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A SIMULATION STUDY ON THE CLOSED-LOOP CONTROL OF SCREW PRESS FORGINGS USING THE IMPACT ENERGY AS CONTROL INPUT

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Abstract

Screw presses are energy-restricted forming machines that use rotational energy stored in a flywheel for forming, which is converted into a linear movement by a threaded screw. Screw presses are widely used for forging steel, aluminum and brass. In a direct-driven electrical screw press, a reversible electric motor is mounted directly on the screw and on the press frame above the flywheel. With directly driven screw presses, the blow energy can be exactly dosed from one blow to the next. However, so far no prior work is known which uses the blow energy as a control input in a targeted manner to influence the properties of the forging. The purpose of the present work is to lay the foundations for property control through blow energy dosing during forging on screw presses. Process control becomes increasingly interesting due to ever increasing customer demands and needs for resource-efficient production. A major challenge is the variation of process parameters, e.g. temperature variations in the furnace, during transport or due to inherent uncertainty in the heat transfer to the dies and the environment. If the process conditions are changing the deviations from the planned process trajectory may lead to an insufficient die filling or undesired final properties. Forged parts require high precision considering the part geometry and material properties. During forming two mechanisms in terms of forming temperature take place: heat conduction due to contact with tools and heat dissipation due to plastic deformation. The heat transfer acts as disturbance, the impact energy can be used as control input. In this work, investigations into process control by impact energy dosing are put forward using FE (finite element) simulations.

Key words: Hot forging, Process control, Material properties, Process simulation

1. INTRODUCTION

1.1 Forging on Screw Presses

Screw presses are widely used for precision forging, stamping and calibration of workpieces with high energy requirements (Dietrich, 2018). For the forming process, the rotational energy stored in a flywheel is converted into a linear motion by the screw (Doege & Behrens, 2010). At the end of the stroke, the total flywheel energy E_k is converted into forming work W_p for carrying out the forging process, frictional energy W_r for overcoming the frictional resistance of the screw and elastic deformation energy W_e of the press and tooling (Dietrich, 2018):

$$E_k = W_p + W_r + W_e \qquad (1)$$

Taking into account the given friction losses and stiffness of the press system, the maximal force depends mainly on the required forming energy (ASM, 1993; Schuler GmbH, 1996).

In general, forging on screw presses does not allow a local manipulation of the workpiece because the forming energy is dissipated mainly in the workpiece volume subject to plastic flow. In directly driven screw presses, a reversible electric motor is mounted directly on the screw, which allows exact metering of impact energy. The precise dosage of

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impact energy could in principle be used in multi-stage forging processes to compensate for unforeseeable changes in the initial conditions (e.g. cooling of the workpiece due to the delayed transport or tempera-ture deviations in the furnace) and to directly control the microstructure evolution and properties during forging. This paper explores the possibilities of controlling the screw-press forging process using the impact energy as control variable.

1.2 Energy balance in screw press forging

The punch of a screw press carries kinetic energy, which is converted into frictional losses, plastic and elastic deformation. If the frictional losses are not taken into account, the energy balance is given by (Lange, 1984):

$$W = W_{pl} + W_{el} = \int_0^s F ds + \frac{1}{2} F_{max} f_z \qquad (2)$$

where: W - the total energy minus friction losses, W_{pl} - the plastic energy, W_{el} - the elastic energy, F - the forging force, s - the stroke, $F_{\max}$ the maximum force, f_z - the deflection.

The heat dissipation during the forming increases the workpiece temperature. The value of the temperature rise depends on the induced plastic deformation, thus the induced energy and temperature rise can be estimated as follows (Lange, 1988):

$$\Delta T_m = \frac{W_{pl}}{\rho c V} = \frac{k_W \varphi}{\rho c} \qquad (3)$$

where: ΔT_m - the mean adiabatic temperature increase, ϱ - the density, c - the specific heat capacity, V - the part volume, k_W - the resistance to forming, φ - the logarithmic plastic strain.

The energy can be used as a control input to maintain the desired trajectory of the forming temperature over the forming steps, which is necessary for the evolution of the microstructure to the required final state. The temperature can be used to control the recrystallization between the forming steps and to establish the desired microstructure in the workpiece. Also, the material flow and form filling can be controlled by controlling the energy dissipation.

1.3 Microstructure evolution in multi-step forging

An important goal in forging is to obtain a fine grain size. For case-hardening steels, the grain size during austenitization prior to hardening depends on the grain size achieved in the previous forming process. Especially for gears, a fine austenite grain size is very important (Bleck & Moeller, 2017). Janbein (2015) showed that a small austenite grain size increases tooth root load bearing capacity. Anzinger (1991) demonstrated for 16MnCr5 that the fatigue endurance in the root of the tooth can be improved by about 12% if the grain size index *G* according to DIN50106 is reduced from 11 - 12 to 7 - 8.

In multi-step forging, the grain size is influenced primarily by the temperature, the plastic strain and the time between forming steps. Since the plastic strain is determined by the part geometry in most cases, the most decisive control variables are the temperature of the work-piece and the time between the strokes. Between forming blows, static recrystallization takes place, for which a certain time is required. However, at the same time the temperature decreases and influences the recrystallization behavior. An unpredictable change in the temperature of the workpiece due to disruptive factors, e.g. a delayed transport or temperature deviations in the furnace, can negatively influence the microstructure evolution and lead to serious changes in the properties of the forged parts. The control of the workpiece temperature (especially the retrieval of the temperature after an unwanted cooling) during the multi-stage process without external heating between the forming steps can only be achieved by increasing the impact energy, whereby certain areas are heated by the dissipation energy. While closed-loop control with geometry feedback are already implemented for open-die forging to adjust the geometry (Nye et al., 2001), no comparable control strategies are known for closed-die forging, which means that closed-die forging processes are open-loop controlled. Usually, only trajectory-tracking controls are implemented for substitute quantities such as the position of the upper tool (Gronostajski et al., 2011; Zhang et al., 2016), the speed of the upper tool (Grandhi et al., 1993) or the temperature of the workpiece (Schwartz et al., 1995; Gronostajski et al., 2011). So far, no work is known which uses the impact energy specifically as control input to directly control the microstructure evolution and properties during forging.

2. FORGING OF GEAR WHEEL

2.1 Process chain of gear wheel forging

Basically, a forging process chain includes prior heating of the billet, transport operations and pause times between the forming strokes. For this article, a three-step forging process chain for a gear wheel is used to demonstrate the influence of variations in the process on the temperature of the workpiece. The process route is shown in figure 1.

2.2 Temperature drop due to variations in the process

An analysis of a multi-stage forging process reveals three potential disruptive factors that can unpredictably occur in the real process and directly affect the temperature of the workpiece: (a) reduction of workpiece temperature due to variations in the furnace temperature, (b) temperature drop due to transport, and (c) temperature drop in the tool by delays in forming strokes. A uniform temperature deviation in the workpiece can be caused by temperature variations at different positions of the workpiece in the furnace (center, wall, and door) or incorrect furnace settings. The temperature drop due to this disturbance factor is time-independent and is usually relatively small (about 1 % of the target workpiece temperature). However, the interference factors (b) and (c) are time-dependent and each of the factors have specific limits that can cause a high cooling of the workpiece, which leads to undesired component properties or even die underfilling. The temperature drop due to transport (b) is characterized by a larger cooling of the workpiece surface. Retardation of the forming step (c) and thereby additional cooling of the workpiece in the tool can lead to a pronouncedly inhomogeneous temperature distribution in the workpiece. In this work, FE simulations considering conductive heat transfer were performed to investigate, how variations in transport time affect the forming of the component geometry as well as the workpiece temperature after the last blow.

2.3 FE model to simulate the forging process

To investigate the temperature distribution in the workpiece and geometry deviations, the forging process of the gear wheel with delay of the transport was simulated. The software QForm with a two-dimensional axisymmetric FE model was used to analyze the form filling and how the workpiece temperature in the reference points reacts to an increased transport time. In the highly stressed components, e.g. the tooth area in gear wheels, the microstructure development during forging is very important to obtain the specific properties of the part. A fine microstructure is necessary only in these areas. Thus, two reference points P1 and P2 were defined for measuring the temperature, especially after the last hit. Their position in the billet before forming and in the forged part is seen in figure 2.
The simulation model considers heat transfer by natural convection in air. Conductive heat transfer between the workpiece and tools is not applied due to the short contact times under forming pressure. In the simulation, friction model proposed by Levanov with constant friction factor of 0.4 and Levanov coefficient of 1.25 was used (Levanov, 1997). As reference, the workpiece has a temperature of 1000 °C. The temperature deviation due to larger transport time is examined for transport delay times of 5 s, 10 s and 20 s. The screw press used in this simulation has a maximum forming energy of 9 kJ. The impact energy E for the reference process is 40 % of the maximum forming energy for each forming step to obtain the desired geometry of the part. The final geometry is achieved, if the distance between the tools is 1.6 mm. A common material for forged gears used in the simulation is the case-hardening steel 16CrNiMo6. The flow curves (for T = 700…1250 °C and $\dot{\varepsilon}$ = 0.01…500 s^{-1}) in the software data base were used for the forming simulation.

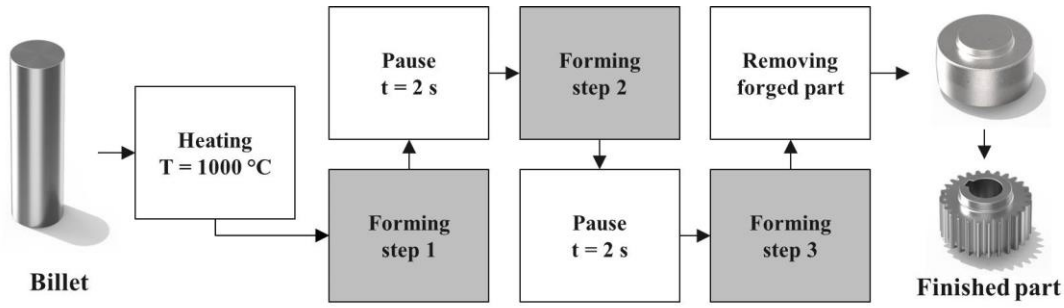


Fig. 1. *Three-step forging process chain of a gear wheel with specific initial temperature and pause times.*

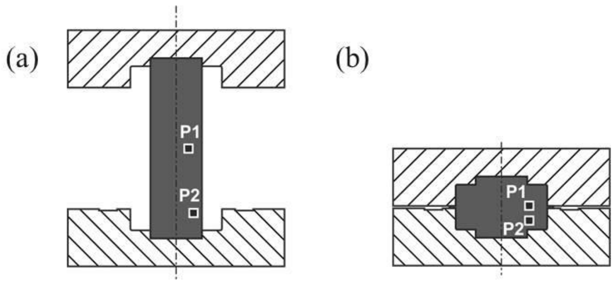


Fig. 2. Position of the reference points P1 and P2, (a) in the billet before forming and (b) in the forged part.

3. RESULTS AND DISCUSSION

3.1 Temperature drop by increasing the transport time

Figure 3 shows the temperature distribution in the workpiece after increased transport times Δ*t*. In the diagram, the temperature drop over the cross section in the middle of the part is illustrated. Due to convection, the workpiece temperature is reduced, so that the difference between the maximum and the minimum temperatures in the workpiece increases from about 40°C at a transport time of 5 s up to 60°C at 20 s transport time.

The temperature curves for the both reference points P1 and P2 are shown in figure 4. The temperature after 5, 10 and 20 s transport time represents the forming temperature in the reference points before the first blow. For shorter transport times of 5 s the temperature difference is about 10 - 20°C. The longer transport time causes a temperature drop of up to 90°C in the reference point P2.

3.2 Influence of the temperature drop on the forming process and geometry of the part

As the geometry of the part is directly defined by the position of the upper die, analyzing the distance between tools after each blow can be used to investigate the geometry deviation. The temperature drop due to transport delay significantly affects the formability of the workpiece. In the diagram in figure 5, the influence of the transport delay on the distance between tools, thus on forming behavior and geometry of the part, can be seen. With increasing transport time, the workpiece geometry is changing in a proportional manner.

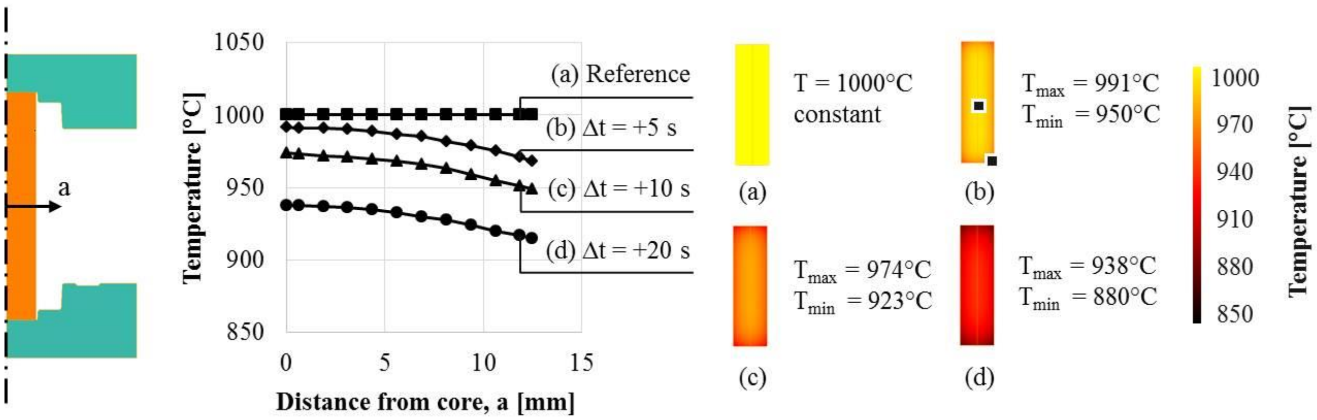
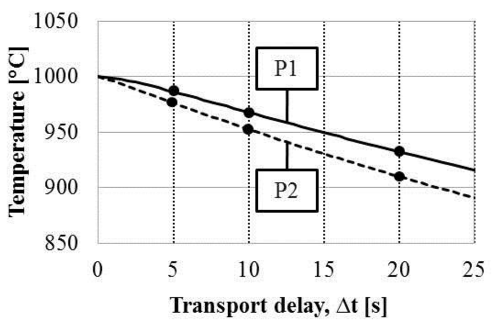


Fig. 3. Temperature gradients in the workpiece depending on the transport time, (a) reference, (b) 5 s, (c) 10 s and (d) 20 s.



	Reference point P1 [°C]	Reference point P2 [°C]
Reference	1000	1000
Δt = +5 s	987	977
Δt = +10 s	968	953
Δt = +20 s	932	910

Fig. 4. Temperature drop at reference points P1 and P2 due to transport times.

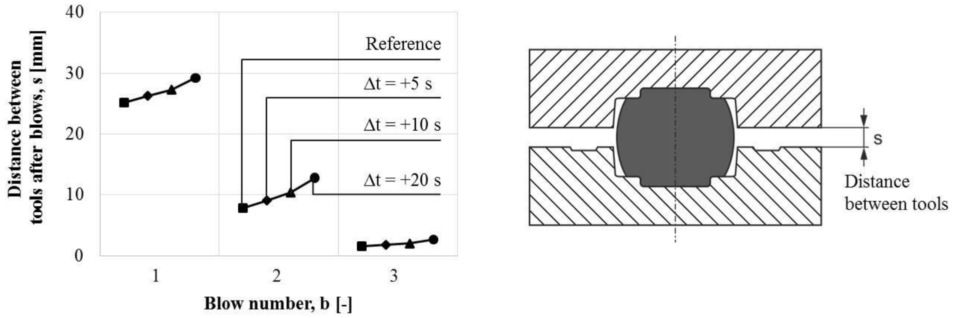


Fig. 5. *Distance between tools after every blow depending on the transport delay.*

The smallest deviation of the distance between tools in comparison to the reference process takes place in the last blow. However, the deviation of the geometry in the last blow is most important, because it determines the geometry of the forged component. The small deviations of the geometry, e.g. caused by 5 s transport delay as shown in figure 6 (b), can be compensated by machining of the finished part. Longer transport delays can provoke greater deviations so that a complete filling of the die cannot be obtained, figure 6 (c) and (d).

3.3 Influence of the temperature drop on the end temperature of the reference points

To analyze the temperature drop inside the part depending on the transport delay, the temperature in the reference points (see 2.3) along the full forging process with three blows was investigated. Figure 7 represents the temperature curves of the reference points for different transport delays compared to the reference process. The analysis of the reference process shows that the temperature of the reference points at the end of the forging process is higher than the temperature before the first blow, 1000 °C vs. approx. 1030 - 1050 °C. This can be explained by the dissipation during forming. Further, the temperature at reference point P1 is higher than P2. This is caused by the smaller distance of P2 to the part surface, where a stronger influence of convection is present.

The influence of the different transport times (delays) on the final temperature in the reference points can be identified very well from the diagrams. A longer delay leads to a larger temperature drop. This applies especially for P2 (edge area of the part), where the temperature drop is stronger than at P1. The temperature difference before the first hit and after the last hit remains almost constant regardless of the delay time.

3.4 Adjusting the impact energy of the forging process

In further investigations it was examined, whether the final geometry and a compensation of the cooling can be obtained by increasing the impact energy during forming.

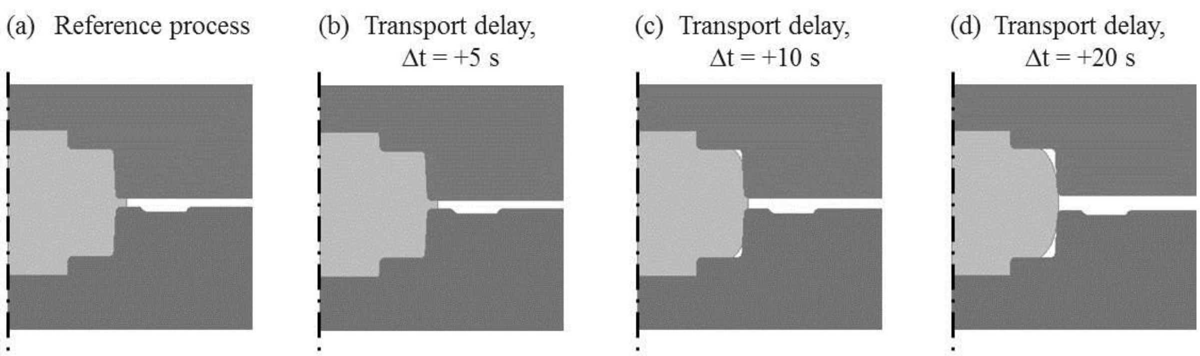


Fig. 6. *Die filling after the last blow depending on the transport delay.*

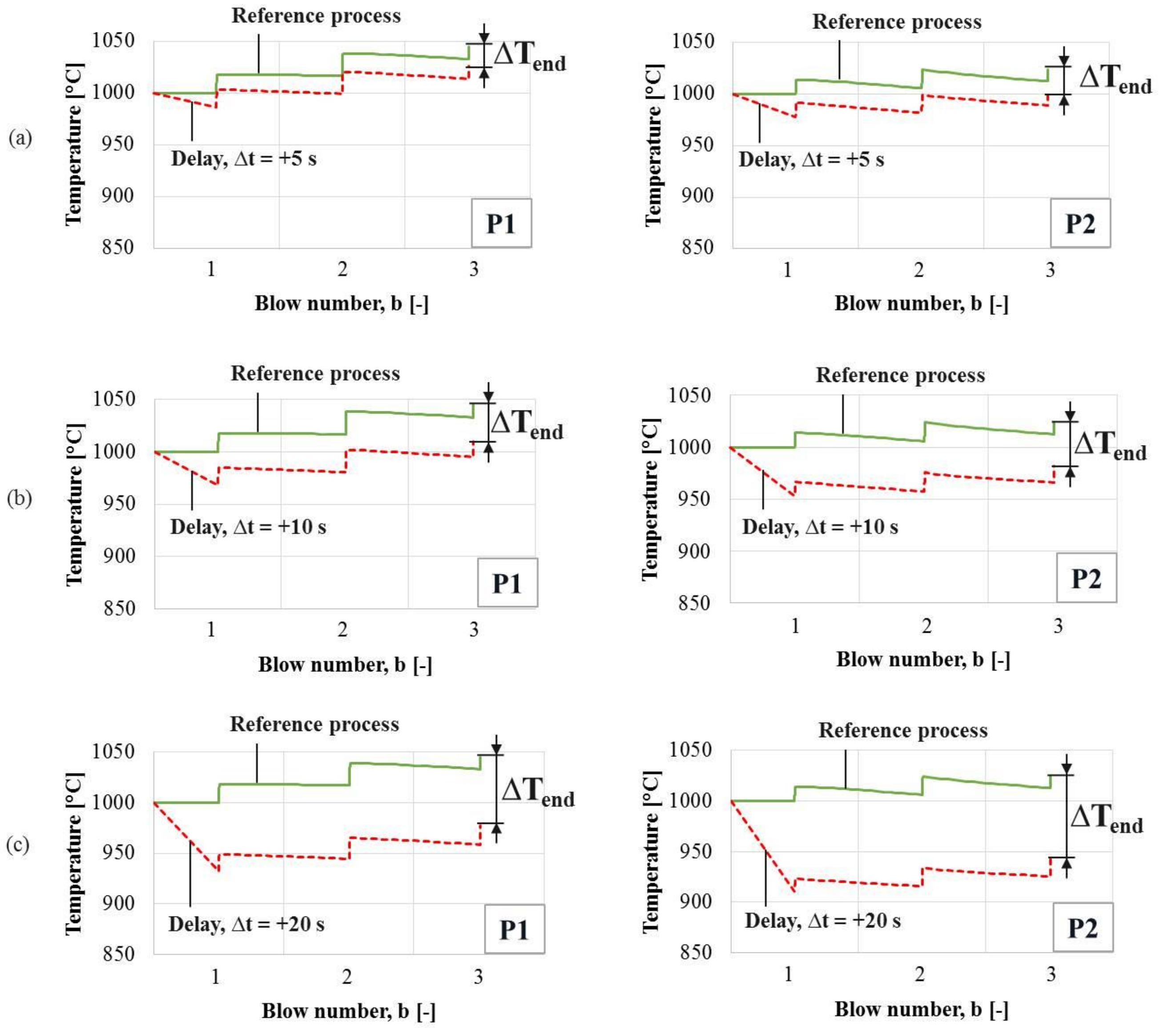


Fig. 7. *Impact of transport delays on the final temperature in the reference points P1 and P2, for transport delays (a) 5 s, (b) 10 s and (c) 20 s.*

Compensation of the underfilling. The final geometry depends mainly on the available press energy and formability of the used material. The increased impact energy can be spread over all next blows after detecting the deviation so that the die filling has to be obtained in the last forming step. Otherwise, an unwanted additional stroke is necessary, or the part must be considered scrap. The required impact energy in the last blow was determined by simulations depending on the transport time figure 8 (a) shows the simulation results with the increased impact energies in the last blow for different transport delays to avoid the die underfilling and to obtain the proper geometry of the workpiece. In contrast to the reference process with 40 % of the maximal press energy in every blow, the impact energy must be increased in the last blow from 47 to 65 %, depending on the transport delay, to fill the tools completely and to obtain the desired geometry. If the deviation can be identified before the first blow, all three steps could be used to compensate the lower workpiece temperature and to forge the part without underfilling. In figure 8 (b) it can be seen, that in this case the necessary impact energy could be reduced to 50 % in every blow.

Compensation of the workpiece cooling. During forming, the dissipation energy causes a temperature rise, which could fully or partially compensate the temperature drop due to the transport delay. In the next step, a simulation study was conducted to investigate how the impact energy has to be adapted as a function of the cooling in specific areas of the forged part. For this purpose, the dissipation should be used to increase the temperature in the reference points. To provide the desired final workpiece temperature, two ways were investigated: (A) adjusting the impact energy to obtain the same temperature before the last blow, compared to the reference process, and (B) adjusting the impact energy to achieve the final temperature after the last forming step. In case (A), the last blow was performed without any changes compared to the reference process, in case (B), the energy of all blows was adjusted. Both ways should induce a similar microstructure evolution by static recrystallization after the last blow, so that the temperature drop in the previous forming steps can be compensated.

The results of the simulation show that the compensation of the temperature in the reference points of the part by increasing the impact energy is much more complicated than the correction of the geometry to avoid die underfilling. The compensation of the temperature could be achieved only for the transport time of 5 s. Figure 9 (a) represents the temperature curve at the reference point P1 during the full process with three blows for the transport delay of 5 s.

In the case (A), the impact energy in the first and second blow had to be increased fivefold in order to reach the same temperature before the last hit. It can be seen that recovering the temperature was possible by dissipation as a result of higher impact energy. However, due to the temperature gradient in the component (less temperature in the edge area), the temperature in the point P1 drops faster in the pause between hits compared to the reference process. Thus, the reference impact energy in the last blow is insufficient to attain the required temperature, so that increasing the impact energy in the last blow is necessary, case (B). Figure 9 (b) shows the temperature differences in the reference point P1 between the reference and adjusted processes for both cases.

In the reference point P2, it was not possible to recover the temperature even with a fivefold impact energy value. The reason is that the dissipated energy is not sufficient for the necessary temperature rise, since lower plastic strains (φ_{P2} = 1.28 vs. φ_{P1} = 1.44) and a stronger temperature drop (ΔT_{P2} = 23°C vs. ΔT_{P1} = 14°C) occur in this area. Figure 10 shows the temperature course at point P2 and the corresponding temperatures in the reference process and after ad-justment of the energy.

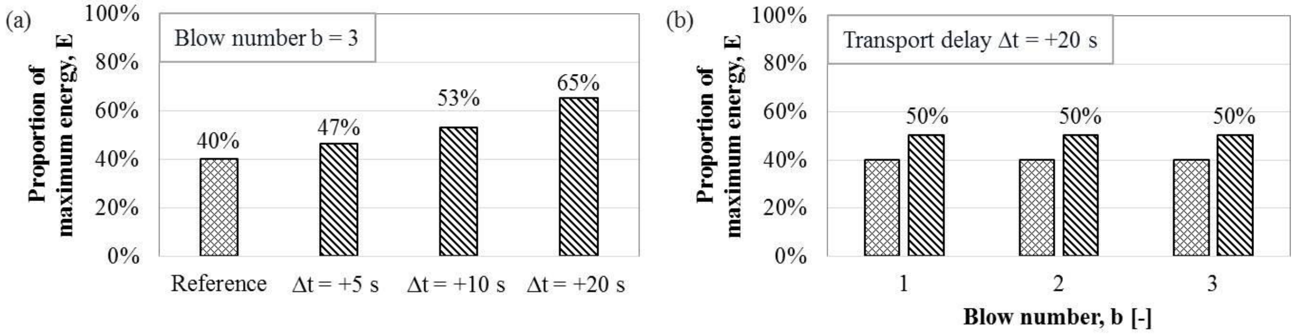
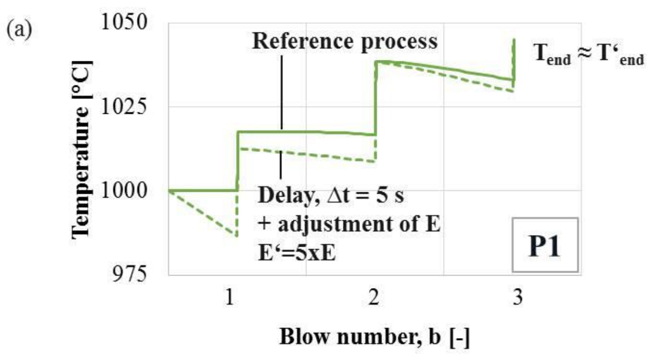


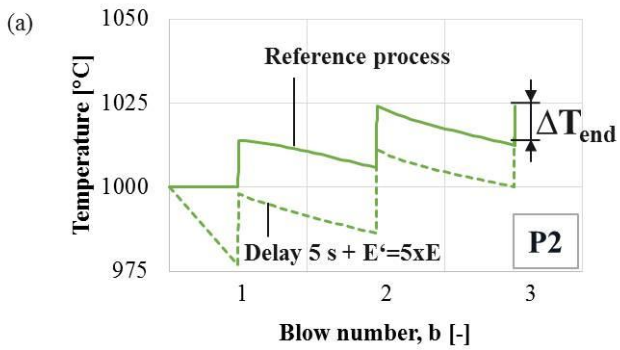
Fig. 8. *Impact energy needed for complete die filling, (a) adjusted energy in the last blow depends on the transport delay and (b) adjusted energy, spread over three blows for a transport delay of 20 s.*



(b)

	Temperature after blow [°C]		
Blow number	1	2	3
Reference	1017	1038	1045
Case (A)	1012	1038	1041
Case (B)	1012	1038	1044

Fig. 9. *Compensation of transport delay of 5 s, due to increase of impact energy; in the reference point P1.*



(b)

Temperature after blow [°C]			
Blow number	**1**	**2**	**3**
Reference	1014	1024	1024
Case (A)	998	1011	1012
Case (B)	998	1011	1015

Fig. 10. *Compensation of transport delay of 5 s, due to increase of impact energy; in the reference point P2.*

4. CONCLUSIONS

This paper aimed to show the influence of the deviations of workpiece temperature on the forming behavior caused by disturbances of the transport time and to demonstrate a suitable compensation method by adjusting the impact energy. The following conclusions can be drawn:

- The transport time has a significant effect on the forging process.
- The temperature deviation after transport and accordingly before the first blow influences directly the temperature of the workpiece at the end of the forging process. This could lead to significant microstructure changes and also to underfilling.
- The underfilling can be compensated by an adapted impact energy in the last blow or by spreading the impact energy over the remaining blows, which reduce the needed impact energy to form the final geometry of the part. For a transport delay of 20 s, the impact energy could be reduced from 65 % (compensation solely in the last blow) to 50 % (compensation over three blows) in the studied part.
- Increasing the temperature by dissipation needs higher impact energies to recover the dropped temperature. The temperature at the end of the process could be compensated in the reference point P1 only for 5 s transport delay. The energy for needed dissipation had to be five times higher to compensate the temperature drop. In the reference point P2 (edge area), no complete compensation of the temperature could be achieved.

The main goal of further investigations is to develop a closed-loop control system for the press, that can calculate and adjust the impact energy in real time and correct the forming process regarding the temperature of the workpiece despite disturbances. The increase in impact energy has to be spread over several hits in this case. Future research will also focus on closed-loop control of microstructure evolution and development of an autonomous system which could be implemented in screw presses and hammers.

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NUMERYCZNA ANALIZA ZAMKNIĘTEGO UKŁADU STEROWANIA KUCIA W PRASIE ŚRUBOWEJ Z WYKORZYSTANIEM ENERGII UDERZENIA JAKO SYGNAŁU WEJŚCIOWEGO

Streszczenie

Prasy śrubowe są energetycznie limitowanymi urządzeniami, w których do odkształcania wykorzystywana jest energia rucho obrotowego zmagazynowana w kole zamachowym. Ta energia jest zamieniana na ruch posuwisty śruby. Prasy śrubowe są szeroko wykorzystywane do kucia stali, aluminium i mosiądzu. W sterowanych bezpośrednio prasach nawrotny silnik elektryczny jest montowany bezpośrednio na śrubie i na ramie prasy powyżej koła zamachowego. W takich prasach energia uderzenia może być bezpośrednio przekazywana od jednego uderzenia do następnego. Nie mnie jednak obecnie nie są znane rozwiązania, w których ta energia byłaby wykorzystywana do automatycznego sterowania i wpływania na własności odkuwki. Celem niniejszej pracy było stworzenie podstaw do kontrolowania własności poprzez dawkowanie energii w czasie kucia. Sterowanie procesem staje się wtedy interesujące i idzie naprzeciw oczekiwaniom klientów i zapotrzebowaniu na zasobooszczędną produkcję. Wyzwanie do osiągnięcia celu są zmiany parametrów procesu, tzn. temperatury w piecu oraz w czasie transportu oraz w wyniku niepewności oceny współczynnika wymiany ciepła między odkuwką i matrycą oraz otoczeniem. Jeżeli warunki procesu zmieniają się to odchyłki od planowanej trajektorii procesu mogą prowadzić do niewypełnienia wykroju lub wadliwego wyrobu. Wyroby kute wymagają dużej precyzji kształtu i własności. Podczas kształtowania dwa mechanizmy mają wpływ na zmiany temperatury: odprowadzanie ciapła do narzędzi i generowanie ciepła w wyniku odkształceń plastycznych. Wymiana ciepła działa jako zakłócenie, a energia uderzenia może być sygnałem wejściowym dla sterowania. W pracy opisano problem sterowania procesem poprzez dawkowanie energii uderzenia, wykorzystując w tym celu symulacje metodą elementów skończonych.

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