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Numerical analysis of tool failure in hot forging processes

Analiza numeryczna uszkodzeń narzędzi w procesach kucia na gorąco

Abstract
The determination of tool failure is of great interest for increasing the efficiency of hot forging processes. This paper presents an enhanced Finite-Element (FE) based approach for die wear calculation, in order to realize a design of hot forging dies which is optimized in terms of tool service life. In the first step, basic investigations concerning the development of the tool material's hardness taking thermal softening into account are introduced, based on a model process. In addition, the approach mentioned is calibrated by substantial industrial data to obtain realistic results over a larger number of operating cycles. Beyond, first results of numerical investigations on thermal-mechanical fatigue of hot forging dies are shown.

Streszczenie
Określanie (przewidywanie) awarii narzędzi jest bardzo ważne dla zwiększenia wydajności procesów kucia na gorąco. Praca niniejsza przedstawia oparte na metodzie elementów skończonych podejście do obliczania zużycia matryc w celu skonstruowania matryc do kucia na gorąco, które byłyby zoptymalizowane w aspekcie trwałości. Najpierw, wprowadzono podstawowe badania nad rozwojem twardości materiału narzędzia z uwzględnieniem zmiękczenia termicznego, oparte na procesie modelowym. Ponadto, podejście to opiera się na solidnych danych przemysłowych, gdzie uzyskano realistyczne wyniki z wielkiej liczby cykli pracy. Poza tym przedstawiono pierwsze wyniki badań numerycznych nad cieplno-mechanicznym zmęczeniem matryc do kucia na gorąco.

Key words: hot forging, wear, fatigue, FEM

Słowa kluczowe: *kucie na gorąco, zużycie, zmęczenie, MES*

1. INTRODUCTION

Due to high thermal and mechanical loads, the tool service life in hot forging is low compared to other forming processes. Heinemeyer [1] identified wear and mechanical crack initiation due the thermal-mechanical material fatigue as the main failure causes of hot forging tools. Regarding the steadily increasing cost pressure, there is a great interest in reduction of tooling costs in hot forging. An optimized process design taking into account the tool service life is a way to increase the efficiency of hot forging processes. Hence, the objective of the work presented in this paper are simulation models for the calculation of die wear and prediction of tool failure due to thermal mechanical material fatigue.

2. CALCULATION OF WEAR

Workpiece temperatures up to 1.300°C in steel forging processes lead to a gradual hardness loss of the tool surface layer [2]. This is caused by an excess of the tempering temperature of conventional hot-work steels. Hence, the tool wear rate increases over a number of forging cycles.

For a reliable wear prediction, it is necessary to include the decrease of hardness into the calculation via an appropriate approach. So far, there have been several research works dealing with the simulation of tool wear in hot forging taking thermal effects into account as well [3, 4, 5]. The authors regard the decrease of hardness due to thermal softening, but the assumptions concerning the present hardness and microstructure within the tool surface layer are not validated with experimental data. Furthermore, the introduced models are only applied to one forging process in each case. There is no investigation concerning versatility to different processes.

2.1. Modeling of Tool Wear

The best-known approach for wear calculation was developed by Archard [6]. This wear model was changed such that the wear depth w for one forging cycle can be calculated according to Equation 1.

$$w = k \cdot \sum_{inc} \left[\frac{\sigma_{\mathrm{N}}}{H(\vartheta, t_{\mathrm{t}})} \cdot v_{\mathrm{rel}} \cdot \Delta t \right]_{inc} \qquad (1)$$

In this equation σ_{N} represents the contact normal stress at the tool surface, $H(\vartheta, t_{\mathrm{t}})$ refers to the hardness at the tool surface, v_{rel} is the relative sliding velocity between workpiece and tool, and Δt represents the duration of one time increment in the FE simulation. The hardness H was not considered constant as done by Archard, but depends on the temperature ϑ and the duration t_{t} of the considered numbers of forging cycles. Due to the complexity of the tribological effects, not all influence factors on wear can be taken into account. Thus, this equation contains the wear coefficient k, which has to be determined by adjustment of computed and measured wear profiles. The identified wear coefficient is valid for similar loading conditions.

A fully thermal-mechanical coupled simulation model is applied for determination of the needed data. The tool components which are considered for determination of wear depth are modeled as deformable bodies with thermo-elastic material behavior. For determination of wear depth, a discrete program which uses data from FE simulation of one cycle was developed. Here, σ_{N}, v_{rel}, Δt and ϑ at the tool surface nodes are read out into a file at the end of each increment of the forging simulation. The wear depth w then is computed according to Equation 1 by summation over the number of considered forging cycles wear taking into account to the present hardness.

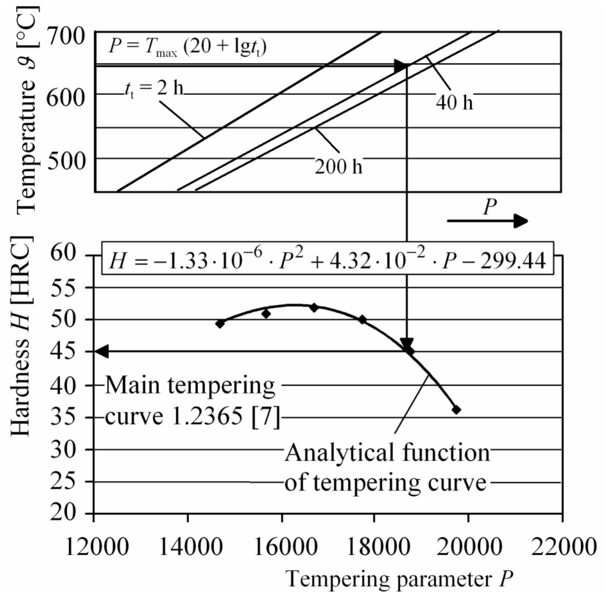

Fig. 1. Schematic procedure for tempering hardness determination

Rys. 1. Schemat procedury wyznaczania twardości po odpuszczaniu

The surface layer hardness was determined by means of the main tempering curve for the tool material and the tempering parameter P. As the change of the microstructure only takes place in the tool surface layer, the maximum temperature $T_{\max}$ at every surface node was used for determination of the tempering hardness. The tempering parameter P was determined using $T_{\max}$ and the process duration t_{t} (in hours), resulting from the cycle duration and the number of forging cycles (Equation 2).

$$P = T_{\max} \cdot (20 + \lg t_{\mathrm{t}}) \qquad (2)$$

The standard procedure for determining the tempering hardness for the hot-work steel 1.2365 (DIN EN standard) used in the basic investigations is shown in Fig. 1. Only nodes with a maximum temperature of above 450°C are included in this procedure. Furthermore, the calculation of tempering hardness starts at process duration greater than one hour.

The initial hardness is used if no hardness calculation is carried out. Since the calculated tempering hardness exists at room temperature, the hardness was considered at process temperature using a hot hardness curve. The described approach for hardness calculation was implemented in the developed program. By matching the computed and measured wear profiles, the wear coefficient k can now be determined.

2.2. Wear Calculation at a Model Process

The wear model was applied first to a forging process with rotation-symmetric parts geometry (Fig. 2).

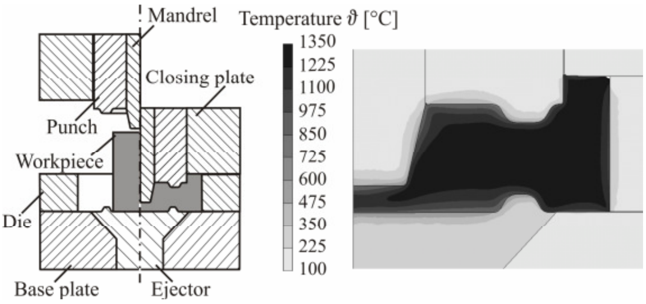

Fig. 2. Considered forging process and calculated temperature distribution

Rys. 2. Rozważany proces kucia i obliczony rozkład temperatur

Additionally, Fig. 2 illustrates the temperature distribution at the end of a forging cycle. It becomes clear that strong heating only occurs in the tool surface layer. In deeper areas, there is only weak heating due to thermal conduction. This proves that the microstructural changes appear solely in the tool surface layer.

As the most wear was expected at the mandrel, it was replaced after 500, 1000 and 2000 forging cycles, in order to investigate wear and the microstructure. By comparison of the initial and the worn geometry of the mandrel the wear was determined.

The micrograph in Fig. 3 shows the microstructural change as a result of the thermal loading. A so-called white layer was found at the mandrel radius due to the fast cooling-down of the heated surface zone at cold tools [2]. In this layer, the hardness increases from the original value 570 HV 30 to 680 HV 0.1. Only at small radii with very high thermal loadings a formation of the white layer takes place. Outside of the white layer, a hardness decrease was observed because of tempering effects.

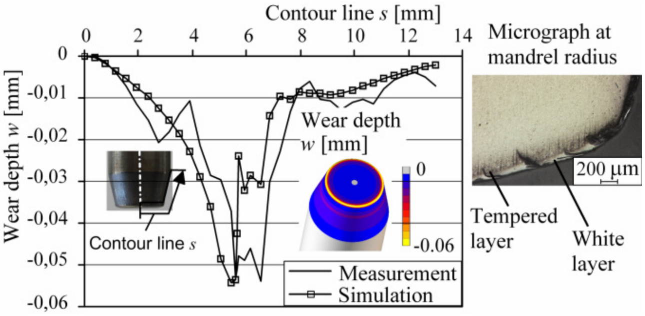

Fig. 3. Comparison of measured und simulated wear profiles at the mandrel

Rys. 3. Porównanie zmierzonych i symulowanych profili zużycia przy trzpieniu

After 500 forging cycles, tactile measurements at the mandrel radius showed not only abrasive wear but also plastic deformation, caused by the white layer sliding on the thermally softened layer. Therefore, the suitability of the wear model was verified by wear calculation between 1000 and 2000 forging cycles, since this interval, there was only abrasive wear. The geometry of the mandrel after 1000 forging cycles was used in the simulation. Moreover, the duration of the first 1000 cycles was taken into account for calculation of the tempering hardness outside of the white layer. The experimentally determined value was assumed for the hardness of the white layer in the mandrel radius area. The wear coefficient k was indentified such that the correct calculation of the maximum wear depth was possible. In Fig. 3 the measured and computed wear at the mandrel are compared between 1000 and 2000 forging cycles. The curves of measurement and simulation match quite well. This indicates the suitability of the proposed model for wear calculation in hot forging considering thermal softening.

2.3. Transfer to Industrial Processes

The empirical wear model described in chapter 2.1. takes essential factors influencing the wear of tools into account, in particular the thermally caused hardness loss of near surface areas of forging dies. However, due to the complexity of the tribologic conditions within the intermediate layer between workpiece and tool, not all process-specific and operational effects can be depicted in detail.

For an improved and more general quantitative estimation of the local tool wear via high cycle numbers, the computational model is additionally calibrated with measured data from industrial processes. As multiple measurements of the tool geometries are not possible in industrial production processes, the wear behaviour is determined by measuring workpiece geometries which are taken from the production process in predefined cycle intervals.

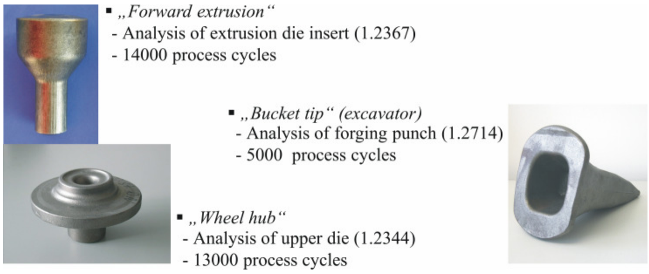

Fig. 4. Considered industrial processes

Rys. 4. Rozważane procesy przemysłowe

The geometrical range of the considered industrial processes includes two rotationally symmetric and a more complex 3D-geometry. Tool systems for forward extrusion, hot forging of a wheel hub and bucket teeth of a hydraulic shovel were analyzed up to 14000 process cycles in particular cases (Fig. 4). The considered die components cover a selection of relevant hot work steels. Material-specific hot hardness characteristics for the hot work steels 1.2714, 1.2344 and 1.2367 (DIN EN standard) were described analytically via approximation functions and embedded into the wear model with respect to usual heat treatment conditions [7]. In addition, specific main tempering curves for the considered hot work steels were obtained from technical data sheets of steel manufactures. The curves were implemented into the computational model by analytical functions.

For the determination of the wear progress, certain characteristic areas of the geometry were investigated. Based on the wear distributions measured for different cycle numbers, wear profiles were evaluated within plane cross sections. Considering the extensive amount of real and simulation results, the systematic calibration of the wear model was realized by means of statistical methods. For input data, local wear depths were each evaluated in discrete positions of the analyzed plane cross sections, and the real values were correlated with the respective simulation results.

Fig. 5. Verification of the computational model regarding an industrial hot forging process of a driveshaft

Rys. 5. Weryfikacja modelu komputerowego dotyczącego procesu kucia na gorąco wałka napędowego

Finally, the modeling approach for die wear calculation was verified based on an industrial process for the hot forging of a driveshaft, shown in Fig. 5. The model was applied to the upper die of the final process stage, made of hot work steel 1.2367 (DIN EN standard), using the calibrated model for this tool material. Identification of this parameter set was based on the analysis of two die components of a tool system for hot forging of a wheel hub and one forward extrusion die.

Measured data and FE results of the wear depth were analyzed along the outline of the tool surface. Fig. 6 shows a comparison of measured and simulated wear profiles after 8000 process cycles exemplary.

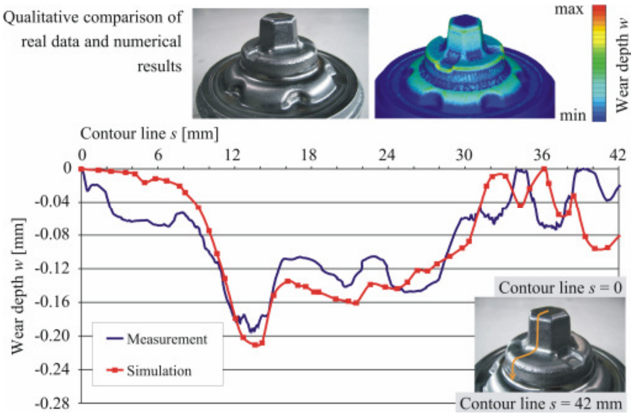

Fig. 6. Comparison of measured and simulated wear profiles after 8000 process cycles

Rys. 6. Porównanie zmierzonych i obliczonych profili zużycia po 8000 cykli procesu

Regarding characteristic features of the wear profiles, the FE results show a good correlation to the measured data. In areas with very high thermal-mechanical load, e.g. the convex radius at the top of the punch, a satisfying quantitative estimation of the wear depth is realized.

3. TOOL FAILURE DUE TO FATIGUE

Next to wear of the die surfaces, fatigue damage due to cyclic loading is second relevant cause of tool failures in hot forging [1]. The life quantity of less than 20.000 load cycles point to Low Cycle Fatigue (LCF) as the cause of failure. This kind of failure is characterized by exceedingly high stress concentrations and, due to this, local plastic deformation of the tool material.

3.1. Basic Approach

The load during the forming process can lead to a local plastic deformation in critical tool areas and to time-dependent hardening or softening of the material. For the exact computation of the tool load and the following lifetime prediction, it is necessary to depict the real behavior of the tool material with high accuracy. In the field of tool failure prediction in hot forging due to fatigue cracking initiation, only few works exist [8, 9]. Fatigue and damage effects on the tool material by loads occurring in the forging process are not considered in the available publications.

There are numerous visco-plastic material models for the depiction of the material behavior under cyclic loads [10, 11]. In the field of forming-tool development, these material models have been applied to tool systems of cold forging only [12, 13]. Although fatigue is a relevant cause of failure in hot-forging processes as well, appropriate material models have not been used and verified in the analysis of hot-forging tools. Thus, the aim of this work is to develop a methodology for prediction of tool failure in hot-forging processes due to thermal-mechanical material fatigue (Fig. 7).

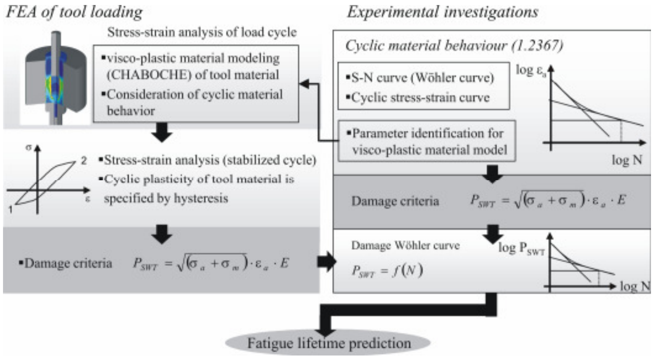

Fig. 7. Computational methodology for lifetime prediction of hot-forging tools, based on FEA

Rys. 7. Obliczeniowa metodyka przewidywania trwałości narzędzi do kucia na gorąco oparta na FEA

Herein, a main focus is on experimental determination of cyclic behaviour of the hot-working steel 1.2367 with respect to the process-specific conditions during forging. This particularly includes the thermo-cyclic material load with high heating-up and cooling rates. By means of strain-controlled dynamic fatigue tests, a Wöhler curve is determined for the considered hot-working steel and used as the basis for an estimation of the tool lifetime. Moreover, a cyclic influence on the material's deformation behavior under tensile load is identified. Based on the experimental investigations, the model parameters required for the application of visco-plastic material models can be identified.

In order to correlate the material's calculated stress-strain state, i.e. the load, and the experimentally determined material properties, i.e. the strength, strain-based damage models are to be used as a first simplification. Regarding the failure due to LCF, the principal strains amplitudes are considered for correlation with the strain Wöhler curve. Furthermore, the damage parameter according to SMITH, WATSON and TOPPER can be applied, which regards the product of the maximum stress and strain amplitudes. The fatigue lifetime prediction is realized by correlation of the damage parameters computed for the respective loading case with the lifetime curves determined experimentally.

3.2. Calculation of Tool Load

For application of the described procedure for prediction of tool service life until incipient crack initiation, an industrial process was chosen. The lower die of this process failed after 1700 forging cycles due to thermal-mechanical fatigue.

In the first step the tool load was investigated, in order to find out if local plastic deformations occur in the lower die. A three-dimensional thermal-mechanical coupled simulation model considering the elastic-plastic material behavior of the lower die was developed (Fig. 8). The plastic properties of the die material 1.2367 (DIN EN standard) was modeled using the temperature dependent yield strength. Strain hardening was neglected since only low strains occur.

Fig. 8 shows the calculated maximum principal plastic strain ε_I at bottom dead centre position of the punch. As clearly noticeable, a plastic deformation occurs in the radius only.

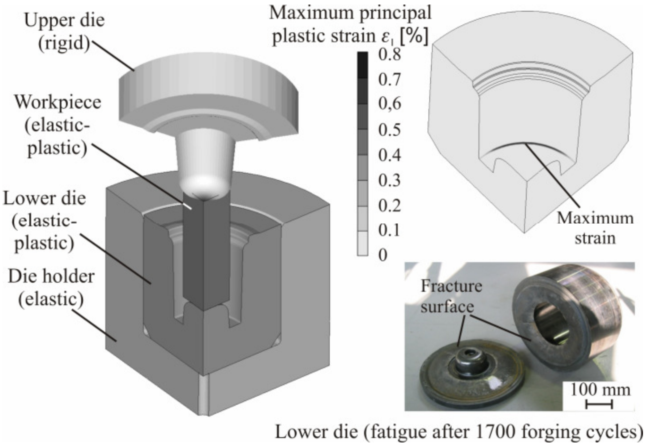

Fig. 8. Calculation of plastic strains for a failed forging die

Rys. 8.Obliczenie naprężenia plastycznego uszkodzonej matrycy kuźniczej

The maximum plastic strain is 0.72 %. Thus, it can be assumed that the failure of the lower die was caused by crack initiation in this radius. In the further course of the research work, an extension of the simulation model is planned, in order to be able to represent material fatigue and damage as the basis of the lifetime estimation as well.

4. SUMMARY AND OUTLOOK

An effective possibility for increasing the efficiency of forging processes is an optimized process design taking into account the tool service life. Thus, the paper introduces a FE model for wear estimation with improved versatility which includes the process related thermal effects on hardness of the tool material. Extensive data from experiments and industrial processes are used for the development and calibration of the approach.

Furthermore, a deterministic procedure for determination of tool failure due to thermal-mechanical fatigue based the local concept is presented. For the application of the developed procedure, the plastic strains are analyzed at a failed forging die in order to allow the crack prediction. The main focus for future works is the experimental determination of material-specific fatigue properties and whose implementation into a FE simulation.

5. ACKNOWLEDGMENT

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