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EVALUATION OF ADHESIVE WEAR MECHANISM FOR APPLICATION IN HYBRID TOOL WEAR MODEL IN HOT FORGING PROCESS

In hot forging process, tool life is an important factor which influences the economy of production. Wear mechanisms in these processes are dependent on each other, so modeling of them is a difficult problem. The present research is focused on development of a hybrid tool wear model for hot forging processes and evaluation of adding adhesive mechanism component to this model. Although adhesive wear is dominant in cases, in which sliding distances are large, there is a group of hot forging processes, in which adhesion is an important factor in specific tool parts. In the paper, a proposed hybrid tool wear model has been described and various adhesive wear models have been reviewed. The feasible model has been chosen, adapted and implemented. It has been shown that adding adhesive wear model increases predictive capabilities of the global hybrid tool wear model as far as characteristic hot forging processes is considered.

Keywords: tool wear, adhesion, forging, wear mechanisms, synergetic model

1. Introduction

Tool life prediction is an important factor deciding about economy and affordability of the process in practical design of hot forging technology. Tool wear is a complex phenomenon, which includes numerous mechanisms dependent not only on process parameters, but also on each other, making prediction of total wear after series of forgings more complex [1]. As number of forgings increases, different effects take place on the die and wear changes its characteristics. Presence of some wear mechanisms accelerates or decelerates progress of another mechanism-related wear. Additionally, lack of other mechanisms often allows to increase degradation, which would not happen otherwise (e.g. accumulation of oxides in an area which is not repeatedly worn by abrasion). During wear progress, surface parameters and characteristics change too, in both its geometry and micro-geometry, as well as in physical properties.

In implementations, mostly in engineering software, a typical approach with a single mechanism model is used. With this method it is possible to predict, in the entire die, degradation caused by that single dominant mechanism. However, additional degradation change caused by other mechanisms, directly or by influencing the discussed former mechanism, has to be taken into account in a majority of hot forging processes. Usually, material or process-related parameters are identified using experimental processes with similar wear mechanisms. It allows to compensate indirectly for existing other mechanisms and to add a correction factor to the model. Such an approach does not allow to generalize the results and makes models less useful in applications to other kinds of processes with different dominant mechanisms. In consequence, it is needed to identify parameters of the model again, what is a costly operation. Problem of an application of the tool wear model to large number of forging is another important issue. Since the model has to be connected with the software (usually finite element – FE), which predicts strains, stresses and temperatures at the contact surface, simulations cannot be repeated several times. It would lead to unacceptable costs of the simulations. Thus, it can be concluded here that an effective and reliable wear model should account for the synergy of various wear mechanisms and should be easily extrapolated to a large number of repetitive forging steps.

Problem of tool wear in hot forging is addressed in numerous publications. The Archard formula [2] is the most frequently used model for prediction of abrasive wear:

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

where: w – wear depth in mm, C – model coefficient, HV – tool hardness, p – normal stress, v – sliding velocity, μ – friction coefficient.

The main idea of this model is based on sliding contact observation, in which the resulting abrasive degradation is deeper if the normal pressure of contacting surfaces and distance of sliding while in contact are larger. The original derivation of the model was based on hemispherical irregularities. A tool material hardness is the main factor determining resistance for

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abrasion. Some modifications of the Archard formula include additional dependencies available from simulations, for which they have been implemented for, such as friction coefficient [3] or hardness ratio [4].

Analysis of the literature on the die wear in hot forging shows that equation (1) is used in a majority of publications, eg. [4-6]. It means that either the abrasive wear mechanism only is considered [7] or other mechanism are accounted for by corrections of the coefficient C in equation (1). When the latter is the issue, typical examples of research focused on investigation of a single mechanism include those dealing with the fatigue cracking [8], adhesive wear [9] and oxidation [10,11]. There is a number of valuable papers showing various mechanisms of tool deterioration [1,3,12] but these papers are limited to an experimental investigation and, although they supply good physical basis for building the models, they themselves do not propose such predictive model.

Few researchers accounted for the hardness evolution in equation (1) due thermal effect [13] or due to progress of the wear in previous operations [14,15]. Some Authors [16] 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 allow to account for the synergy of all mechanisms and for repetitive forging steps.

To use formula (1) in wear prediction for a series of forgings, it is needed to add extrapolative capabilities to it. It can be done by including hardness dependency on wear depth, temperature or number of forgings, as well as making coefficient C dependent on existing wear depth [14]. Thus, by successfully integrating consecutive steps, the wear after larger number of forgings is calculated as:

$$w = \int_0^t C\left(w_{prev}\right) \frac{\mu p v}{HV\left(w_{prev}\right)} dt \tag{2}$$

where: C – model coefficient, HV – tool hardness, p – normal stress, v – sliding velocity, μ – friction coefficient, w_{prev} – existing wear.

For such model, identification of hardness (based on measurements) and C coefficient evolution has to be performed. After verification of dominant mechanisms in a specific process, it is possible to include wear caused by another mechanism by modifying Archard formula, however, it decreases the accuracy and reliability of predictions when other dominant mechanisms are present. To predict other mechanisms and separate them from each other, another mechanism models have to be used.

The models based on artificial intelligence should be mentioned as effective alternative modelling methods [17,18]. However, although they give promising results in tool wear predictions, they do not have physical background and their contribution to understanding of various phenomena involved in die wear is limited.

The objectives of the present paper were formulated with the above comments in mind. As it has been shown, the majority or published works deal with various mechanisms of wear separately and there is a need to develop a hybrid tool wear model which includes multiple wear mechanisms. To reach this goal it is needed to evaluate the importance of each mechanism and to include this mechanism into the hybrid model with an adequate weight. Finally, it is also important to maintain possibility to extrapolate results into large series of forgings and not only obtain a total wear value, but also obtain results classified by various mechanisms. Such results may be used in the future to aid the tool design process. The particular goal of the present research was to evaluate possibility to add adhesive wear to an existing hybrid tool wear model for predicting wear in hot forging processes.

2. Hybrid tool wear model

The main idea of a hybrid tool wear model in hot forging process is to take into account not only different wear mechanisms, but also relations between these mechanisms, as well as extrapolation to predict tool wear after large number of forgings. To build such a model, mechanisms models must be dynamically adjustable by external dependency (to account for acceleration or deceleration of wear in consecutive forgings) using parameters deciding on an impact of wear mechanism. Such significance factors are computed also using results of process simulation and correspond to importance of the mechanism in specific circumstances. A schematic illustration of the model proposed by the authors in [19] is shown in figure 1. Such model accounts for both mechanisms significance as well as extrapolation. It also covers the situation, in which extrapolative capabilities of mechanisms models are exhausted.

The input data to the model contains results of a computer simulation using FE package. This simulation consists of initial geometries in a form of meshes, model coefficients, kinematics and piloting definitions, material properties in form of model coefficients and initial settings for models, including wear formulas. Beyond this, a target number of forgings and initial distributions of temperature and, optionally, other properties (such as hardness) can be passed. Such data is then used in the FE package for computing simulation of the first forging, to obtain process data. The data is then used to compute values for individual mechanisms blocks. Each mechanism is computed using two models:

– As value of degradation being a result of a specific mechanism, computed from specific mechanism model (e.g. Archard formula for abrasive wear). This is a degradation which would be present if the calculated mechanism is the only mechanism present without any other influences.
– As significance value calculated from a separate model (as a formula or effect of e.g. analysis of geometry-related dependencies). This significance corresponds to acceleration or deceleration of the mechanism due to such external factors as other mechanisms presence, existing degradation or extrapolation factor. In consequence, it is possible to include effects of mechanisms directly responsible for degradation, as well as mechanisms which cause change in other ones.

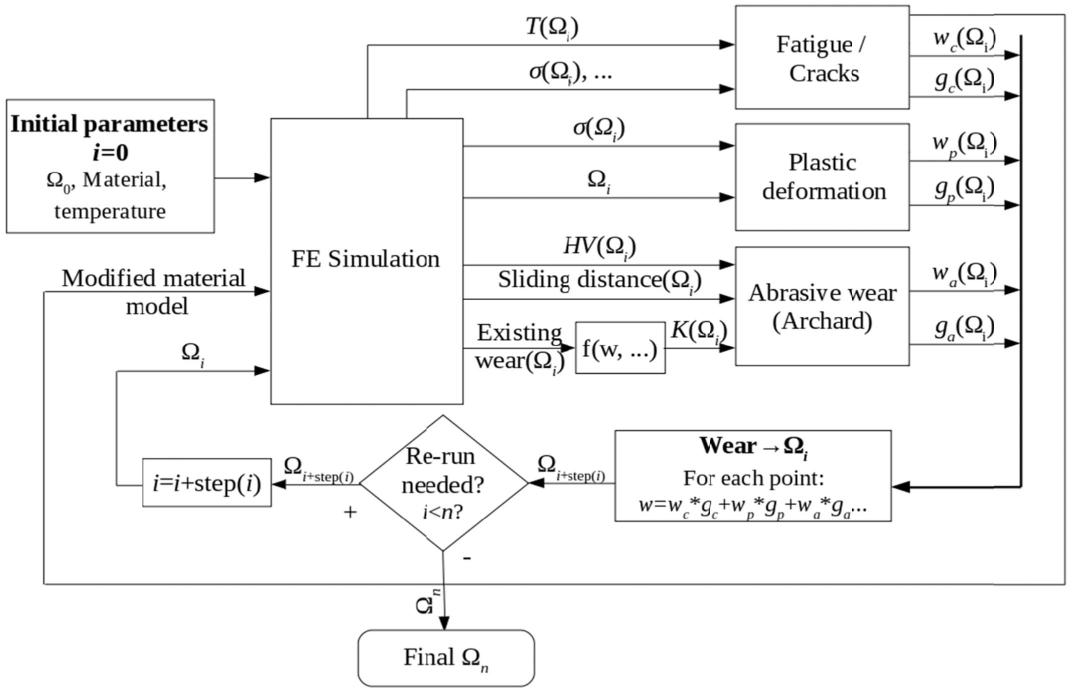

Fig. 1. Schematic of a proposed hybrid tool wear model in hot forging process

Each of the significance values is stored in the tool mesh. Additionally, the final value of the wear in a surface element is computed using a formula:

$$W_{total} = g_{abrasive} W_{abrasive} + g_{adhesive} W_{adhesive} + \\ + g_{plastic} W_{plastic} \cdots \quad (3)$$

In equation (3) significance and wear values are joined and summed. If at this stage the extrapolative capabilities of mechanism blocks are not exceeded, total wear is returned as a result. However, in the most cases some additional calculations are needed to account for surface and geometry changes and to re-run models for the next part of series. Thus, the geometry changes are accounted for in the mesh, fields corresponding to modified variables are modified, the tool is re-meshed using routines built in the FE package and additional parameters are corrected. Then, the simulation is started again and another iteration of the model is executed.

The function *step*(i) is non-linear and it depends on properties of models used in mechanism blocks, and is a subject to second stage of hybrid model parameters identification. After identifying coefficients of the models used in the mechanism blocks, the second stage should be performed using processes with different dominant mechanisms and significant distributions of them. That way it is possible to discover maximum values for extrapolation and determine limits, in which computation results are sufficient for prediction.

For abrasive wear, a modified Archard model [2] was used, as described in [14]. Its extrapolation capabilities are based on coefficient dependencies. Adaptation of coefficient allowed to include both existing wear and properties change being a result of other mechanisms.

Plastic deformation, as a volume-related factor having impact after significant number of forgings, is computed from existing stresses and geometry-based method. This method detects areas, in which such mechanism has impact on the total wear [20].

To determine impact of the mechanical fatigue, a porosity value has been calculated based on the modified Oyane equation [21]. With this approach it was possible to obtain areas of both distributed and highly localized mechanical fatigue cracks. Although this method is not suitable for detecting particular cracks, as micro-scale and totally coupled multi-scale models do, it has appeared to be efficient in detecting areas, in which fatigue cracks have impact on the total wear without significant increase in computational cost.

3. Adhesive wear

In metal forming, adhesion of the formed material causing tool wear occurs in situation, in which large temperatures, pressures and sliding distances are present. Adhesion is dominant in processes with significant sliding distances, such as processes with elongation of the material in parallel to narrowing parts of the die, as well as in processes in which material is expanded into a cavity or elongated against pushing die (e.g. cylindrical containers extrusion). In these cases, typical round shaped degradation is visible in the surface of the die, being a result of parts linked by adhesion, deformed and broken off. This is one of the characteristic signs of adhesion which can be used to distinguish it from other wear mechanisms.

According to [9], adhesive wear progresses by plastic deformation of inter-metallic connections between billet and tool material. Such join is deformed with material flow until the material becomes broken away off the surface. However, some processes have a similar sliding distances and in these cases adhesive wear is less significant, although abrasive wear grooves are still visible. In such cases temperature of working surface is lower, mostly due to usage of lubrication or cooling solutions. Although in macro scale this may be considered as a result of the lowered temperature, it may be possible that in the micro-scale the oxidation wear or electrostatic forces change surface properties up to 0.2 mm inside the die [22]. Thus, electrostatic and oxidation components, which have to be computed in the micro scale, may be not included for this specific computation scale.

The interaction between micro-irregularities is the factor deciding about the type of the wear present on the surface. Thus, a few types of interface situations have been characterized by the sliding distance between the two materials:

– No significant changes: Asperities slide between each other without noticeable volume transfer. This type of interaction occurs in small-load processes and at the beginning of sliding, when the wear is not yet developed and sliding distance is small.
– Surface adhesion: The volume material transfer is limited only to surface area of asperities. In this stage, a surface adhesion can be related to electrostatic and chemical phenomena and the wear starts to change surface roughness. This type of interfacing was described in [23] as the initiation of other wear-related mechanisms. The repetitive smoothing by plastic deformation of adhered points is visible there more than in previous type of contact.
– Cutting: The smaller micro-irregularities cut through each other, causing mechanical abrasive wear amplified by debris. If micro-cracks are then present, it is possible to remove a volume of material larger than asperity which has to be taken into account when identifying C coefficient for Archard equation (nevertheless minimized by smaller contact of asperities).
– Degradation by complete adhesion: Increasing amount of larger interlocked irregularities group and displace, creating a larger inter-metallic join. This connection is plastically deformed and ends with removal of one solid material, not only related to specific asperities. This material may be removed by transfer to formed workpiece, but in some cases it may, as in other wear mechanisms, be freed as the debris or be plastically laminated into further surface. A typical result of this wear are round or oblong degradation in dies commonly associated with adhesion.

As an approximation, it has been proposed to focus on abrasive interaction (Archard equation) and separating complete adhesion interface (Modified Archard) from abrasive wear to obtain separate values. Although using micro scale to distinguish surface adhesion wear may increase predictive capabilities, especially in adhesion initiation points, considering the roughness with scale up to asperities will make the model less useful for practical applications, due to increase of the computational costs. Since this interaction works also on oxide layers, possibility of future adding oxidation wear model into hybrid tool wear model must be performed with separating such contact.

To conclude, to predict adhesive wear and separate adhesive component from other mechanisms, it is important not only to predict the wear itself, but also the places on the die, in which the adhesion happens and progresses into plastic deformation of linked areas. According to [24], the source of inter-metallic link is in micro-irregularities of surfaces. During sliding contact, these irregularities interfere with each other. When sliding distances are low, the main action is cutting through each other, which results in abrasion. When sliding distance is high enough and temperature allows to displace surface parts, larger irregularities interlock each other forming a link, which then can be displaced with further material flow. To properly implement this phenomenon in the hybrid system, it is needed to apply two models:

– Adhesion criterion model for identifying the dominant mechanism. This model decides whether the contact taking place during current step is related to abrasion or adhesion. In practical application, a critical temperature obtained from material model was used to ensure that the plastic deformation will happen with sufficient material flow. Then it was needed to determine whether the sliding is large enough to create adhesion between parts of the surface.
– Adhesive wear model, in a form of a value of degradation due to adhesion. This model should be chosen from currently developed adhesion models depending on compatibility with the first criterion, identification and implementation possibilities.

4. Modelling of adhesive wear in hot forging processes

In the majority of hot forging processes adhesion is not a dominant mechanism for the tool material removal. It usually occurs in specific conditions on the surface, in which significant amount of material flows in contact with a smaller part of the tool surface. Such situation happens if the tool has cavities, channels or narrowed parts, in which billet elongation occurs. These situations, dominant in some processes such as extrusion, may also take place in hot forging or in processes on the boundary like container forging by elongating sides against hollow die. As it can be seen, for adhesion model in hot forging processes it is more important to determine if the adhesion takes place in a specific place on analysed die than to exactly calculate the wear in a low scale by the cost of computational power. It is then proposed to use a numerical criterion to detect adhesion and then to use a chosen simpler model to compute adhesive degradation value in detected areas, separating them from other mechanisms.

4.1. Sosenushkin model

Since there is a dependency between adhesion and contact surface as well as stress at this contact, it is possible to develop a model based on critical stresses in the calculated interface area. The volume of degradation dV can be specified, in the general form, as [9]:

$$dV = p\delta dF, \quad p = \frac{\sigma_{ts}^2}{\sigma_{ts}^2 + \sigma_{bc}^2}, \; dF = \eta vBdt \tag{4}$$

where: σ_{ts} – destructive stress threshold of material (identified experimentally in the tensile test), σ_{bc} – bending strength limit, v – sliding velocity, B – width of contact interface (normal to flow direction), dt – time increment.

A typical problem in this model is related to identification of coefficients in surface properties change domain. As the wear progresses, surface becomes degraded to a degree, in which its wear influences interface dimensions required for the model. This problem was solved by adding a multi-scale factor reflecting the incompatibility of contacting surfaces. However, this approach requires dependency on die surface evolution and initial properties resulting from tool preparation technology, not only its material.

The workaround for this problem was achieved by using procedural generation of the contact surface situation [25]. If only the material flow boundary is taken into account, it is possible to generate replacement geometric values and parameters corrections from existing degradation calculated in the previous step of computation. However, since for each element under contact analysis surface characteristics have to be calculated and applied to the model's input values, this approach increases computational costs significantly.

4.2. Energetic criterion

Similarly to abrasive wear model [26], it is possible to obtain an energy-related criterion for adhesion to happen between materials under contact and to specify the energy needed to deform and remove the adhesive join. Such an approach has been proposed by Warren and Wert [27] as a ratio between adhesion energy to total cohesive energy. To predict adhesive wear at the interface of materials A and B it is possible to use equation, which predicts when material A has higher hardness, as follows:

$$\frac{Energy\ of\ adhesion}{Cohesive\ energy} = \frac{1}{2} + \frac{\gamma_b}{2\gamma_a} + \\ - \frac{Y_b}{32\gamma_a}\left(\frac{\Delta a}{a_a + a_b\sqrt{\left(Y_a / Y_b\right)}}\right)^2 - I_{ab}\sqrt{\left(\gamma_b / \gamma_a\right)} \tag{5}$$

where: γ – energy on the interface, Y – elasticity modulus, a – inter-atomic spacing of the material.

To account for differences between surface materials, atomic incompatibility index I_{ab} has been defined as a measure of incompatibility between atoms of A and B [28]. This index is identified experimentally. The biggest advantages of this model are: i) ability to be used in a wide temperature range defined by coefficient dependencies and ii) possibility to couple with FE mechanical energy-based calculation for more precise results, including not only forming of adhesive join, but also deforming and breaking it.

The main disadvantage of using this model in practical applications is the fact that even if the incompatibility index gives reliable measure of micro-irregularities influence, it is still difficult to identify it for situation on a die, which has already been a subjected to wear. The surface parameters are changed enough to e.g. make irregularities resulting from machining irrelevant, but not changed enough to make influence of existing e.g. fatigue cracks not important. An example of such wear evolution is shown in figure 2. When this implementation is used, identification requires to simulate not only the effects of wear, but also its changes in a lower scale to compensate for this evolution.

4.3. Modified Archard model

By analysing situations, in which adhesive wear occurs, it is possible to use a model similar to Archard formula [2] proposed for abrasive wear. However, it requires to be adapted to adhesion conditions [29]. Die hardness has been replaced with workpiece hardness, and coefficients a, b and c have been added. In such model, the wear is defined as:

$$w = \int_0^t C(N)\frac{\mu p^a v^b}{HV_N^c}dt \tag{6}$$

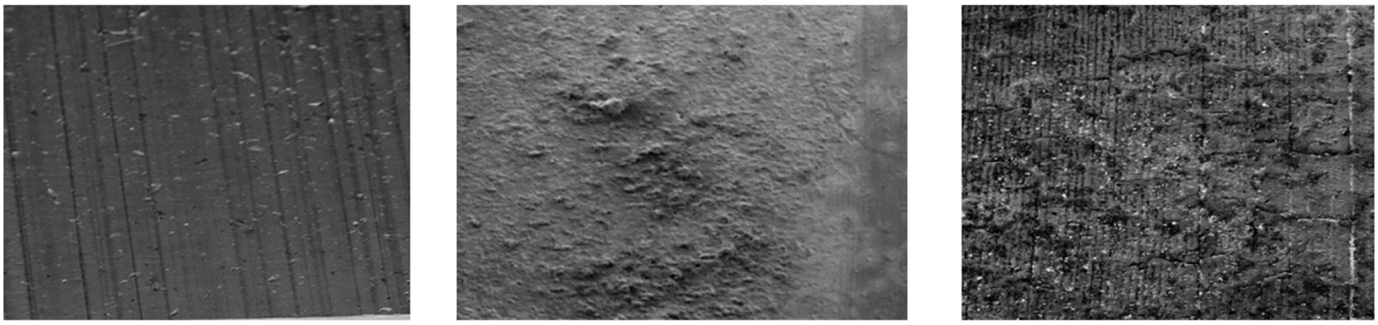

Fig. 2. Surface of a specific region of a die after 550, 1900 and 9500 forgings. Source: Research of University of Technology Wroclaw, in project no. 2011/01/B/STB/02056

Such an approach was successfully used in polymer-metal wear analysis [30]. In this approach it is also possible to use similar extrapolation techniques as in abrasive model, as well as implement it with hybrid tool wear model using similar formula.

In the present work it has been proposed to implement this model into the hybrid tool wear model. In order to separate adhesion-related wear from abrasive wear an additional criterion has been used. This criterion determines whether the friction contact leads to abrasion or adhesion. According to such criterion, different target variables for sliding distance are integrated and both Archard formulations are recalculated with their sliding distance values. The proposed criterion includes critical surface temperature, in which it is possible to interlock micro irregularities and displace the link, as well as sliding distance (identified inversely with measurements), in which abrasive wear ends, join is created and displaced with further flow.

5. Implementation

The implementation has been made as a module for FORGE FE software, adapted to implement hybrid tool wear model. A complete solution shown in chapter 2 has been implemented by application of user routines as equations computed during process and pre/post processing modules for final computations and data flow control. By using own implementations of pre/post processing tools, it was possible to modify meshes according to scalar fields, add correction variables and repeat FE computation if extrapolation capabilities have been exhausted. The results of model are accessible as typical fields for normal post-processing. Identified functions corresponding to changing parameters (e.g. $HV(T)$) have been specified as variable evolution routines. The implementation of an adhesive model was performed in two modules:

1. Implementation of sticking condition (Fig. 3) as a binary field, filled by user routine verifying temperature, stress and sliding distance. According to this value, target variable of sliding distance during its integration is dynamically changed.
2. Another instance of Archard equation was installed in the data file, with additional sliding distance variable as a source and different coefficients, to be computed as abrasive wear according to equation (6).

This particular type of implementation was chosen to minimize need of recalculation. By using separate instances the abrasive and adhesive components are computed separately from the beginning and can be checked in processing. Additionally, it minimizes complexity of model.

6. Verification

In a majority of the hot forging processes, a typical adhesive wear is not dominant mechanism. To verify the proposed model it was needed to find process containing parts with variable sliding distances and significant influence of the adhesive wear. The process described in [31] has been chosen. In this process the material flows through the narrow part, which elongates the workpiece and the smaller narrowing contains edge surfaces. These surfaces are prone to abrasive wear. The joint casing forging is a multi-stage operation and the second stage of this process has been chosen. Billet material was XC45, die material was Unimax. The general shape of die has been analysed in previous works as subject to optimization [32] in which the factor deciding about the tool life was related to stresses distributions in the die and the forging power used. Tool temperature was 250°C and billet temperature was 920°C. The critical temperature, which determines the plastic displacement of surface asperities with present stresses, has been chosen as 550°C. This temperature has been obtained from material model, by using present tangential stresses as factor which causes deformation at the surface. The value has been identified by checking whether the deformation is possible with existing stresses at specific temperature, which is needed for surface adhesion. By comparison with measurements,

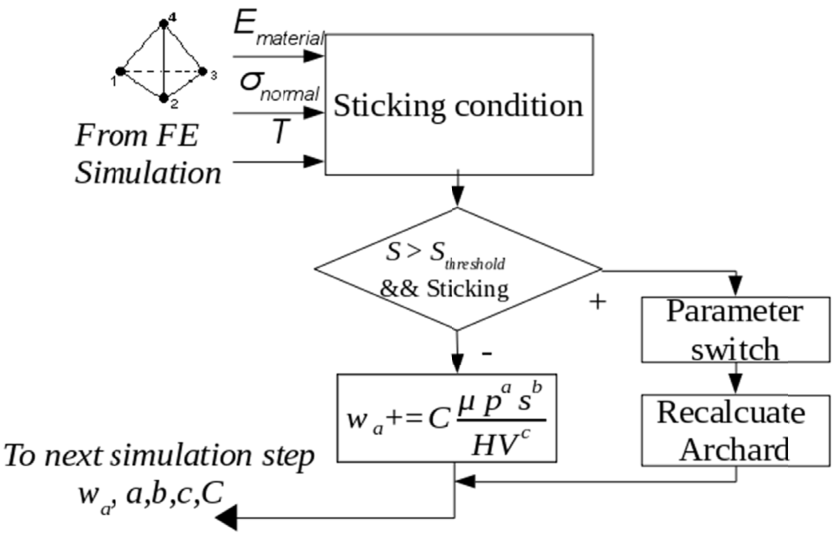

Fig. 3. Scheme of the proposed adhesion model

the critical sliding distance has been identified as $S_{threshold} = 56$. Coefficients for the modified Archard equation have been taken from publication [33]. The only exception which was identified with measurement results was C coefficient (6.551×10^{-4}) as it directly influences the result and, when extrapolation capabilities are used, it works additionally as scaling factor, partially compensating its errors. Separate identification of this particular factor by using comparison with experimental data, as well with computational experiments, is important because it directly influences significance of adhesion, which is already calculated by sticking condition. This is critical when this model has to be used in processes, in which even small geometry changes resulting from wear cause significant changes of the sliding distance (e.g. extrusion with floating middle die). In such a case the condition based on the contact distance will then be extrapolated with error until computation is repeated. The solution here would be compensation by using model coefficients or making the *step* function values smaller, which will result in more computation and bigger computational costs. For example, computation time for a single forging of the investigated process is about 2 hours for this process (with symmetry planes). Additional forgings needed to take parameter changes into account would require additional 2-hour computations. These were obtained on 16 cores of Xeon-based computer (2.66 GHz) and 64 GB of RAM, of which about 12 GB was used. However, times may vary by a small value as total machine workload, I/O throughput and re-meshing during computation is highly dependent on the process or even on the external factors.

Comparisons with measurements from [31] and [32] are shown in figure 4. A total wear has been measured using a 3D scan, as a difference between a new die and die after the process. It can be seen that using only the adhesive wear model without additional adhesion indicator gives overestimation of the wear, even after filtering out the abrasive component computed with Archard equation. This overestimation has its source in applying the same contact as a source of both adhesion and abrasion effect. With adhesion indicator, it is possible to at least identify regions, in which adhesion takes place and, with identified thresholds, which part of sliding contact is responsible for adhesive wear. This allows to calculate adhesive component of wear with minimized interference.

7. Conclusions

In the research, existing methods of predicting adhesive wear in metal forming processes have been reviewed and evaluated for application in the hybrid tool wear model. Since adhesion is not the dominant mechanism in the majority of hot forging processes, the criteria of evaluation focused on good separation between adhesion and other mechanisms. The objective was to compute them separately in a hybrid model and to avoid overestimation of the wear. Simplicity of the application and implementation, resulting in smaller computational cost than with multi-scale models, was another objective. A modified Archard formulation has been chosen as a solution, which has some generalization, but with proper separation from other wear mechanism is sufficient for implementation. By analysing circumstances of adhesion, sticking condition and a method to determine impact of adhesion on total wear has been developed. By using such indicator, it was possible to reduce overestimation of the wear when using both abrasive and adhesive modified Archard formulas. Model parameters have been identified and results have been compared with measurements. By analysing the results it was concluded that it is possible to predict at least places, in which adhesion has dominant influence on the total tool wear.

It has been shown that it is possible to use multiple tool wear prediction models to separate different wear mechanisms by applying specific significance factors calculated from

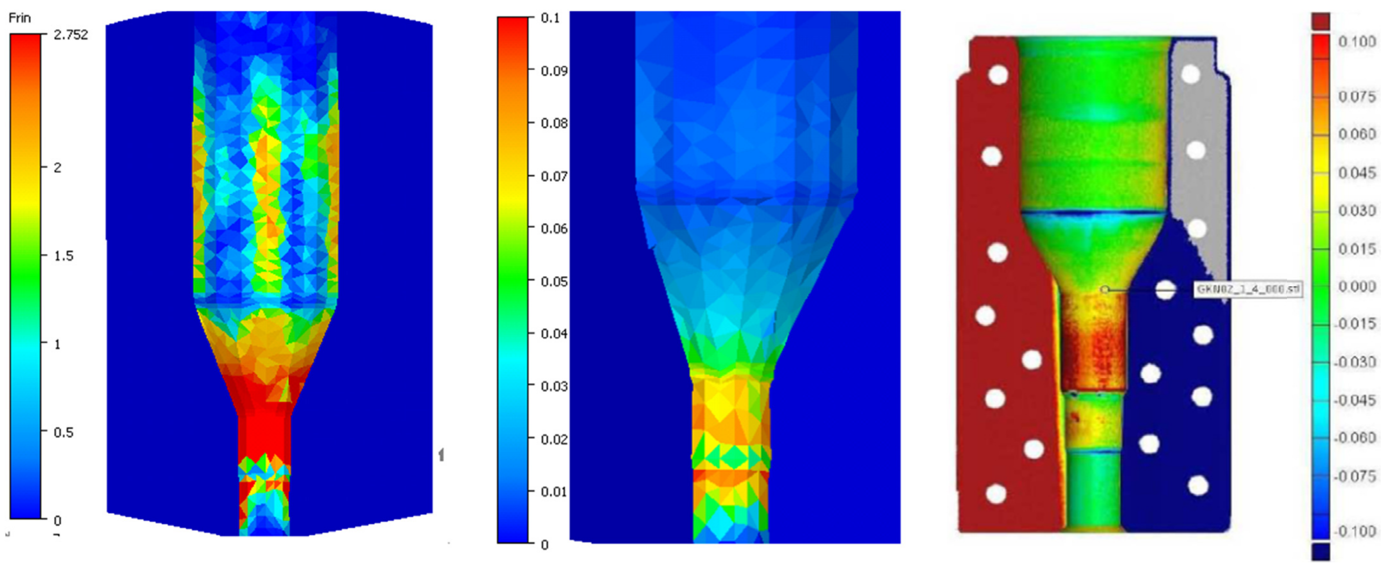

Fig. 4. Comparison between degradation computed from modified Archard formula with total sliding distance identified (pure abrasion filtered out after computation) (a), the same formula with sticking condition (b) and wear measurements from [32] (c). All units are mm

physical mechanisms of degradation, such as sticking criterion based on displacements and temperatures and criteria related to mechanism-specific situations. Obtaining such information from hybrid tool wear model makes the model useful in design applications, as it is possible to optimize tools and to maximize the profitability of forging process or make the tool fail in a more predictable way.

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