = w_1 b_1 = \left[w_0 \left(\frac{h_0}{h_1} \right)^a \right] \left[b_0 + \left(\frac{b_0 (\lambda - 1)}{1.5} \right) \right] \quad (9)$$

The predicted forging/deformation force F_d of the forging during the elongation process for the single draft is as follows,

$$F_d = K_d A_d \sigma_p \quad (10)$$

Based on (10), the curves of predicted forging/deformation force F_d as a function of the unit draft ε_h for different deformation temperatures T are shown in Figure 6, and for different strain rates $\dot{\phi}$ are shown in Figure 7.

Figure 6: Curves of the predicted forging/deformation force F_d as a function of the unit draft ε_h for different deformation temperatures T and constant strain rate $\dot{\phi} = 1 \text{ s}^{-1}$

Figure 7: Curves of the predicted forging/deformation force F_d as a function of the unit draft ε_h for different deformation strain rates $\dot{\phi}$ and constant deformation temperature $T = 900^\circ\text{C}$

3 Discrete model of the 80 MN hydraulic press

The diagram of the dynamic model of the 80 MN hydraulic press used to simulate and control the elongation forging process is shown in Figure 8.

The dynamic model of the hydraulic 80 MN forging press, taking into account the movement of the main plunger and the movement of the return plungers. The dynamic model of the hydraulic press has been written in the form of a nonlinear discrete-time state-space model,

$$\begin{cases} x(k+1) = f(x(k)) + g(x(k))u(k) \\ y(k) = Cx(k) \end{cases} \quad (11)$$

with constraints:

$$u_{min} \leq u(k) \leq u_{max} \rightarrow u_{min} \leq y(k) \leq y_{max}$$

Figure 8: Diagram of a dynamic model of the 80 MN hydraulic press: A1 – main plunger cylinders, A2 – return plunger cylinders, V1 – 4/4/directional control valve, P – water pump station, A – high-pressure water accumulators, Ub – upper beam, Ud – upper die, Ld – lower die, Up – upper plate for fixing the upper die, Ta – table for fixing the lower die

where $x(k) \in R^n$ is the state vector, $u(k) \in R^m$ is the input vector, $y(k) \in R^p$ is the output vector, $f(x(k))$, $g(x(k))$ are the nonlinear matrices, $C \in R^{p \times n}$ is the linear matrix, u_{min} and y_{min} are vectors of lower bounds, u_{max} and y_{max} are vectors of upper bounds.

In the modelling and control of the 80 MN hydraulic press takes into account three phases of the forging process: the drop of the upper die into contact with the forgings; the forgings deformation process; the return of the upper die to the initial position. The initial working movement of the hydraulic press from the contact of the upper die and the forging was considered; when the initial position of the plunger is $y(0) = 0$ and the initial speed of the plunger $v(0) = 0$.

Based on the dynamic model of the hydraulic press (11), the dynamic responses of the plunger displacement $y(t)$ (re-

Figure 9: The simulation results of the forging process: plunger displacement $y(t)$, forging deformation $h(t)$, and plunger speed $v(t)$

Figure 10: The simulation results of the forging process: working pressure $p_1(t)$ and return pressure $p_2(t)$ in the press cylinders

duction of the height $\Delta h(t)$ of the forgings) and the plunger speed $v(t)$, as well the pressures p_1 and p_2 in the main plunger cylinder and return plunger cylinders are shown in Figures 9 and 10.

4 Predictive control of the 80 MN hydraulic press

The predicted parameters of the forging process were the basis for development of a predictive control system of the 80 MN hydraulic press. The predictive control algorithm is based on the use of knowledge about the predicted deformation of the forgings to determine the control parameters of the forging process. The schematic diagram of the predictive control of an 80 MN hydraulic press is shown in Figure 11.

Figure 11: Schematic diagram of the predictive control of the 80 MN hydraulic press: S1 – infrared temperature sensor T , S2 – position transducer $y(t)$, S3 – pressure transducer $p(t)$, CV – control valve

A predictive control system based on the generalized predictive control (GPC) algorithm has been implemented in the control system of the hydraulic press. Predictive control of the hot open forging process for selected predicted operating parameters was developed, such as the predictive forging force/deformation and the predicted deformation of the forgings. The industrial forging process is preceded by an analysis of the deformation of forgings and a simulation of the forging process on a hydraulic press. A schematic diagram of the predictive control system of the 80 MN hydraulic press is shown in Figure 12.

Figure 12: Schematic diagram of the predictive control system of the 80 MN hydraulic press

The predictive control system of the hydraulic press includes the following modules: generalized predictive control (GPC) of multiple-inputs and multiple-output (MIMO) system, the predictive forging force model (PFFM), the recursive polynomial model estimator (RPME), and the non-linear discrete-time state-space model of the hydraulic control system (HCS). The GPC algorithm uses the HCS model in the form of the nonlinear discrete-time state-space model. The RPME estimates the discrete-time of the HCS polynomial model. In the developed control system, multiple GPCs were used, which include two independent control algorithms concerning the forging force (pressure) and the displacement of the upper beam (change of the height of the forging). The predictive control is based on the measurement of input parameters recorded in real-time, i.e. the displacement $y(t)$ of the moving beam, including the height $h(t)$ of deformed forging, and the load pressure $p(t)$ in the main plunger cylinder. The forging temperature T is measured at the beginning of the forging process. The predicted parameters $y_{pre}(t)$ and $p_{pre}(t)$ are defined in the processing of measurement signals and parameters of the dynamic model. The trajectories of the reference parameters $y_{ref}(t)$ and $p_{ref}(t)$ determined from simulation model for the analysed forging process are shown in Figure 13. The reference pressure curve $p_{ref}(t)$ is a smoothed dynamic response of pressure using locally weighted polynomial regression (LWPR).

The GPC algorithm uses reference state and predictive control signals to obtain the optimal input vector by solving the optimization problem [18, 19]. The GPC algorithm minimizes the difference between the reference parameters $y_{ref}(t)$, $p_{ref}(t)$ and predicted parameters $y_{pre}(t)$, $p_{pre}(t)$ for optimal input signals u_y , u_p to the control valve [7],

$$\begin{cases} \min u_y J_h(y_{ref}, y_{pre}) \\ \min u_p J_p(p_{ref}, p_{pre}) \end{cases} \quad (12)$$

where J_h and J_p are objective functions.

Figure 13: Trajectories of the reference parameters $y_{ref}(t)$ and $p_{ref}(t)$

Figure 14: Trajectories comparison for optimal input signals: a) upper beam displacement $y(t)$ for the range of deformation height $h(t)$ of the forgings, b) load pressure $p(t)$ in the main plunger cylinder: 1 – trajectories of reference parameters, 2 – trajectories of predicted parameters

Figure 14 compares the trajectories of reference parameters $y_{ref}(t)$, $p_{ref}(t)$ and the trajectories of predicted parameters $y_{pre}(t)$, $p_{pre}(t)$ for optimal input signals u_h , u_p .

The use of predictive control for an industrial hydraulic press gives the greater possibilities of shaping heavy, large steel forgings in the hot open die forging process. The main advantage of this control method is the repeatability of the forging process and the minimization of dimensional deviations of the forgings. The forging process can be carried out with maximum accuracy and cost effectiveness.

5 Conclusion

The paper presents the result of the study carried out in cooperation with the industrial partner FPD CHO, in the implementation of a research project supported by the National Center for Research and Development (NCRD) under the Smart Growth Operational Program (IDOP) 2014-2020, the aim of which is to improve the quality and durability of forged products as well as increase the energy efficiency of the forging process. Predictive control based on the GPC algorithm was proposed, which applies to the hot open forging process on a hydraulic press in FPD. The developed GPC algorithm aimed to optimize the objective function as a quadratic “cost” function defined in a finite horizon based on the predictive (future) control signals and the reference parameters of the forging process. The main advantage of predictive control is the repeatability of the forging process and the minimization of forgings’ size deviations. The use of predictive control made it possible to optimize the forging force and increase the frequency of the hydraulic press cycle. As a result, the greater degree of deformation of forgings and reduce the time of forging operations, including inter-operative heating, was achieved. Reducing the number of intermediate reheating operations results in a decrease in gas consumption, which increases the energy efficiency of the forging operations and is environmentally advantageous. Increasing the energy efficiency of the forging process also benefits the environment. The presented research results are of practical importance in the steel industry.

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