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AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE
Informatyka w Technologii Materiałów

Vol. 7, 2007, No. 1

FINITE ELEMENT ANALYSIS OF DIE WEAR IN HOT FORGING CONSIDERING INDUSTRIAL PROCESSES

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Abstract

The efficiency of hot forging processes significantly depends on the service life of the dies. As a consequence of thermal and mechanical interactions between workpiece and tool surfaces during the forming process, adhesive and abrasive die wear occurs, that is a major failure reason of hot forging tools. Due to the high forming temperatures, the annealing temperatures of the tool steels are exceeded. This leads to a decrease of the die material's hardness that results in an increased tool wear particularly in areas of the die cavity with high relative velocities and contact pressures between tool surface and workpiece.

Within the process design by means of Finite-Element analysis, a quantitative prediction of the die wear in consideration of thermal conditions is limited at present. In terms of the reachable process cycles, the design of the forging tools is generally based on the know-how of the engineer.

This paper shows an enhanced FE-based approach for die wear calculation that includes relevant thermal effects on the tool material. In addition, the mentioned approach is calibrated by substantial industrial data, to obtain more realistic results. The wear behaviour of several industrial forging dies, that cover an extended range of geometries, was determined by optical measurement technology over long operating times. Based on the obtained results, the approach for die wear calculation was calibrated by statistical analysis. Exemplary, the simulation concept was implemented into a commercial FEA-package for the simulation of bulk metal forming processes by means of user subroutines, considering material-specific wear properties for some common hot forming tool steels. The modelling approach is finally verified regarding an industrial process with complex tool geometry.

Key words: hot forging, tool wear, finite-element-analysis

1. INTRODUCTION

Hot forging tools have to withstand a combination of high mechanical, thermal, tribological and chemical loads. The service life of the dies is low, compared to other forming processes. The abrasive wear of the die cavities is the main reason to failure within 70% of all failure reasons (Huskic, 2005). Due to the high process temperatures up to 1300°C, the annealing temperatures of conventional tool steels are exceeded in surface areas of the dies (Walter, 1999). This leads to a decrease of the die material's hardness that results in an increased tool wear particularly in areas of the die cavity with high normal pressures and high relative velocities between tool surface and workpiece (Bobke, 1991; Doege et al., 1994).

The prediction of the die wear in consideration of thermal conditions by Finite-Element analysis is limited at present. Due to complex geometries of industrial processes and various interdependencies of process parameters it is not possible to use model experiments for an exact wear prediction. Thus, the design of the forging tools in terms of the life cycles is generally based on the expert knowledge of the engineer. A couple of research projects dealt with an FE-based die wear estimation, taking into account the hardness loss due to thermal softening effects of the tool material (G. A. Lee & Im, 1999; H. C. Lee

 ISSN 1641-8581

et al., 2003). The main objective of the investigations presented in this paper is to develop a die wear model that features an improved versatility concerning the die geometries and the employed hot work tool steels by calibration with substantial industrial data. The FE-based approach introduced in this study allows the identification of wear-critical tool areas and a quantitative estimation of the local wear depth throughout multiple forging cycles.

2. NUMERICAL SIMULATION OF THE DIE WEAR

The described approach for the die wear calculation is based on the conventional Archard's wear model, which considers the normal pressure σ_N, relative velocity v_{rel} between tool surface and workpiece and the hardness of the tool material. The process variables are calculated within thermal-mechanical coupled FE-simulation with elastic tools. The discretisation of the tool geometries with finite elements allows a local calculation of the wear depth in surface areas of the element mesh.

$$w = k \sum_{1}^{n} \left[\frac{\sigma_N(t)}{H(T)} \right]^a \cdot v_{rel}(t) \qquad (1)$$

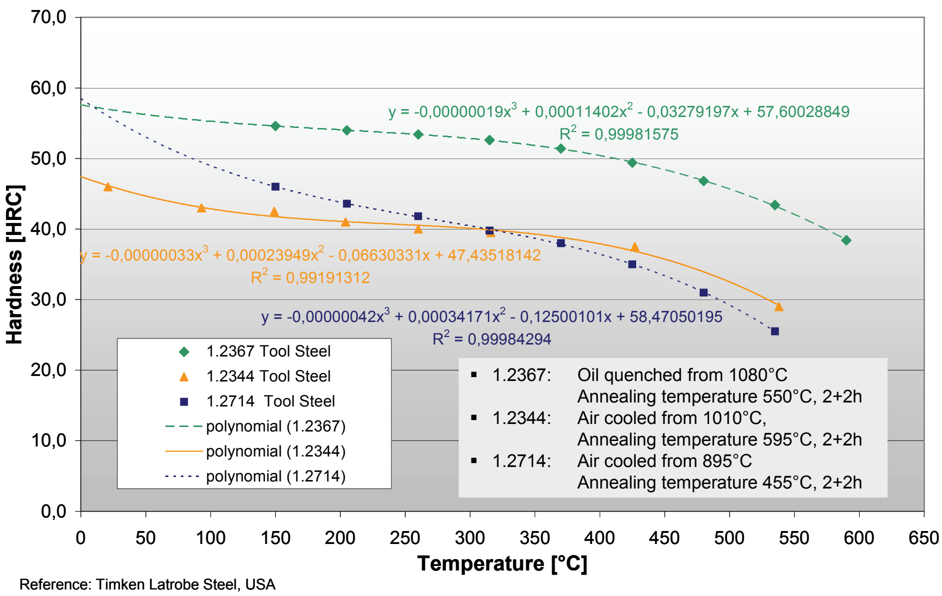

Fig. 1. Hot hardness curves of conventional hot work tool steels.

The approach includes essential effects on the die wear. Due to the complexity of the tribological effects between workpiece and tool surface, not all process specific factors are taken into account. Thus, to get quantitative results of the wear depth, a calibration of the wear model is required. In addition to the calibration parameter k, the exponent a was embedded into the calculation model, which facilitates a weighting of the parameters σ_N and the temperature dependent hardness $H(T)$ relative to v_{rel}.

The introduction of the temperature dependent hardness $H(T)$ of the tool material makes it possible to consider significant thermal effects, which are essential in hot forging processes. The temperature dependency of the tool material's hardness is characterised by hot hardness curves (Schruff, 1989), that are implemented for the common hot forming tool steels 1.2714, 1.2344 and 1.2367 (DIN EN standard) of specific heat treatments as presented in figure 1. The curves are specified by analytical functions embedded into the calculation model.

In addition to the hot hardness curves, the tempering parameter P is used in order to consider thermal softening effects throughout multiple forging cycles (H. C. Lee et al., 2003; Behrens & Schaefer, 2005). The tempering parameter, which is known from heat treatment of steels, characterises the interdependency of the tempering temperature T and the duration of the thermal load t. The constant parameter a is 20 for hot tool steels.

$$P = T \cdot (a + \lg t) \qquad (3)$$

In order to estimate the tempering hardness, the relevant tempering temperature T is considered as arithmetic mean of the base tool temperature and the initial workpiece temperature (Müller et al., 1988). The period t is calculated from the process time and the number of forging cycles, whereas the process time is assumed as sum of forming period and wait times. Starting from the calculated tempering parameter, the current hardness is determined on the basis of material specific main tempering curves as shown in figure 2.

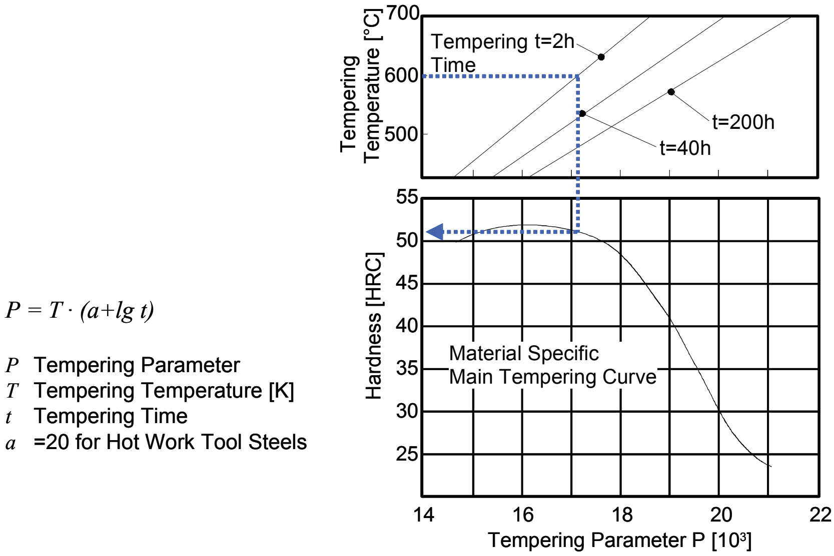

Fig. 2. Consideration of thermal softening effects based on the tempering parameter.

Specific main tempering curves for the considered hot work tool steels were obtained from technical data sheets of steel manufacturers. The curves are implemented into the die wear model by analytical functions as shown in figure 3.

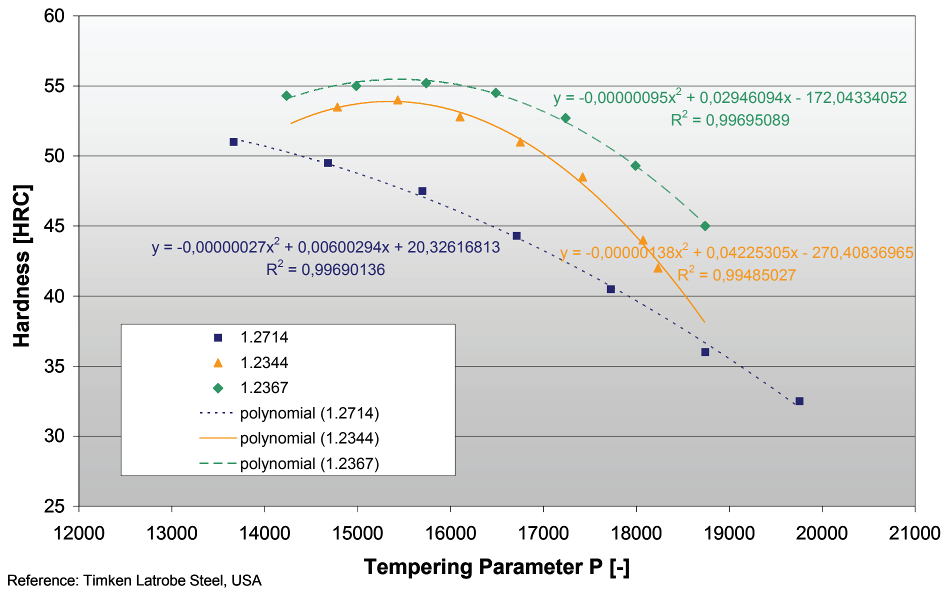

Fig. 3. Main tempering curves of the considered hot work tool steels.

The consideration of thermal effects on the die wear requires the determination of the temperature distribution within the dies. Hence, all calculations were carried out in thermal-mechanical coupled Finite-Element-Analysis, with the tools modelled as elastic bodies. The schematic chart in figure 4 represents the prototypic implementation of the wear modelling into a commercial FE-code for the calculation of bulk metal forming processes.

3. CALIBRATION OF THE DIE WEAR MODEL

The die wear model includes essential influencing factors, whereas not all relevant operational and process specific factors are taken into account. The interface layer consists of a mixture of lubricant, scale and abrasion particles, which result in complex tribological effects between workpiece and tool surface. To obtain realistic results and to realise a quantitative estimation of the local die wear, the calculation model was calibrated by substantial industrial data. The selected tool range covers the mentioned hot work tool steels. The progress of the die wear was determined by measuring the geometry of the forgings after specified process cycles, since multiple measurements of the die geometries themselves are not suitable within the industrial production flow.

The geometrical range of the considered industrial processes includes two rotationally symmetric and two more complex 3D-geometries. As illustrated in figure 5, the geometrical measurements were carried out with the optical measuring system GOM ATOS that allows an effective 3D-digitising of the forgings with an adequate accuracy. Based on the measuring data, the wear progress was determined for characteristic areas of the tool surfaces. Local wear distribution was analysed by wear profiles within plane sections, which allow a detailed comparison with the simulation results.

Considering the extensive data base of measured data and FEA results, the calibration of the calculation model was carried out systematically by means of a statistical software system. Thus, the proceeding wear depth was evaluated at discrete points of the considered plane sections for both, the measured data and FEA result respectively.

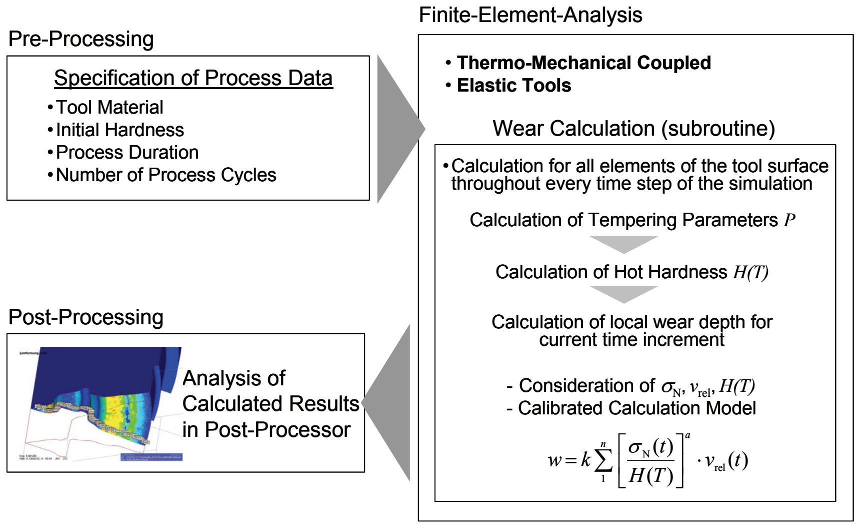

Fig. 4. *Implementation of die wear calculation into a commercial FE-code.*

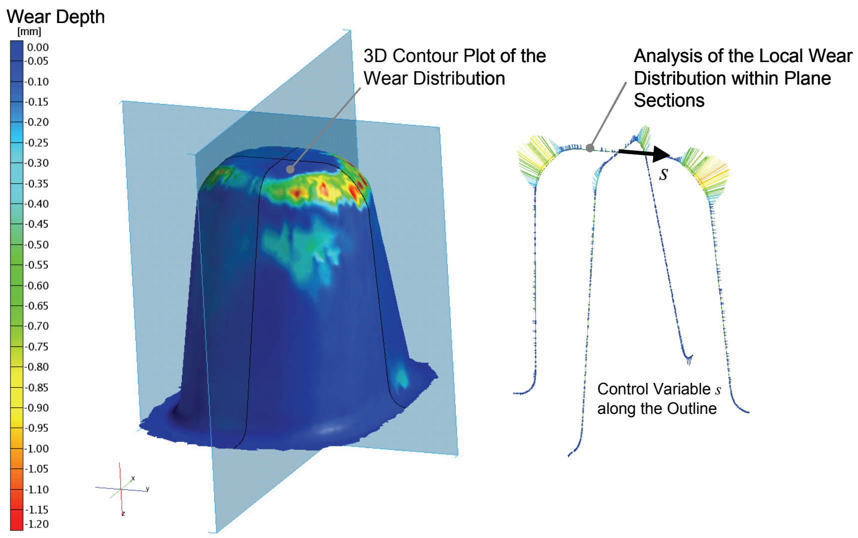

Fig. 5. *Determination of the wear progress of an industrial forging punch throughout long operating times by optical measuring techniques.*

As a result of the statistical evaluation, the adaptation of the exponent a allows to assess the influence of the relative velocity v_{rel} on the die wear with reference to the normal pressure σ_N, and the temperature dependent hardness of the tool material $H(T)$. Furthermore, the calibration factor k is identified against the number of process cycles and the type of the applied hot work tool steel.

4. VERIFICATION OF THE NUMERICAL RESULTS

The modelling approach for die wear calculation was verified regarding an industrial process for the hot forging of a driveshaft, shown in figure 6. The model was applied to the upper die of the final process stage.

Measured data and FEA results of the wear depth were analysed along the outline of the tool surface that is also represented in figure 6. Figure 7 shows a comparison of measured and simulated wear profiles after 4000 and 8000 process cycles exemplary.

Regarding characteristic features of the wear profiles, the FEA 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, the quantitative estimation of the wear depth is satisfying. The consideration of thermal softening effects on the tool material allows to consider the increasing progress of the abrasive wear between 4000 and 8000 process cycles.

5. CONCLUSION

The applied approach for die wear calculation considers the thermal softening effects in the tool surfaces, which are essential for hot forging processes. The versatility of the wear model was enhanced by statistical calibration, based on the analysis of the wear progress of several industrial forging dies. The considered industrial processes cover a range of relevant hot forming tool steels. For the examined range of geometries and tool materials, a quantitative estimation of the abrasive die wear could be realised throughout multiple process cycles. The calibrated wear model allows to compare different hot work tool steels regarding their wear resistance within the process design by means of FEA. Thus, it is possible to enhance the process design concerning the die life and the selection of an adequate tool material. With the knowledge about wear progress in mind, set-up times of tools can be scheduled more exactly. Thus, in terms of the production process, the possibility of die life estimation improves an effective production control.

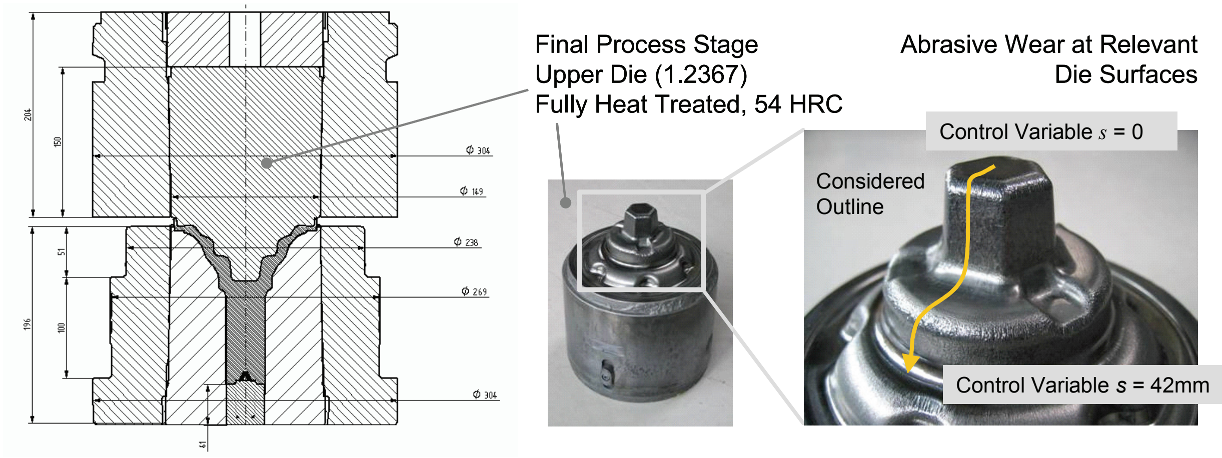

Fig. 6. *Verification of the wear model regarding an industrial hot forging process of a driveshaft.*

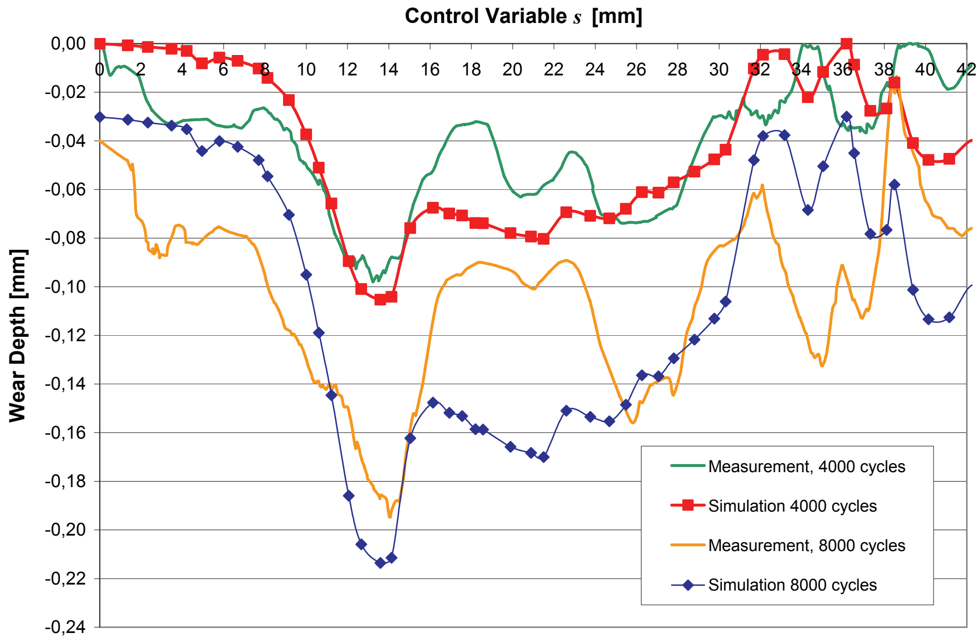

Fig. 7. *Comparison of measured and simulated wear profiles at certain numbers of process cycles.*

Acknowledgement. The presented work has been financed with budget funds of the "Bundesministerium für Wirtschaft und Arbeit" (Federal Ministry of Economics and Labour, Germany), by the „Arbeitsgemeinschaft Industrieller Forschungsvereinigungen" (AiF) and the „Forschungsgesellschaft Stahlverformung" (FSV). The final report of this research project is available at FSV, Germany.

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ANALIZA NUMERYCZNA PROCESU ZUŻYCIA NARZĘDZI W PRZEMYSŁOWYM PROCESIE KUCIA

Streszczenie

Efektywny proces kucia na gorąco zależy znacząco od cyklu życia matryc. W konsekwencji termicznych i mechanicznych interakcji pomiędzy materiałem wsadowym i powierzchnią narzędzia, okazuje się, iż głównym powodem awarii matryc jest zużycie spoiwa i ścierniwa. Poprzez przeprowadzanie procesu w wysokich temperaturach następuje przekroczenie temperatury wyżarzania narzędzi stalowych. Prowadzi to do zmniejszenia twardości materiału matrycy i zwiększenia jego zużycia. Ilościowa predykcja zużycia matrycy za pomocą metody elementów skończonych z uwzględnieniem warunków termicznych jest obecnie dość ograniczona. Natomiast projekt narzędzi wykorzystywanych w procesie kucia jest przygotowywany głownie w oparciu o wiedzę inżynierów i posiadane know-how. Niniejszy artykuł przedstawia podejście zaproponowane w oparciu o rozszerzoną metodę elementów skończonych przeznaczoną do obliczeń związanych ze zużyciem matryc. Model skonfigurowano przy wykorzystaniu rzeczywistych danych z przemysłu, aby uwiarygodnić otrzymywane wyniki. Wykorzystane dane przemysłowe otrzymywano za pomocą pomiarów optycznych. Zaproponowaną koncepcja zaimplementowano przy użyciu komercyjnego pakietu FEA. Podejście zostało ostatecznie zweryfikowane również za pomocą danych przemysłowych wyposażonych w kompleksowe informacje na temat geometrii narzędzi.

Submitted: September 26, 2006
Submitted in a revised form: October 17, 2006
Accepted: December 4, 2006