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AKAPIT

COMPUTER METHODS IN MATERIALS SCIENCE
Informatyka w Technologii Materiałów

Vol. 17, 2017, No. 4

SYNERGETIC APPROACH TO DIE WEAR MODELLING IN HOT FORGING PROCESS

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Abstract

A proposition of the 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, passing modified die geometry and optionally material parameters into the next iteration of die wear modelling. Developed model consists of the FE simulation to which the following process parameters are supplied by the user: wear mechanisms blocks containing adequate models, significance models and extrapolation routines for results or input parameters, component to apply computed wear value as a die geometry and control the computation of 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. Comparison of predictions and measurements confirmed improvement of the model predictive capability when synergy of the three mechanisms was accounted for.

Key words: Hot forging, finite element modelling, die wear, wear mechanisms, synergetic model

1. INTRODUCTION

Hot forging processes have a significant role in the modern industry. Many mechanical components used in consumer, machinery, automotive, aerospace and other applications are manufactured using hot forging processes (Altan, 2004; Kaur, 2016). To maintain quality aspects, process parameters and tooling conditions must be monitored. Especially, dies conditions have significant influence on final product dimensions, determining economic efficiency of the process.

Forging tools wear leads to deterioration of their parameters and, in consequence, to product dimensions falling out of tolerances or even complete failure of the tool making it irreversibly damaged. Thus, it is needed to predict their wear in industrial processes in a way that accounts for multiple wear mechanisms, as well as for large-series production cycles. Computer simulation is a common step in modern design of industrial processes (Chenot et al., 2010). Finite element (FE) application packages are usually used for this task, being a source of data about final workpiece geometry, stresses acting on the material, possibility of folds or interlocks (Andrietti et al., 2015). However, current applications of this tool in the die wear predictions are limited to a single mechanism model, as well as to a single forging, while in the industrial manufacturing processes there are thousands of forgings made with the same tool set (Behrens & Schaefer, 2005). Computing a whole series of forgings with FE package is computationally very expensive, therefore, other methods have to be used to perform extrapolation of

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results. Moreover, the main limitation of the current wear predictions is due to considering a single wear mechanism only. Abrasive wear is the most commonly investigated. Since in an industrial forging process other mechanisms cannot be excluded, their influence has to be accounted for (Gronostajski et al., 2014a). Beyond this, identification of the model parameters has to be performed. Some Authors (Choi et al., 2012) have tried to eliminate one of the wear mechanism from measurements results using a model to obtain wear related to another mechanism, however, it still did not account for all mechanisms synergy and repetitive forging steps. In consecutive processes, wear mechanisms cause new layers of surface to be exposed. In industrial applications, tool surfaces are enhanced in different ways (e.g. by nitriding, etc.) to achieve desired material properties, so layers under enhanced surface have different properties and responses for stresses, friction and temperature. Making wear mechanisms models dependent on existing wear is important to take these changes into account. Tool altered by wear, both degradation to geometry and dimensions, as well as modified material parameters, has different response in parameters and different results are computed for it. This phenomenon has to be included in the model by using repetitions of process simulation as additional step of extrapolation.

Having above comments in mind, a theoretical hybrid tool wear model was proposed in the present paper. It incorporates both models responsible for different die wear mechanisms, as well as extrapolation models for predicting die wear after large series of forgings. The model is based on the FE simulation package as a source of process parameters and data, commonly used in design of forging industrial processes. Additionally, method of parameters identification (coefficients in both models and extrapolation specifications) is proposed.

2. WEAR MECHANISMS AND THEIR MODELS

In a hot forging process, final wear is related to many mechanisms and is a result of many components (Lavtar et al., 2011; Gronostajski et al., 2014a). The progress of the material sliding on the tool surface with large forces causes abrasive wear. Cyclic stresses and temperature changes result in initiation and growth of thermal and mechanical fatigue cracks. In large cycles of forgings die is subjected to cumulative plastic deformation, which changes its geometry. In some edge cases, wear related to surface oxidation has its significance, where oxidized parts of dies are easier to wear off. However, this factor has larger influence in processes other than hot forging.

In current engineering applications, complete tool wear is usually predicted using one model responsible for one wear mechanism, while other mechanisms are either taken into account by identification of coefficients or are ignored by selecting process with the smallest influence of them. Archard (1953) die wear model with the materials constant identified to account for cumulative wear due to various mechanisms is commonly used (Wang et al., 2012). Such identification allows to predict wear in specific conditions, but tends to give larger errors when significance of various wear mechanisms is different. Multi-mechanism approach is rarely used (Abachi et al., 2010). On the other hand, for fast predicting die wear, metamodelling can be applied. Typical method is using artificial neural networks as an adaptable modelling tool. Although properly prepared ANN model can predict wear this way, there is no possibility to acquire exact physical interactions between mechanisms from such model. For identification of particular mechanisms, separate models or expert systems have to be used, see for example (Gronostajski et al., 2016). Wear prediction after large amount of forgings is another problem. Since complex FE computation with die analysis takes significant amount of time and computational resources, it is practically unsuitable to perform large series of such simulations. Typical commonly used approaches include modifications of the die material parameters (softening) or linear extrapolation of wear made after one forging (Marashi et al., 2016). Authors' work (Wilkus et al., 2015), in which material parameter in the Archard model is changed with increasing number of forgings, can be an example of such method. The efficiency of these approaches is limited because wear progress depends in a non-linear scheme on mechanisms' significance and changes parameters of a forging tool.

2.1. Abrasive wear

Abrasive wear, caused by friction taking place between the workpiece and the die, is one of the major phenomenon contributing to the total die wear. In most cases it is predicted using Archard (1953) model adapted to multi-step computation, which makes the total wear depth (*w*) dependent on normal stress (*p*), sliding distance or slip velocity

(v), die hardness (HV) and friction coefficient (μ), as well as identifiable parameter C, according to the formula:

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

Although in some approaches even more simplified versions of this model are used, which include hardness as part of identified coefficient (Neupane & Farhat, 2015), hardness is still an important factor to consider. However, this model in its base form does not take into account the change of parameters with increasing die wear. In repetitive forgings performed with the same dies set, like in industrial processes, wear progresses into surface deep enough to change its parameters. Methods to solve this problem involve making parameters dependent on other factors accessible from simulation: Temperature (Lee & Jou, 2003), number of forgings, contact time (Kang et al., 1998) or even "wall" time (Behrens & Schaefer, 2005). In the Archard model, parameter C can be dependent on existing computation results. During series of forgings, when surface changes its properties, both hardness and C coefficient change. It has been previously shown that it is possible to predict the abrasive wear on the larger series of forgings by using adaptive coefficient (Wilkus et al., 2015) with non-linear dependency on existing wear. The computation was performed during forging simulation or in post-processing and using existing wear (from previous steps) and a new deterioration increment in each solving step was computed. It is also possible to make the coefficient dependent on a number of forgings (when simulating series) or temperature (if hardness HV cannot be made dependent on it).

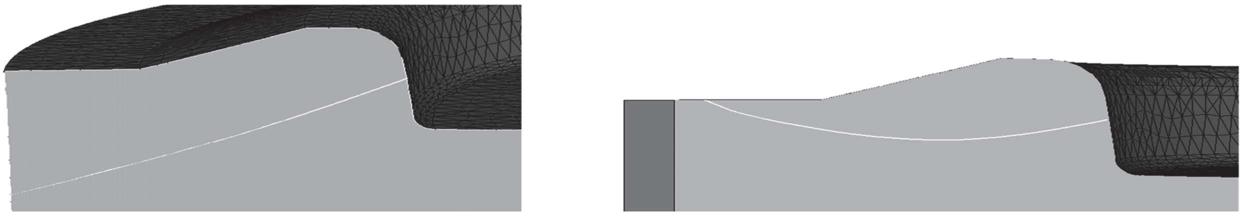


Fig. 1. Plastic deformation measurement line, the result of the extrapolation algorithm in (a) separate die, (b) die in a non-deformable casing.

2.2. Plastic deformation

Although in a single forging pass plastic deformation is minimal, in a large cycles it becomes a significant component of the die wear, in some cases being the secondary cause of the die failure (Chen, 2013). Dimensions degradation related to plastic deformation increases non-uniformly by small increments in each cycle. Measuring of only plastic deformation significance in a die is difficult as other wear mechanisms are also present. In the paper Choi et al., 2012, by selecting the specific industrial process and cancelling abrasive wear out by subtracting Archard model results from measurements, reliable data sufficient enough to be fed into metamodel were acquired. The complete prediction of the die plastic deformation can be performed with a series of FE computations (Groseclose, 2010), but this approach requires long computation times and is not feasible for a high number of forgings (e.g. 10 000 forgings).

During die design, plastic influences are minimized by properly locating openings on a die surface to have larger amount of material in places, in which plastic deformation occurs (Diko, 1992). This concept can be used in the finite element analysis as a simple, quantitative model for estimating of both significance and value of wear related to plastic deformation in a series of forgings. First, the cross-cut of a small deformation present after single simulation is found and the deformation is used for linear extrapolation until the line reaches the wedge of a die. The length of the extrapolated line in the die volume is inversely proportional to plastic deformation in an analysed point. Normalized coefficients are used for estimating impact of plastic deformation on the die wear. If a die is completely open on its sides, linear extrapolation can be used. Contrary, if the die is in harder-deformable casing, polynomial or composite-function extrapolation has to be used (figure 1). This approach was applied as a part of the synergic model in the present work. For the current implementation, a constitutive equation from FE package was used (Norton-Hoff).

2.3. Fatigue cracks

Thermomechanical fatigue is another important factor in die wear prediction. Cracks initiation and propagation are caused by both repetitive temperature changes as well as cyclic stresses on a die

(Lavtar, 2011). Finite element modelling allows to predict single crack growth in the multiple cycles (Osipov, 2017), however, for a simple one-dimensional stresses it is computationally expensive. Beyond this, repetitive computation becomes too complex when stress distribution is multiplied, e.g. while billet is formed on a die. Despite these limitations, existing models combined with extrapolated input data can predict fatigue wear.

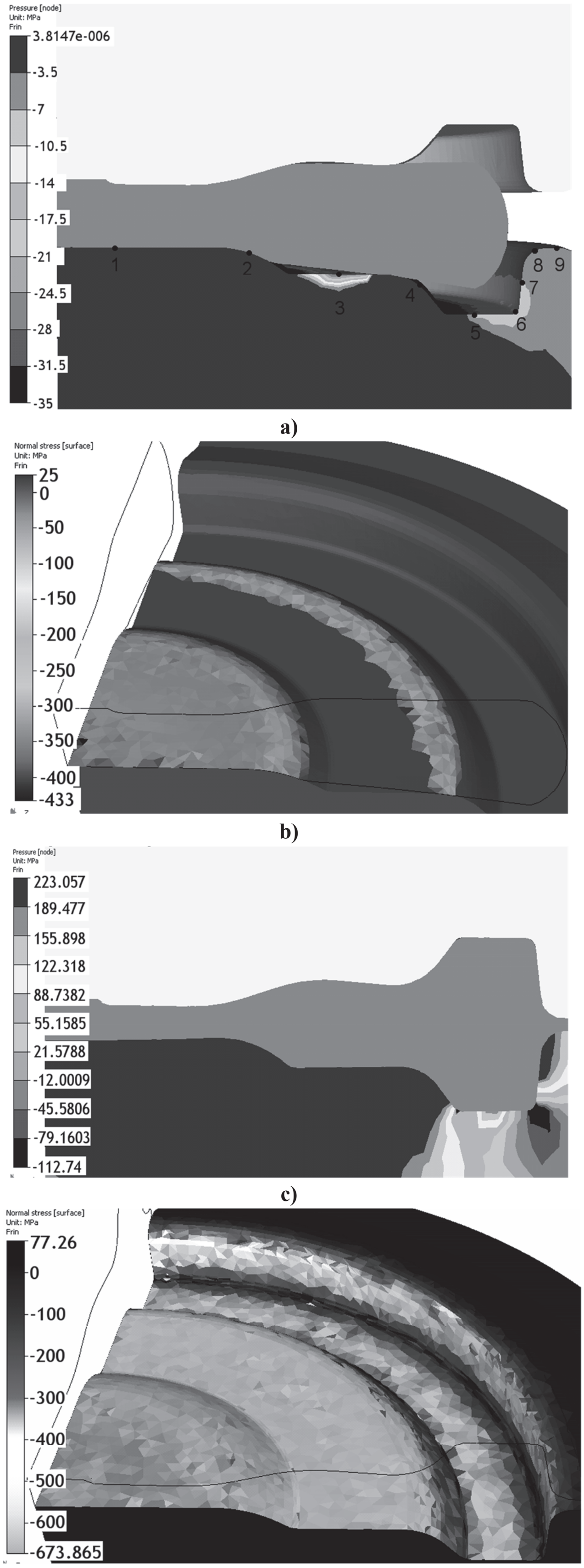
To maintain dependencies between other wear models, the influence of cracks presence on material parameters should be included. It can be achieved with voids-based approach, in which tensile forces cause increase of the porosity. A modified version of Oyane (1980) model, which indirectly includes porosity changes by pressure classification can be used, as shown in the following formula:

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

where: p – hydrostatic pressure, σ_{eq} – equivalent stress, ε – equivalent strain. Coefficient K is dependent on behaviour of stresses in a selected point:

- if hydrostatic pressure is negative (tensile stresses), the coefficient K is a constant parameter determining porosity and cracks growth,
- if pressure is positive (compression forces), its value is $KcVp_{i\text{-}1}$, where $Vp_{i\text{-}1}$ is a previous value and Kc is a parameter (for identification with processes). This way, it is possible to compensate existing porosity for compressive stresses, what corresponds to closing of cracks when compression is acting on a die part.

A second operation in the process described in (Gronostajski et al., 2014b) was used for comparing the fractures. Numerical tests described in the paper were performed for the lower die in the second operation in forging of a clutch wheel, described by Gronostajski et al. (2016). The whole investigated process was carried out in three progressive operations: i) upsetting, ii) blocking forging and iii) finishing forging. The initial temperature of the billet was 1150°C. The tools in the investigated second operation were lubricated by suspension of graphite, therefore, the temperature of tools was 250°C. The lower die with the marked points of interest is shown in figure 2. During the process, two interesting moments have been noticed.



a)

b)

c)

d)

Fig. 2. *Contacts leading to cracks initiation according to pressure model for stage 1 (a, b) and 2 (c, d) with pressure values (left) and normal stress values (right).*

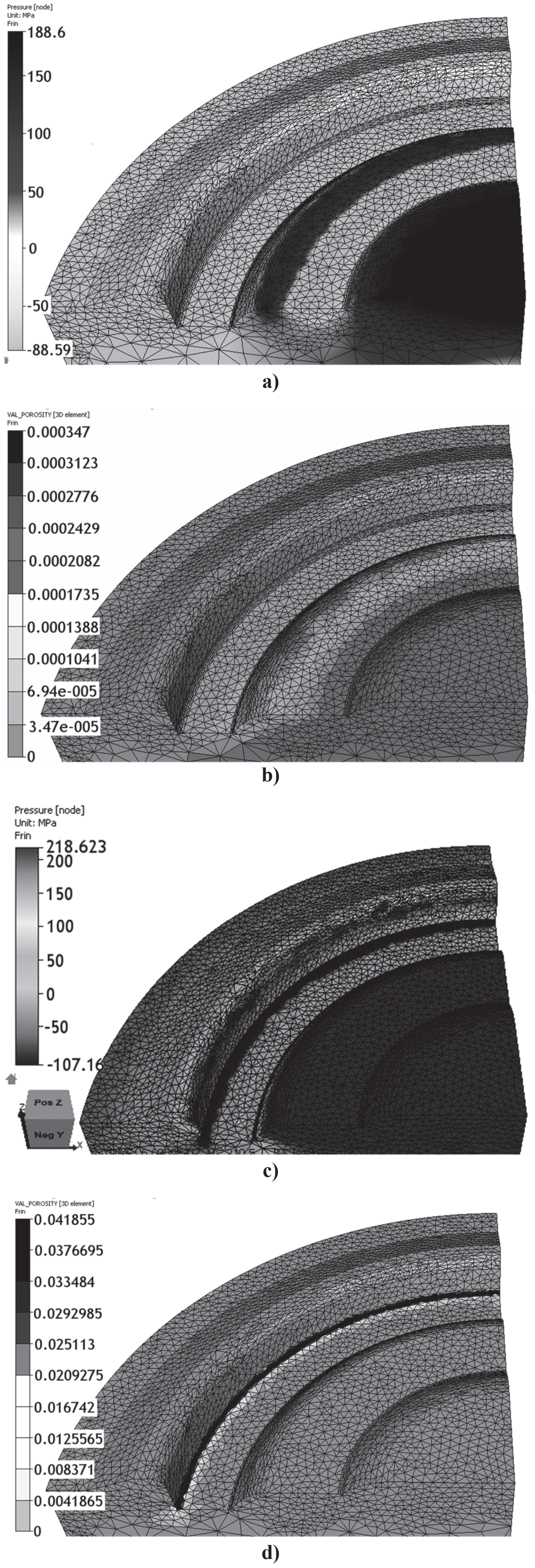


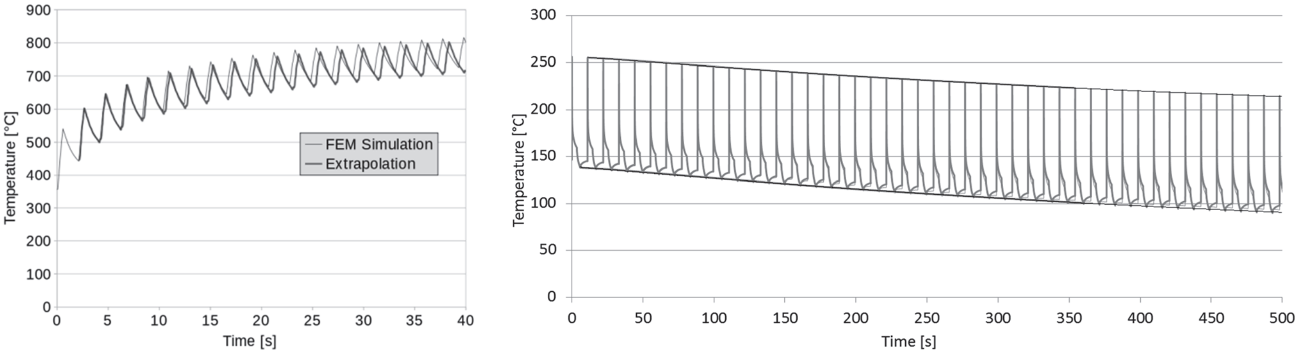
Fig. 3. *Pressure (left) and porosity (right) values from numerical simulation with proposed model in stage 1 (a, b) and 2 (c, d).*

The initial results with pressure values diagrams (for indicating places where compressive and tensile stresses act) are shown in figure 3a. The pressure has been chosen because it is an input data to fatigue model. There are two significant stages during forging. In the middle of the process, the edge of billet pressed the die causing tensile stresses in parts closer to the centre. It resulted in smaller fracture on the surface, see figure 3b. By the end of the process, pressure of the billet causes tensile stresses acting perpendicularly to the die vertical part, leading to a growth of the crack in this area (figure 3d).

For a thermal cracks model, a typical method of acquiring temperature information in large series of forgings is a 2-step steady-state simulation. First, an initial complete thermomechanical simulation is performed, while thermal boundary conditions are stored for each increment. After first computation, the next step is computed only thermally, with thermal boundary conditions re-applied to a die mesh desired number of times. This way, any number of cycles is computed faster than the first one. Thermomechanical computation and temperatures can be used as an input data for other wear mechanisms models (Andrietti et al., 2014). However, this approach still requires significant computational power with large amount of forgings while supplying function, which is easy to mathematically extrapolate. In the present paper the solution with 3 thermal steady-state steps was proposed:

1. First, a complete thermomechanical simulation is performed.
2. Thermal boundary conditions from simulation are re-applied into the die. This way, first few thermal cycles can be calculated with small computational effort.
3. When thermal changes of a few cycles are known, it is possible to find its characteristic points (in simple curves – minimum and maximum) and to extrapolate them by typical mathematical methods (e.g. polynomial extrapolation, logarithmic or composite curve fitting, etc.). In this way the cycle is modulated what allows to estimate quickly thermal steady state with complete temperature changes in time.

A typical result of such extrapolation for a single point of a die is presented in figure 4, for two forging processes in which tooling thermal behaviour is different. Figure 4a shows a simple heating-up die reaching a steady state, extrapolated from 5 numerical simulations (1 thermomechanical, 4 thermal). While computing a steady state from more complex process, like one with immediate air cooling followed by lubricating solution cooling applied by spraying between passes, then lubricant vaporizing and air-cooling again, more thermal simulations (even 30) have to be performed (figure 4b). Simulation of this process has been started with pre-heated die, so the temperature drop can be observed. The exact number of simulations needed to perform properly the extrapolation is found by comparing the result of extrapolation with result of additional simulations. If the error is significant, more thermal simulations have to be included in extrapolation to minimize the error value. Simulations and comparing procedure are repeated until the error becomes acceptable.



a) b)

Fig. 4. *Extrapolation of thermal steady-state of a simple heating-up die (a) and a complex process with pre-heated die (b).*

It is worth noting that these values are computed quickly enough to be supplied to any chosen thermal cracks model. Using this method it is possible to predict a complete thermal cycles in any point in a time domain. The only important thing to maintain is the process timing in simulation, which is critical for proper prediction of thermal steady state in any algorithm (Liu, 2007). It should be mentioned that it is still possible to use other modelling methods in which different material characteristics and phenomena for stress and thermal cycles are applied. Although computationally expensive, the multi-scale approach is a solution which illustrates microstructural changes and resulting change of material parameters of the solid (Rauch et al., 2016). It can be implemented using cellular automata reflecting microstructural state as well as e.g. geometry-based methods in which FE is computed on microstructure element. Because complete geometry cannot be modeled this way, usually a representative volume element is used to illustrate general behaviour of material. Although this approach speeds the microstructural computation up, it is still not feasible for typical design workflows. Identification of parameters for such models is difficult and requires complex material measurements to acquire initial microstructure (e.g. grain layers analysis) and its properties (e.g. mechanical properties of different components).

3. SYNERGY OF WEAR MECHANISMS

The analysis of factors, cumulative wear of which is mutually dependent, shows that all mechanisms influence each other in some extent. Material loss caused by abrasive wear have influence on the changes of stress enough to change behaviour of cracks initiation and growth, as well as influence on forces acting on the die by the deformed workpiece. This modifies plastic deformation of a die. Reversely, plastic deformation causes geometry changes which influence sliding distance for abrasive wear, and thermomechanical fatigue influence change of material parameters which affects both abrasive and plastic component. By plastic deformations acting with pressure, fatigue cracks may close where compressive stresses are present. When total degradation of a die progresses in depth, the enriched layer wears out changing surface properties significantly (figure 5). To cover these dependencies, the hybrid die wear model must include not only particular mechanisms degradation values, but also significance of each mechanism and the mutual relation between them. Significance models have to be computed for a surface domain and their results are decision factors in various models applications. Additionally, to include material parameters change, modified material parameters should be taken into account by a feedback, passing modified die geometry and optionally material parameters into the next iteration i.e. after some extrapolated number of forgings.

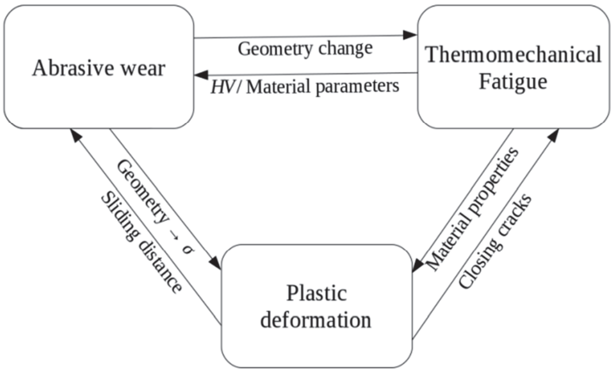


Fig. 5. *Simplified scheme of dependencies between wear mechanisms.*

wear mechanisms blocks, containing both mechanisms models, significance models and extrapolation routines for results or input parameters (dependent on a selected model), component to apply computed wear value as a die geometry and control the computation of multi-iteration wear prediction. Some mechanisms blocks must contain additional components for computing, e.g. correction of surface material parameters altered by thermomechanical fatigue, cracks or increased porosity.

Thus, the flow of calculations is following:

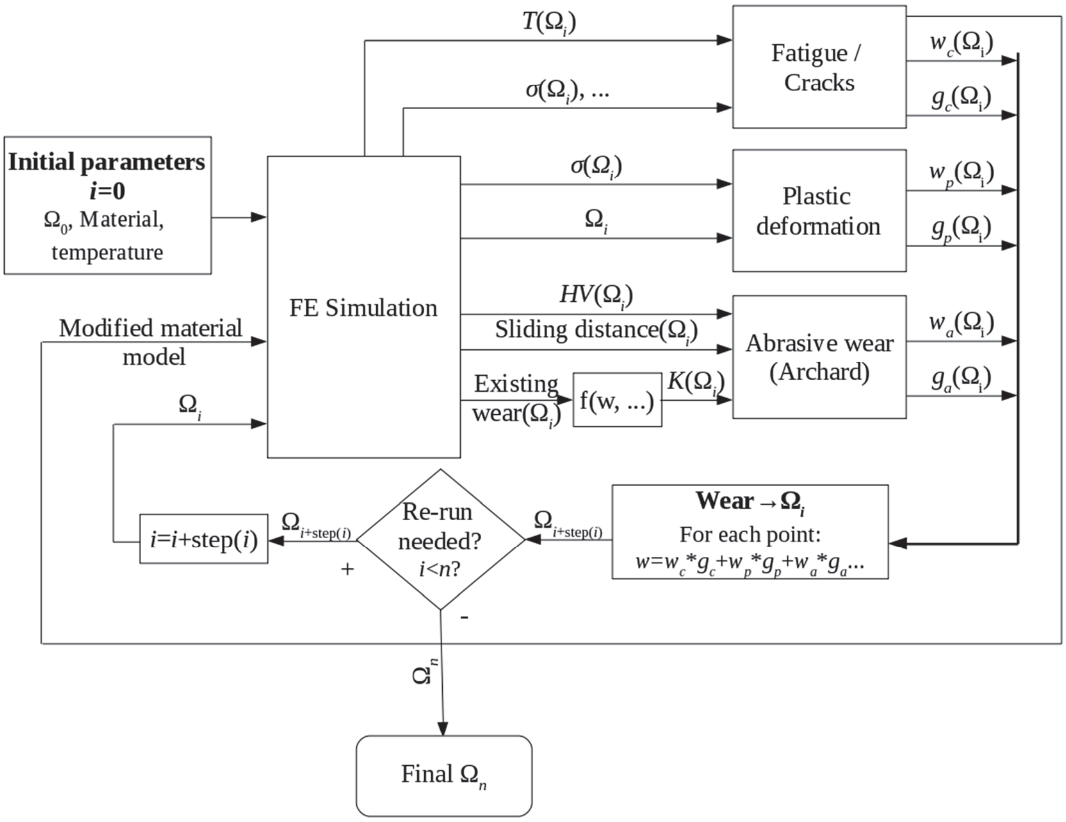


Fig. 6. *Schematic illustration of the hybrid model with extrapolation and feedback.*

4. HYBRID MODEL INCLUDING SERIES OF FORGINGS

The main idea of the model is based on a fact that multiple wear mechanisms have to be predicted using multiple models. Additionally, multiple forging cycles should be estimated using extrapolation method when possible, not repeating every simulation in n-forgings cycle, which would be time and resource consuming. Schematic illustration of the model with extrapolation and feedback is shown in figure 6. The model consists of the FE simulation to which process parameters are supplied by the user,

1. The process parameters, amount of forgings in series, complete die geometry and models coefficients are fed to FE simulation to acquire first results corresponding to wear on the new die.
2. The FE simulation is computed. Its results are passed to different wear mechanisms models.
3. Wear components: depths as well as their weight values, are calculated using different models:
3a. To compute abrasive wear, sliding distance and hardness (*HV*) is acquired from simulation results by abrasive wear block. Existing die wear (computed as dimension difference between new and used die) is acquired too. Coefficient *K* for Archard's model is calculated from existing wear and possibly other

factors acquired from computation using a separate function as shown in (Wilkus et al., 2015) to take first *i* forgings into account. As the result, wear values and weights for different points are obtained.

3b. Plastic deformation is also computed in a similar way, using model with geometry analysis, so both stresses and whole geometry containing strains is passed into model. The deformation path is extrapolated on die's cross-cut and stresses are used to compute both wear related to plastic deformation after cycles as well as significance of this mechanism in each point. These are components for wear depth calculation.

3c. Thermomechanical cracks initiation, propagation and wear model is computed from results of simulation and additional extrapolation algorithms. During the first forgings, temperature cycles may reach, or may be reaching thermal steady state. It is also needed to compute extrapolated thermal cycles as it was shown in section 2.3. The cracks function supplies wear geometry, significance, and modified material parameters are the result of cracks progression as well as change of surface parameters. Passing of material parameters allows to include the influence of thermomechanical fatigue mechanism on the other considered wear mechanisms.

4. Composite wear is finally computed from its components by using weights which are result of mechanism model blocks (Formula 3). As it was shown in (Wilkus et al., 2016), weight values are estimated for each point as wear values, apply them as global coefficients (what is common in engineering practice) gives worse fit to measurements. Using weighted average instead of straight sum for the wear components, more mutual dependencies between mechanisms are taken into account and some mechanisms can be minimized and compensated by another mechanism just by computed weight coefficient:

$$w_{total} = g_a w_a + g_c w_c + g_p w_p \ldots \tag{3}$$

where: w_{total} – total wear, w_a – abrasive wear value, g_a – abrasive wear significance, w_c – cracks or fatigue-related wear, g_c – significance of cracks/fatigue-related wear, w_p – plastic displacement wear, g_p – significance of plastic displacement-related wear.

5. Then, the wear is held as a scalar (to include existing wear in next computations) as well as modified die solid. Modified geometry contains wear after performed number of forgings. To this step, the prediction made by model does not correspond for any existing wear influence which can be included in FE simulation because a new die was initially introduced. Thus, it is necessary to provide feedback for at least taking into account these dependencies.

6. Since prediction of a large series of forgings by using one forging simulation is not accurate, the result of prediction, in form of die geometry, correction to its material parameters and temperature/residual stresses distribution is feedback to the simulation to perform calculation of wear after *i+step* forgings. Then wear computation and extrapolation after next part of series is performed until *i* finally reaches target number of forgings *n*. Because the behaviour of surface and its parameters in domain of forgings count is not linear, *step* may be a constant value or function dependent on e.g. existing number of forgings. The obtained simulation can be performed again, and another part of series is extrapolated using the models. If target number of cycles is reached, further re-computation is not needed and final wear of a die is the result.

5. PARAMETERS IDENTIFICATION

Since models included in hybrid approach are commonly applied in prediction of particular mechanisms, identification of their parameters was performed with classic identification method based on comparison of predictions to geometry measurements performed for selected specific numbers of forgings. This is the first step of identification in hybrid model approach and it has to be conducted by comparison with measurements. However, since various mechanisms are separated in the model, identification should guarantee that including additional mechanisms in the considered one is avoided. Thus, forging processes used in the identification should be chosen that way that at least in some important points the significance of the identified mechanism is dominant.

The second part is the identification of extrapolation parameters, both globally and in the individual models. During step increment identification, the result is compared to measurements of a complex die after specific number of forgings. Following this, if needed, the forgings step is decreased and simulation is rerun with modified geometry and material properties to achieve acceptable extrapolation accuracy. This method allows to identify an optimal forging step for a complex die. Usually, for more complex dies the finer step increments will be identified, which in simpler dies will allow to achieve at least the same accuracy of final results.

the porosity-based model one can conclude that the model accounts for mechanical fatigue on the surface analysis.

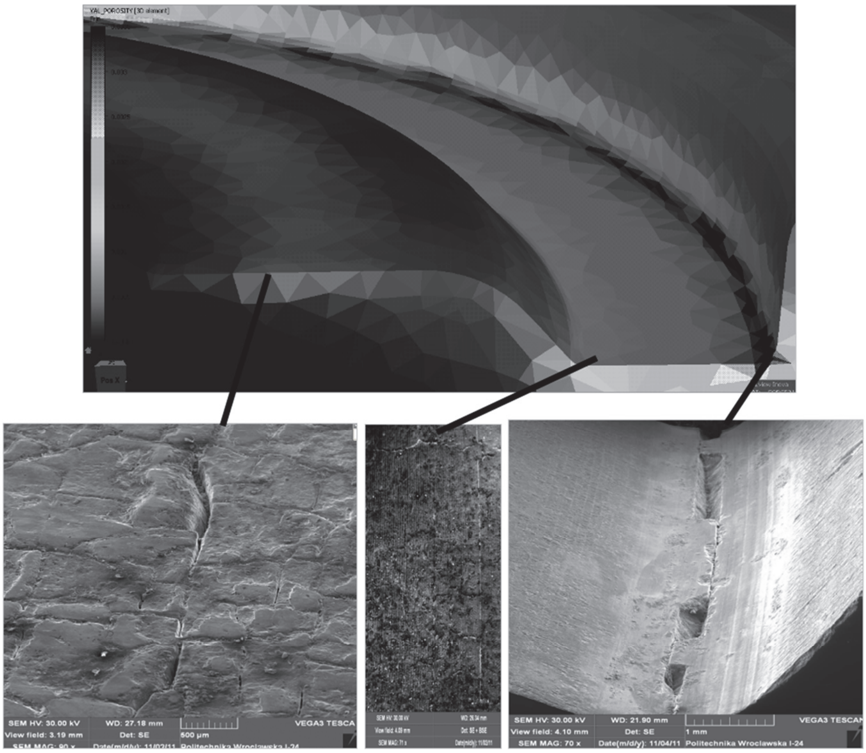


Fig. 7. *Comparison between porosity model results and microphotography of a die after 9500 forgings.*

The measurements have to be performed including not only geometry change, but also direct and indirect results of thermomechanical fatigue. The process analysed in this paper was measured with surface scanning (Gronostajski et al., 2011), what allowed to evaluate general wear by subtracting results from a new die dimensions. However, since resolution of surface scanning often is not sufficient for cracks, augmenting with other physical analyses was needed to get details of surface shape (Danzl et al., 2011). This situation, shown in figure 7, makes the material parameter feedback essential to include influence of cracks on the total wear measured with means. In some points (e.g. point 6 in figure 3) only degradation resulting from fatigue was taken into account to the next step of computation. In the points, in which two mechanisms occur (e.g. point 8 in figure 3) eliminating one of the mechanism in the identification step makes this procedure more reliable, but more complex.

As it was shown in (Wilkus et al., 2016), the two-factor results computed including both abrasive wear and plastic deformation are mostly coherent with scan-based measurements. However, with comparison of the surface microphotography after 9500 forgings shown in figure 7 and predictions of

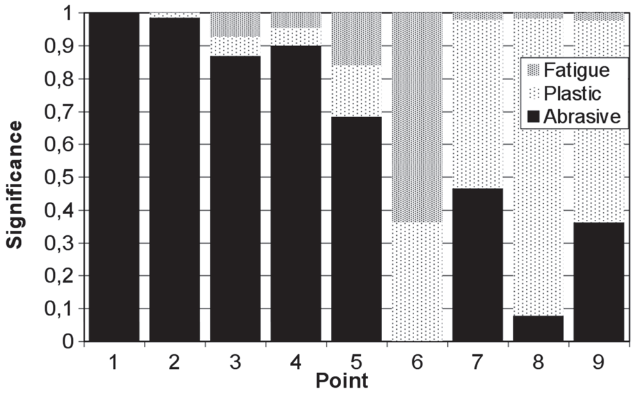


Fig. 8. *Significance values for abrasive wear, plastic deformation and mechanical fatigue in measurement points of a die.*

Existing cracks are located in places of significant tensile stresses. As it was shown in pressure and porosity visualizations, these cracks are present in places predicted by the model described in section 2.2 with literature-based coefficients (Simionato et al., 2008). Additionally, the significance factors for mechanical fatigue were computed using the minimum value of negative hydrostatic pressure as a rough measure of crack initiation in material (scaled to 0…1 relatively to the minimal pressure of the die during single forging), which is presented in figure 8. Significance coefficients for plastic mechanism determined with method described in paragraph 2.2 as well as abrasive wear significance values determined for this process, are also shown in figure 8.

Using these values as weight coefficients and existing computation, a total die wear was computed and compared to measurements and the results of earlier versions of the model. It can be seen in figure 9 that there are no significant differences in most points except for point 6, in which the fatigue-related damage exceeded measurement values. It can also be the result of including the fatigue-related wear (caused by e.g. easier degradation of cracked surface) in Archard wear identification step, where a full scan of the die was used. In consequence, the fatigue-related wear was compensated in abrasive model in that specific case, but it may not be sufficient in other processes where significances of mechanisms are different.

tion depth values and methods for computing significance values for various wear mechanisms, dependencies between these mechanisms could be included in model.

Identification of parameters for individual mechanism should be performed separately for each block. Since including effects of other mechanism in the considered block may degrade prediction accuracy, it is critical to separate mechanisms in experiments used to identify models parameters. The processes to identify parameters for a single mechanism in the hybrid wear model must be selected that way that no other mechanisms (or mechanisms easy to predict) are present. This requires analysis of multiple processes or complex design of the experiment and it will be the subject of the future works.

Identification of the step increment parameter of hybrid model was performed using known process with complex geometry and different mechanisms taking place. The parameter identified became sufficient for other cases, in which simpler die designs and mechanisms distributions occurred.

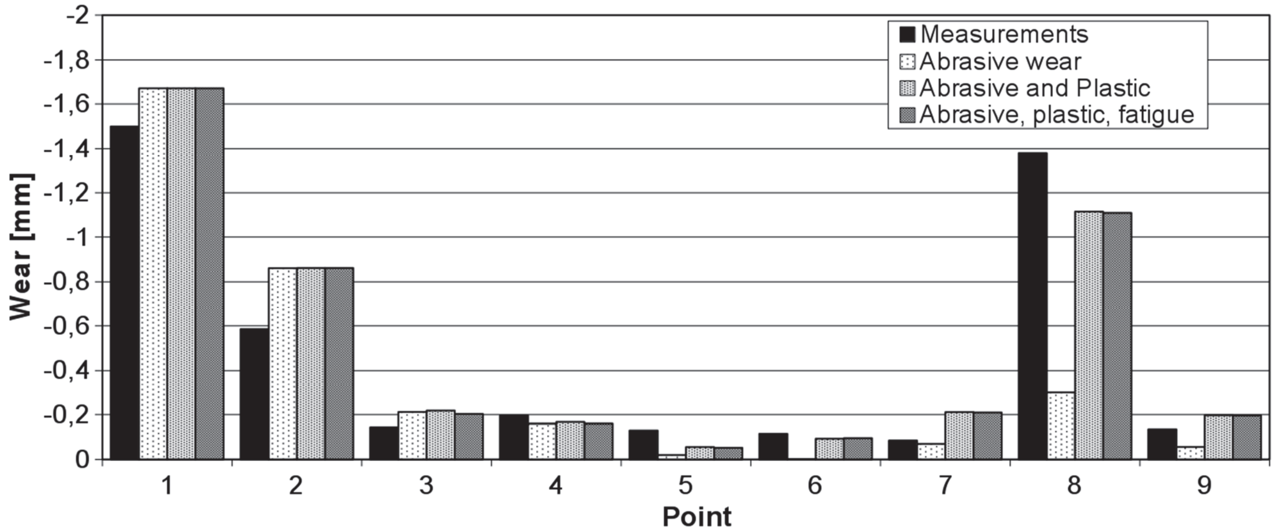


Fig. 9. *Comparison of the measurement of the total wear in points shown in figure 2 with calculations using various upgrades of the hybrid model.*

6. CONCLUSIONS

It was shown in the paper that it is possible to combine different wear mechanisms in a one hybrid model, which can be used for a larger series of forgings. By dividing the series into steps, it is theoretically possible to minimize computationally expensive FE simulations and maximize its use as information source for die wear models in large series of forgings. This way, repetitive performing of simulation is applied only to include existing wear and modified material parameters into computation of the next step. By using joining function for degrada-

Performed analysis and results of simulations allowed to draw the following conclusions:

- Synergetic approach to wear prediction may be done using different models when proper separation and significance evaluation techniques are used.
- Computationally, this approach is more efficient than many multi-scale methods and may be used instead if identification of parameters for multiscale models is difficult. This approach can point to dominant mechanisms in different

points of analysed tool, which can be later used e.g. in optimization.
- Simulating tool degradation in large series of forgings using existing models is difficult and computationally expensive. By using various extrapolation methods, both purely mathematical or based on FE components, can reduce this time by reducing the number and complexity of computations.
- As it was shown in mechanical fatigue analysis, non-linear physical dependency in pressure-related significance values should be considered.

Further research should additionally include developing a complete three models synergy by including parameters modification (e.g. by material model feedback), as well as methods for mechanisms separation enough to identify parameters precisely and filter out the results from other mechanisms.

ACKNOWLEDGEMENTS

Financial assistance of AGH project no 11.11.110.291 is acknowledged.

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SYNERGETYCZNE PODEJŚCIE DO MODELOWANIA ZUŻYCIA NARZĘDZI W PROCESIE KUCIA NA GORĄCO

Streszczenie

W pracy opisano hybrydowy model zużycia narzędzi w procesie kucia na gorąco. Idea modelu bazuje na rozróżnieniu mechanizmów degradacji narzędzi i ocenie ich wpływu na siebie. Analiza czynników, których sumaryczne zużycie jest wzajemnie zależne, wykazała, że wszystkie mechanizmy wpływają na siebie. Aby to wziąć pod uwagę, opracowano hybrydowy model uwzględniający istotność każdego z mechanizmów oraz ich synergię. Dodatkowo uwzględniono zmianę własności materiału narzędzia w czasie kucia kolejnych odkuwek. Zrealizowano to poprzez sprzężenie zwrotne przekazujące nowy kształt narzędzia i własności materiału do następnej iteracji. Opracowany model obejmuje symulację metodą elementów skończonych z następującymi parametrami wprowadzanymi przez użytkownika: blok mechanizmów zużycia zawierający odpowiednie modele, procedury ekstrapolacji dla parametrów wejściowych i wyjściowych, modele istotności, komponenty przeliczające zużycie na kształt narzędzia oraz blok sterowania iteracyjnymi obliczeniami zużycia. Niektóre bloki dla mechanizmów zużycia zawierają dodatkowe składniki pozwalające korygować parametrów powierzchni uwzględniając wpływ termomechanicznego zmęczenia, mikropęknięć i wzrostu porowatości. Numeryczne testy modelu zostały przeprowadzone dla drugiej operacji kucia koła czołowego sprzęgła. Porównanie wyników obliczeń i pomiarów potwierdziło poprawę dokładności kiedy zastosowano model uwzględniający synergię trzech mechanizmów.

Received: 23.10.2017
Received in a revised form: 11.11.2017
Accepted: 13.12.2017