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MULTISCAL SYNERGETIC MODEL OF THE DIE WEAR IN HOT FORGING PROCESS

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Abstract. Tool wear in hot forging is responsible for a significant increase of the costs of production and various degradation mechanism are investigated to decrease these costs. A proposition of the multiscale hybrid model of the tool wear in hot forging is described in the paper. The idea of the model was based on distinguishing various mechanisms of the tool wear and evaluation of the mutual influence of these mechanisms. The analysis of factors, cumulative wear of which is mutually dependent, confirmed that all mechanisms influence each other in some way. To cover this, the hybrid die wear model was proposed, which includes significance of each mechanism and the mutual relation between them. Additionally, to include change of material parameters, modification of these parameters was account for by a feedback. This feedback passes modified die geometry and optionally material parameters into the next iteration of die wear modelling. Developed model consists of the macro scale FE simulations, which supply data regarding local pressure, temperature and distance of slip. The following process parameters are supplied in the micro scale: wear mechanisms blocks containing adequate models, significance models and extrapolation routines for results. Three degradation mechanism were considered in the present approach: abrasive wear, plastic deformation and thermomechanical fatigue. The calculated wear is represented as a die geometry and together with changes of die material properties control the multi-iteration wear prediction. Some mechanisms blocks contain additional components for computing correction of surface parameters altered by thermomechanical fatigue, cracks or increased porosity. Numerical tests of the model were performed for the second operation in the forging of clutch wheel. Weights for mechanisms were calculated for characteristic points of the die.

Comparison of predictions and measurements confirmed improvement of the model predictive capability when synergy of the three mechanisms was accounted for.

1 INTRODUCTION

Hot forging processes have a significant role in modern industry. With such processes, it is possible to obtain repetitive final product in a large series, maintaining a short time of single part manufacturing.

A large part of hot forging technology expense is cost of tools used in process. Tools: Dies, punches or holders, are subjected to wear with consecutive forgings. The lifespan of tools used in hot forging is a significant factor determining profitability of the process. During process design, the life of tools is considered to minimize costs resulting from degradation [1]. Engineering software for simulation of plastic processes is usually equipped with one or more tool wear models, starting from simple damage model (e.g. Archard formula), through commonly found formulas like Archard abrasive wear criterion, to complex models involving material structure. By proper identification of mechanisms is it possible to create a hybrid model involving multiple models for different wear mechanisms or to eliminate unwanted interferences from data used in parameter identification process [2]. However, even hybrid approach in simulations is difficult when estimation of wear after thousands of forgings is needed. In such cases, usually simple linear extrapolation is used, ignoring dependencies between different wear mechanisms. Compensating progress of wear by changing physical parameters of tool (e.g. temperature, softening factor, multiplying sliding distance) gives similar result and makes the simulation useful only to predict single aspect of the phenomenon [3]. Repeating simulation to include existing wear in forging cycle requires significant amount of time and computational resources so it is not commonly applied.

The main objective of the present research was to develop a hybrid die wear model in hot forging processes. Such model must include both common wear mechanisms as well as interactions between them and mutual influence of their effects. Wear progression in consecutive forgings with the same die set must be considered as well. A source of data for such model is a finite element simulation. Since FE computations have significant requirements of computational power and are time-consuming, it is important in the model design to minimize amount of FE simulation runs. Although single run of FE computation is preferred, to include effects of already present wear on forging parameters it will be needed to re-run the FE computation to some degree.

2 WEAR MECHANISMS AND THEIR MODELS

Die wear is a phenomenon consisting of multiple mechanisms depending on multiple factors. Moving surface of workpiece along a die under high pressure causes abrasive wear on die surface which is a primary wear factor in the most modelling approaches. Cyclic stresses cause small plastic deformations which become significant in total die degradation in large series of forgings. With consecutive tensile stresses, some regions of die develop mechanical fatigue cracks, while thermal stresses caused by repetitive contact with hot workpiece, then ambient air or lubricant working as coolant cause thermal fatigue cracks. The presence of such cracks accelerates friction-related wear. Additionally in some specific cases in which sliding distance is significantly bigger, inter-metallic joins are created between workpiece and die material. Plastic displacement of such micro-scale joins causes their deformation to the point in which they are removed from the die causing adhesive wear. Although adhesive wear is a mechanism dominant in processes with large sliding distances (e.g. extrusion), there are some specific hot forging process where workpiece expansion on elongated die parts causes some adhesive wear.

To cover multiple wear mechanisms, methods other than typical modelling can be used. It is possible to use artificial neural networks [4] or other metamodelling techniques to include multiple mechanisms. However, such models loose the ability to identify specific wear mechanisms and their physical dependencies, what is an important feature which may be used in die design and design optimization for maximizing die lifespan. Although some expert systems have been developed to predict share of different mechanisms [5], the strict values given by such systems are limited to similar cases to ones which were used to program the system and their principle of operation is based more on programmed cases than physical phenomena.

2.1 Abrasive wear

In practical applications, the abrasive wear model is the most frequently used model for die wear prediction, being implemented in most engineering and simulation tools in different forms. Usually, the Archard model [6] is used for predicting abrasive wear, in most cases including material hardness and friction coefficient.

$$w=\int_0^t C\frac{\mu p v}{HV}dt \tag{1}$$

The material degradation (w) is dependent on normal stress (p), sliding velocity (v, computed as sliding distance), hardness (HV) and friction coefficient (μ). The coefficient C is left for identification as material-specific or process-specific parameter. To take more dependencies into account, it is possible to include additional factors in the formula by making its components dependent on them. For example, the hardness (HV) can be made dependent on temperature, number of forgings, or existing wear. The friction coefficient may also be modified to include changed friction parameters of a worn die surface.

It has been shown in [7] that by dynamically adapting coefficient C it is possible to simulate abrasive wear of a larger forging series using numerical simulation of a single forging. The coefficient has been made dependent on existing wear in the form of a threshold value to cover rapid increase of abrasive wear in the following forgings. This increase can be caused both by either other mechanisms influence on a total degradation or surface properties change with surface layer wearing off, or both.

2.2 Plastic deformation

During series of forgings, the billet causes significant stresses on a die surface. Although single occurrences of these stresses do not cause measurable plastic deformation, during cyclic forgings the wear caused by plastic deformation of a die increases by small values, negligible in single forging. For a quick estimation of plastic deformation influence in different parts of a die, a typical approach in hot forging is to run specifically modified version of process simulations with increased thermal softening parameters [8]. However, this approach requires additional computation only to account for plastic deformation and includes unwanted interference from thermal simulation. To include plastic deformation in a wear model, an extrapolation method based on geometry analysis has been proposed by authors [9].

The principle of operation is based on a quantitative approach, in which amount of volume needed to be moved to cause plastic deformation is analysed. The die geometry is analysed in wear calculation points. First, the track of the small deformation in the first simulation is found and extrapolated mathematically in the die volume. It is important here to use proper extrapolation function. While in many situations it can be linear, in a cases where the die is enclosed in harder deformable casing, the function should be polynomial to include the full amount of material which needs to be moved for plastic deformation to occur. The smaller the amount of material is (represented by smaller length of the extrapolated curve), the more prone the point is to degradation resulting from plastic deformation. This approach can be based on results from any numerical simulation packages.

Result of such calculation shows the points in which the influence of plastic deformation on a total die wear is important. In these points, this type of degradation should be considered and added to the total wear.

2.3 Thermomechanical fatigue

The initiation and propagation of fatigue cracks is an important factor in the die wear prediction. Appearance of fatigue cracks on a die surface accelerates abrasive wear and causes change of material parameters. There are numerous models for fatigue crack prediction, from simple cycle-based equations to complex, multi-scale models involving deep simulation of detailed material parameters. These models, although can give precise result, require significant computational power and proper identification of material parameters [10]. Using representative elements can minimize computation cost, but still requires complex research of the material.

As a compromise between ease of computation and model predictive capabilities, it was decided to compute a micro-scale porosity value in a simulation and then use it to modify macro-scale parameters to account for cracks presence on a die surface. To compute porosity, a modified Oyane criterion has been proposed [11], which is dependent on situation taking place on a die.

$$Vp=\sum_{i=0}^{n} K \frac{p}{\sigma_{eq}} \varepsilon \tag{2}$$

The porosity increase is dependent on hydrostatic pressure (p), equivalent stress (σ_{eq}), equivalent strain (ε) and coefficient K, which K is dependent on the current stress at a die element. If tensile stresses are present (determined by negative hydrostatic pressure over element), the porosity increases by giving a non-negative value of K. However, when compressive stresses are present, it is needed to simulate cracks closing. Thus, the value of K is $KcVp_{i-1}$, where Vp_{i-1} is a previous porosity value and Kc is a model parameter (for identification on the basis of experiments).

An important factor for this model is accuracy of a simulation working as data source for it. In many cases, the edge parts of the die are subjected to mechanical fatigue cracks and proper prediction of cracks in these regions is dependent on stresses. To properly reflect the stresses, the die filling process during forging must be accurately simulated, especially the order of contacting parts of the die by formed workpiece.

For simulation of thermal fatigue, a cycle-based model can be used [12]. In such case the input data for the model will be the value of temperature in current stage of a forging cycle. In practical applications, temperature in a point can be predicted by the following approaches:

a. Repetitive simulation of a full forging cycle, keeping temperature values with a die geometry and passing them between simulation. Although precise, this approach is computationally unfeasible for industrial cycles in with thousands of forgings.

b. Computation of a single thermo-mechanical simulation and then using thermal boundary condition values recorded from simulation to perform consecutive thermal cycle simulations. Such approach is currently used in numerical simulation software [13], but still requires significant computational power and time for larger forging series. Usually this approach is used to compute temperature values until a custom defined steady-state is achieved.

c. Using previously mentioned solution as data source for mathematical extrapolation of temperature values. The amount of thermal computations needed for proper extrapolation is variable, but it is generally proportional to simulation complexity and can be estimated by analysing convergence degree to steady state in consecutive thermal simulation passes. Then, the extreme points of temperature cycles are a base to extrapolation. Having extrapolated functions, the cycle is repeated in the band defined by extrapolated functions, giving a new temperature range and possibility to compute the value of temperature in given forging time. If additional steps are taken during forging cycle (e.g. re-heating of the die) it may be applied using die temperature field computed with this model in form of thermal simulation or, later, as repetitive step.

The downside of this method is high sensitivity to timing errors, as well as easy cumulation of such errors, while differences in process timings are not uncommon in industrial forging.

2.4 Adhesive wear

During hot forging processes, the main component of wear is abrasive. However, the adhesive component can take place in a specific processes where e.g. the workpiece flows through elongated part of a die. In such cases the sliding distance is large enough to cause plastic displacement of die surface where it is connected with billet for longer time.

The adhesive wear can be predicted by using a modified Archard criterion, in which die hardness has been replaced with workpiece hardness and coefficients a,b and c for other factors have been introduced (formula 3) [14]

$$w = \int_0^t C \frac{\mu p^a v^b}{HV^c} dt \tag{3}$$

Because the adhesive wear component is not dominant in most typical hot forging processes, it has not been introduced into hybrid model. However, it is possible to include it in model by modifying Archard equation and introducing the integrated value of sliding distance in a die surface domain. If this value is larger than identified threshold, the parameter switch to the Archard model is executed and the wear is re-calculated using new formula.

3 HYBRID APPROACH

As it was shown in section 2, there are multiple wear mechanisms having impact on a total die wear. The share of various mechanisms varies in different locations of a die and moments of forging. Additionally, each mechanism has influence on other mechanisms. These factors, as well as possibility of applying model to forging in series, have to be considered.

To address these issues, model presented in Figure 1 has been proposed. The main component and data source for the wear model is a FE simulation of a forging process. This simulation works both as a source of the data and way to include existing wear in further computations. The initial process parameters are supplied to FE simulation by the user in a form of project, initial model parameters are supplied in a form of model and field values.

The wear mechanism blocks consist of two models. One computes the material degradation itself while another is responsible for computation of significance of the particular mechanism in total wear in a specific point. Thus, the result is not only the wear value, but also importance of the mechanism in a specific point.

To compute the final wear value (w_{total}), it is needed to join results of all model blocks. It is done by using the following formula:

$$w_{total} = g_a w_a + g_c w_c + g_p w_p \ldots \tag{4}$$

This formula is a weighted sum including all results of abrasive (w_a, g_a), cracks/fatigue (w_c, g_c) and plastic (w_p, g_p) wear mechanism blocks. Additionally, modified material parameters as well as Archard model's coefficients are result of mechanism blocks. As it was previously shown, presence of fatigue cracks accelerated abrasive wear, so it is needed to take it into account.

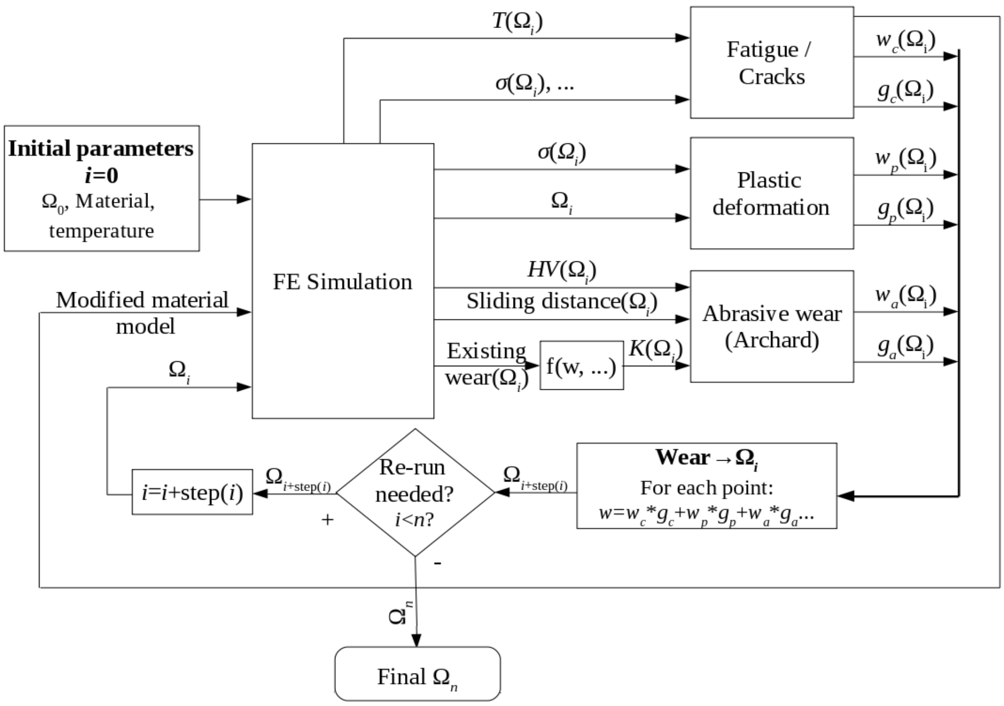

Figure 1: Block diagram of proposed hybrid model

However, majority of the wear mechanisms models have limited extrapolation capability, which is frequently not sufficient for proper estimation of die wear after large series of forgings. Additionally to include result of forging using partially worn dies on simulation results it is important to perform simulation with not only a new die, but also with modified die geometry and parameters reflecting existing wear. This part is implemented by a feedback from wear mechanisms blocks which supplies modified material parameters or corrected Archard model coefficient to the next simulation.

The next simulation represents dies after i+step(i) forgings, with corresponding wear and modified parameters passed from mechanisms models. This way, mutual influence of mechanisms as well as change of operation parameters of process resulting from existing die wear are taken into account.

The process of parameters identification must consist of two parts. First is determining of separate models parameters to compute wear after specific amount of forgings. Then, the second part is identifying the step function to investigate limits of extrapolation of different mechanisms blocks. For this part, a significantly complex process should be used to clearly specify the limits of extrapolation when it is needed to re-run simulation.

After desired number of forgings have been achieved, the algorithm is finished and the final die with wear, as well as with significance values for different mechanisms, is returned.

4 NUMERICAL EXPERIMENT

To verify effectiveness of different models of wear mechanisms and their significance coefficients, FE simulation of an existing process have been used. The simulations have been made in FORGE software package, customized to include additional models outputting data as user-definable fields in mesh, as well as to automate computation and passing modified parameters between program modules. Additionally, a post-processing engine has been developed to automatically read data from result geometry and appropriately modify the input files for another simulation run.

The analysed stage is a second operation in the process of clutch front wheel forging [15]. The entire process consists of 3 operations: Upsetting cylindrical billet in the first operation, then wheel forging, finishing with third operation in which the final shape is completed and the needed holes are made. The billet is made of 20MnCr5 steel while tools are made of WCLV (52HRC after heat treatment). The tool temperature after maintaining steady state was about 250°C. The shape is axisymmetric and is shown in figure 2 as a cross-cut drawing.

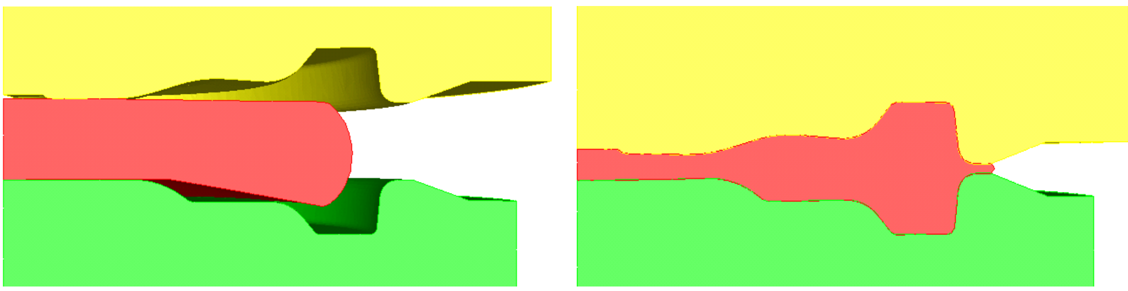

Figure 2: Dies and workpiece alignment at the beginning and near the end of process.

First, the proposed model was used to compute significance of different wear mechanisms in selected points of the die. The points have been chosen by visual analysis of a worn dies to illustrate different wear mechanisms taking place (Figure 3). The evaluation has been made using both inspecting the die and its microphotography.

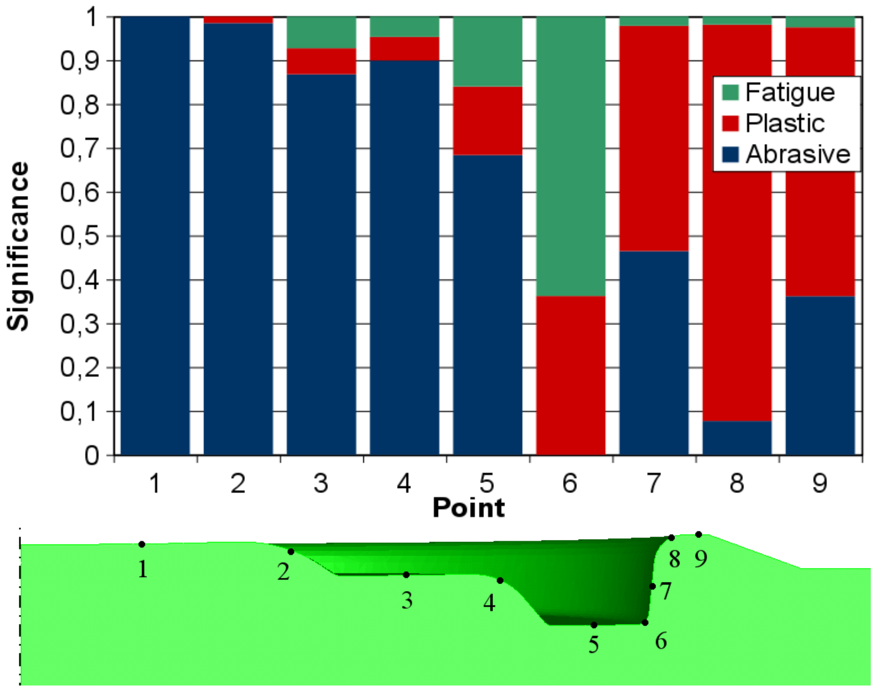

Figure 3: Wear significance values and measurement points at a lower die

Although the position of point 3 suggests that mostly compressive stresses take place there, there is a significant time during each forging in which the workpiece acts compressively on point 4, while not contacting with point 3. Thus, when there is still contact with point 1 (and 2), tensile stresses are created which introduce fatigue cracks and accelerated abrasive wear in this point. Point 6 is prone to fatigue cracking with extreme tensile stresses acting in point 8. These stresses also introduce enough forces to cause the plastic shift of the surface in point 8 in a large series of forgings.

Using obtained result, a complete wear of the die has been calculated and compared with measurements [16] of a die after series of 9500 forgings (figure 4).

It can be seen that, while abrasive wear is a dominant mechanism in most points, including plastic deformation makes results more accurate where friction is not the only mechanism causing degradation (points 5-9). Including fatigue cracks as a wear factor introduced small changes in a total die wear, which could be caused by performed identification of abrasive wear coefficients including the acceleration caused by fatigue.

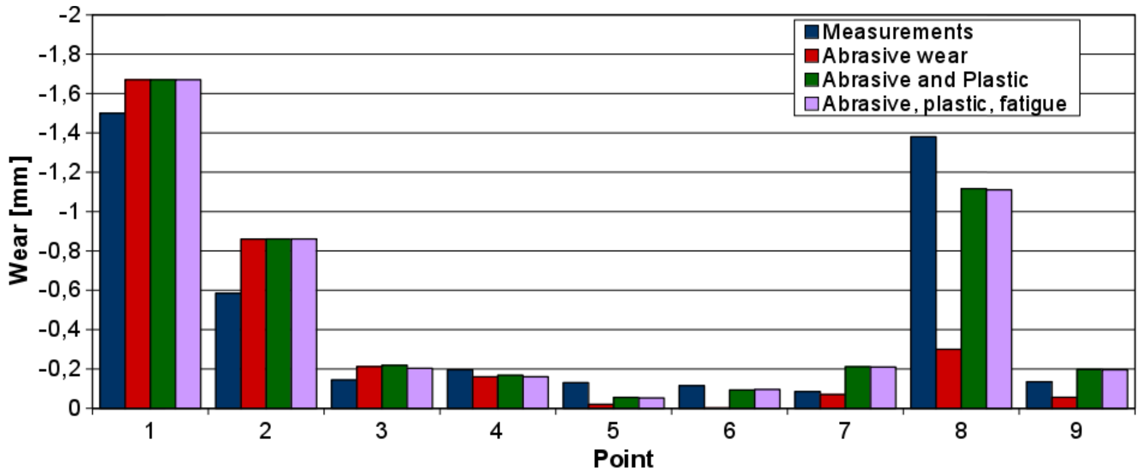

Figure 4: Total wear values of different models compared to measurements in lower die.

5 CONCLUSIONS

It was shown that it is possible to combine various tool wear mechanism models into one hybrid model, capable of predicting both degree of wear as well as significance of specific mechanism in the die region.

By using feedback, it is possible to take into account the total wear after large series of forgings and the influence of using die subjected to wear on work parameters in a hot forging process.

The multi-scale model of mechanical fatigue wear based on porosity calculation allows to predict significance of cracks and locate places vulnerable to crack initiation. However, being based on local stresses this model is sensitive to order of die filling and contact areas, so this part should be included in a simulation precisely.

Further research should include parameters identification methods for mechanism blocks as well as model for feedback parameters generation (e.g. correction of Archard wear coefficient).

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