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Original Research Article

Cellular automata model for prediction of crack initiation and propagation in hot forging tools

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ABSTRACT

The paper presents design and implementation of the cellular automata (CA) model, which predicts damage of forging tools due to fatigue. The transition rules for the model were developed on the basis of known information regarding crack initiation and propagation. The coefficients in the model were determined by the inverse analysis of the thermal fatigue tests performed on the Gleeble 3800 simulator and in the special device with a rotating disc. The CA model was coupled with the conventional abrasive wear model. The layers of cell in the CA space, which are in contact with the workpiece, were removed successively following the abrasive wear of the tool. The CA model was connected with the finite element (FE) programme, which simulates stresses in tools during forging. Since this multiscale approach appeared to be extremely demanding as far as computing times are considered, an efficient implementation of the model on heterogeneous hardware architectures was prepared. Results of simulations were compared with the industrial data and good predictive capabilities of the model were confirmed.

1. Introduction

Die forging has been known for years and is now an advanced forging technique used in the mass production of critical parts. Low durability of the forming tools is an important limitation of this process. It is estimated that the costs of the tools may amount to as much as 8–15% of the total production costs. Actually, if the time needed to replace the worn out tooling are accounted for, the costs may increase even further. Moreover, tool wear significantly contributes to deterioration in the quality of the produced forgings. Basic information on wear can be found in [1] and a review of the degradation mechanisms in forging tools was presented by Gronostajski et al. [2]. Problem of wear of tool steels has been widely investigated in several laboratories, see research [3,4]. The most common forging defects caused by tool wear are die cavity filling errors, i.e. under-filling, laps, burrs, distortions, scratches, delamination and micro- and macro cracks. The defects affect the functionality of the end product made out of the forging. Manufacturers of die forged products make efforts to reduce their costs and improve the quality of the forgings, e.g. [5]. Numerical modelling of the tool wear can be helpful in reaching this goal.

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Problem of modelling of tool wear has been of interest for researchers for few decades now. Analysis of the literature shows that overwhelming majority of developed models was based on the fundamental Archard law [6], who described the wear due to sliding between the forging and the tool by the following equation:

$$w = C\frac{p\Delta L}{H} \tag{1}$$

and after integration during the whole deformation:

$$w = \int_0^t C\frac{p\Delta v dt}{H} \tag{2}$$

where w – thickness of the tool material layer, which is removed due to wear, p – pressure normal to the die surface, H – hardness of the tool material, ΔL – sliding distance, Δv – sliding velocity, t – time, C – parameter dependent on the tool material and process conditions.

Models based on Eq. (1) were commonly used by researchers to predict tool wear for various hot forging processes. Problems with calibration of this model (determination of the parameter C for a given tool material and conditions of forging) were the main factor limiting wider application of Eq. (1) to quantitative prediction of the wear. The commonly used procedure was connection of Eq. (1) with the finite element (FE) code, which simulates forging process, and comparison of calculated wear with measurements of dies after forging of various numbers of pieces [7,8]. Authors of [9] determined constant value of parameter C for AISI L6 tool steel. Relation of this parameter on the tool temperature was probably the most frequently investigated aspect of the tool wear and the subject of research in [4,10–13]. Correlation between parameter C and tool heat treatment, in particular surface treatment, was introduced in [14] and the effect of the tool surface oxidization was studied in [15]. Authors of [16] accounted for the changes of the tool hardness and determined changes of the parameter C with increasing number of forged pieces.

All these works and a large number of similar publications are based on the assumption that abrasive wear is the only wear mechanism in hot forging. It has been, however, pointed out by many authors [2] that beyond abrasive wear the tool wear is due to a number of mechanisms such as oxidization, thermomechanical fatigue and plastic deformation and the interdependences between them. Availability of publications in this area is much smaller. Fatigue of the forging tools was studied in [17] but only for mechanical loading in cold forging. A complex material model combining kinematic and isotropic hardening with continuum damage mechanics was used in that paper to simulate the elastic–plastic material behaviour and damage development was based on fundamental works of Lemaitre [18] and Chaboche [19]. Similar analysis of fatigue of the cold forging tools was performed in [20]. Thermomechanical fatigue of hot forging tools was analyzed in [21]. Authors of that paper used classical theory to predict fatigue of the tools. To account for softening of tools during forging and to keep computing time on a reasonable level, they applied the fatigue life curves established by using the mechanical parameters that are identified from the first hysteresis loops of fatigue experiments. Good agreement between experimental data and the new law was obtained.

All the listed above papers were based on classical approaches, which do not account directly for the microstructure of the tool material. As far as multiscale modelling is considered, there are no papers dealing with industrial forging processes. A lot of research was done on multiscale investigation the contact interaction and wear of deformable bodies with rough surfaces in general [22]. In those works the models to study the wear rate for various microgeometry parameters were developed and used for mathematical formulation of the contact problems at macroscale. Thus, those works should be rather classified as multiscale modelling and tribo-simulation techniques. Indeed, theoretical solutions proposed in those works can be directly applied to develop multiscale wear models for hot forging tools, but to Authors knowledge there are not publications dealing directly with forging tools wear accounting for the microstructure of the tool steel. The publication dealing with multiscale analysis of forging tools [23] deals with curing of carbon-epoxy tooling material presenting a specific mesostructure, which is far from the microstructure of tool steels. Thus, development of the multiscale model for hot forging tools was the main objective of the present work. Cellular automata (CA) method has capabilities which allow reaching this goal and this method was selected to predict fatigue due to thermal-mechanical loads of the tools.

Several examples of successful applications of the CA technique to simulation initiation and propagation of microcracks can be found in the literature. Examples for modelling fracture in steels [24], creep [25], fatigue [26], deformation of multiphase steels [27] confirmed very good predictive capabilities of this method. On the other hand, application of this method to fracture simulation in forging dies requires connection with the Finite Element (FE) method in the macro scale (so called CAFE method). In this approach states of strains and stresses in the macro scale are calculated using FE code and crack initiation and propagation in the micro scale is calculated using CA attached to the FE nodes. The local states of strains and stresses are used as boundary conditions for the CA space. This approach, although very accurate, requires very long computing times. A possibility of decreasing of these times was the subject of the paper [28] and an efficient implementation of the CA model on heterogeneous hardware architectures was proposed. This implementation was applied in the present work.

2. Experiments

Three experiments were performed for identification and validation of the model. Details of these experiments are given in other publications and only main parameters are repeated below.

2.1. *Thermal fatigue tests on Gleeble 3800 simulator*

Tool steel samples measuring $\phi 10 \times 120$ mm were placed in fixed dies and were subjected to cyclic changes of the temperature with the cycle of 8 s. Due to thermal expansion