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Title: Formulation of intermediate layer laws for advanced simulation models of precision forging

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Precision forging represents a process which is suitable for producing components with a high specific strength in high quantities. However, the economic use of this process requires the minimisation of the development costs. The aim of this project is the development of an advanced simulation model based on the Finite-Element-Method (FEM). The model is to meet the specific requirements which the precision forging process imposes on the simulation with the aim of increasing the accuracy.

In precision forging processes, there are high contact pressures and temperatures, therefore, the existing laws which describe the intermediate layer are not appropriate in terms of accuracy. Hence, a new friction and a new heat transfer law have to be developed for the desired advanced simulation model. To achieve this, extensive experiments based on a backward can extrusion process featuring an innovative combined measurement tool have to be carried out. This combined measurement tool is both a forming tool and a measuring device. With the combined measurement tool it is possible to record the temperature and strains in the lower die during the forming process. In the next step, a FE-model of the backward can extrusion process involving the combined measurement tool is to be set up. The FE-model is to contain appropriate approaches for the intermediate layer laws. Each of the approaches contains a set of unknown parameters. The determination of these parameters takes place employing the numerical identification method. The numerical identification method brings the process data of the simulation in line with the equivalent experimental process data through repeated variation of the unknown parameters under application of optimization algorithms. The intermediate layer laws determined in this way permit the local determination of the intermediate layer conditions and, therefore, they are independent of the geometry and in general applicable for precision forging processes.

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1. INTRODUCTION

The accuracy of a FEM-calculation depends on the choice of the numerical calculation method used and in general on the accuracy of the FE-model used. Hence, the mechanical and thermal characteristics of the workpiece material and, if necessary, of the dies have to be described in the FE-model accurately. Furthermore, the accurate description of the boundary conditions is important to obtain numerical results which are equivalent to the real forming process. In general the boundary conditions in a process are in general the frictional shear stresses $\tau_R$, the contact normal stresses $\sigma_N$, the heat transfer $q$ and the relative sliding velocity $v_{rel}$ between the contact partners and also the surface temperatures $\dot{\vartheta}_{workpiece}$ and $\dot{\vartheta}_{die}$ of the workpiece and the dies. All these quantities describe the conditions of the intermediate layer between the workpiece and the dies and will be denote in the following as intermediate layer quantities. Fig. 1 shows a diagram depicting the intermediate layer and the intermediate layer quantities.

![Diagram of the intermediate layer and the immediate layer quantities](image)

Fig. 1: Diagram of the intermediate layer and the immediate layer quantities

However, because of the high contact pressures and temperatures in precision forging processes the existing laws are not suitable to describe the intermediate layer quantities. One characteristic of precision forging is the production of components near to the final geometry with very low size tolerances. Therefore, intermediate layer laws in form of a new friction and a new heat transfer law have to be formulated and then implemented in the FE-model. This advanced FE-model featuring the accurate description of the intermediate layer quantities is suitable for the simulation of precision forging processes.

2. PROBLEM DEFINITION

For increasing the accuracy of the FEM-simulation of precision forging processes intermediate layer laws are needed which describe intermediate layer quantities like friction or heat transfer between the contact partners in a forging process. The formulation of the intermediate layer laws takes place under application of numerical methods on the basis of measurement results.
However, especially the measurement of intermediate layer quantities in a forging process with one plastically deforming contact partner is very difficult. One characteristic of forging processes are the inhomogeneous conditions in the intermediate layer. Hence, the local determination of the intermediate layer quantities is necessary. But many of the presently existing measurement methods are not suitable for the local determination of the intermediate layer quantities. These methods do only permit the measurement of an averaged value of a quantity which is derived from all local values of the intermediate layer. The drawback of these measurement methods is that the results measured are strongly dependent on the geometry of the forging process. All other methods existing up to now are measuring the intermediate layer quantities directly in the intermediate layer. This methods allow the local measurement of the quantities and, for example, their dependence on the contact pressure. But the drawback of the direct measurement is the influence of the measurement tool on the conditions in the intermediate layer. Because of this influence the measured results get inaccurate and are not suitable for an accurate description of the intermediate layer.

As the actual state of affairs, there is no accurate measurement method to determine the intermediate layer quantities. Hence, there is no accurate description of the intermediate layer existing. Therefore, a measurement method has to be developed which is suitable to obtain accurate results. With the help of the FEM under application of MSC.Marc AutoForge [1] the results of the measurements will be used to formulate suitable intermediate layer laws. The procedure to develop the intermediate layer laws will be explained in the next chapter.

3. PROCEEDING

3.1. Indirect and local measuring method for the determination of intermediate layer quantities

For the accurate determination of intermediate layer quantities an indirect and local measuring method has been developed. This method does not base on direct measurements in the intermediate layer. Instead, indirect quantities which are dependent on the intermediate layer quantities are measured. Therefore, the measurement tools have no influence on the intermediate layer conditions.

The local determination of the intermediate layer quantities takes place numerically using the measured indirect quantities. In addition, because of the local measurement of the indirect quantities the numerically determined intermediate layer quantities will be independent from the geometry of the forging process.
The measurements will take place in a backward can extrusion process which has contact pressures and temperatures similar to a precision forging process. Therefore, the backward can extrusion process is most suitable to carry out the necessary measurements. Fig. 2 shows the layout of the backward can extrusion process and the measurement tools. There are several bores in the lower die. Strain gauges and thermo couples are fixed in the bores for the measurement of the strains and temperatures in the lower die.

3.2. Numerical Identification of the intermediate layer laws

The strains in the lower die are an effect of the contact normal stresses in the intermediate layer between the lower die and the workpiece whereas the temperatures in the lower die are an effect of the heat flux from the intermediate layer in the lower die. Hence, the measured quantities depend on the intermediate layer quantities.

The Numerical Identification is a method which uses the dependency between known and unknown process parameters to determine the unknown parameters. This method is presented in the work of DOEGE and WERNER [2] and is to be applied for the formulation of the intermediate layer laws. Thereby, the desired laws have to be local and time variable functions of the intermediate layer quantities. The formulation of local and time variable functions are equivalent to the functionality of the FEM. With the FEM the quantities are also calculated locally for every node and every time increment. The functionality of the Numerical Identification method is shown in Fig. 3:
Fig. 3: Numerical Identification of the coefficients for intermediate layer laws

where \( \vartheta^{\text{Exp}} \) are the measured temperatures, \( \varepsilon^{\text{Exp}} \) the measured elastic strains, \( F^{\text{Exp}} \) the measured forming load, \( \vartheta^{\text{Sim}}(\tilde{a}, \tilde{b}) \) the calculated die surface temperatures, \( \varepsilon^{\text{Sim}}(\tilde{a}, \tilde{b}) \) the calculated elastic strains and \( F^{\text{Sim}}(\tilde{a}, \tilde{b}) \) the calculated forming load. The indices \( i \) and \( j \) identify the quantities over location and time. The unknown parameters \( \tilde{a}, \tilde{b} \) are defined below.

For the Numerical Identification of the intermediate layer quantities first a FEM-model of the backward can extrusion process with the bores for the measurement tools is to set up. On the right side of Fig. 3 a quarter of the lower die of the FEM-model of the backward can extrusion process is shown. On the left side a quarter of the lower die of the measurement device with the measurement tools is shown. The FE-model of the backward can extrusion process is to contain appropriate approaches for the intermediate layer laws. Thereby, the approaches have the following form:

Every surface point of the forging tools which is a potential contact point to the work piece is assigned to a scalar evolution quantity \( O \) which includes the accumulate sliding way of the work piece material:

\[
O(t) = \int_0^t \nu_i(t') dt'
\]  

(1)

where \( t \) is the time and \( \nu_i(t) \) the relative sliding velocity between work piece and die.

The implementation of the friction law takes place using the interface UFRIC of MSC.Marc AutoForge [1] which allows the definition of a function for the Coulomb friction coefficient \( \mu \). Under assumption of the von Mises flow theory the shear yield stress is obtained by
which is also the maximum possible frictional shear stress \( \tau_{\text{fric,max}}^{(t)} \). Hence, the function for the friction coefficient \( \mu \) chosen has the following form:

\[
\mu^{(t)} = \frac{\min(\tau^{(t)}, \tau_{\text{fric,max}}^{(t)})}{\sigma_N}
\]

(3)

where \( \tau^{(t)} \) is the frictional shear stress depending on the friction law used and \( k_f^{(t)} \) the flow stress of the work piece.

The local determination of the frictional shear stresses takes place using the assumption

\[
\tau^{(t)} = \sigma_N^m \left[ a_1 \cdot \sigma_N^n + a_2 \cdot \left( \frac{\sigma_v}{k_f} \right)^p + a_3 |v_r|^{r} \right]
\]

which includes the effective stress \( \sigma_w \), the flow stress \( k_f \) of the workpiece, the relative sliding velocity \( v_r \), the contact normal stress \( \sigma_N \), the scalar evolution quantity \( O \) and the unknown constant parameters \( \bar{a} = [m, a_1, n, a_2, p, a_3, r]^T \).

In the existing investigations about heat transfer in hot bulk metal forming is shown that the heat transfer increases with the contact normal stresses between forming tool and work piece. The reason for this behaviour is that the increasing contact normal stresses smoothe the surface profiles of the forming tools and the work piece. Hence, the real contact face increases too. The lubricant film and its dependency on the true strain has another influence on the heat transfer. An upper boundary of the heat transfer for very high contact pressures is the value resulting due to heat conduction. In consideration of these behaviours the following approach for heat transfer results:

\[
\alpha = b_1 + b_2 \cdot \arctan \left[ \sigma_N \left( b_3 + b_4 \cdot \sigma_N^s + b_5 \cdot O \cdot \left( \frac{\sigma_v}{k_f} \right)^r \right) \right]
\]

with the unknown constant parameters \( \bar{b} = [b_1, b_2, b_3, b_4, b_5, r]^T \). The implementation of the heat transfer law takes place with the interface UHTCON.

The determination of the unknown parameters \( \bar{a} = [m, a_1, n, a_2, p, a_3, r]^T \) and \( \bar{b} = [b_1, b_2, b_3, b_4, b_5, r]^T \) takes place employing the Numerical Identification method. The Numerical Identification method brings the indirect quantities of the simulation in line with the equivalent measured indirect quantities through repeated variation of the unknown parameters under application of optimization algorithms.
The intermediate layer laws determined in this way permit the local determination of the intermediate layer conditions and, therefore, they are independent from the geometry and are applicable for precision forging processes in general.

4. CONSTRUCTION AND ANALYSIS OF THE BACKWARD CAN EXTRUSION PROCESS

The construction and analysis of the backward can extrusion process takes place through simulation with MSC.Marc AutoForge [1]. Especially the construction of the horizontal bore for the strain gauges in the lower die like in Fig. 2 shown is important. To obtain an extended data basis of measured data with a wide spectrum of contact normal stresses and relative sliding velocities in the intermediate layer, several punches with different diameters are to be used. In addition, several work piece temperatures and punch velocities are to be employed.

The determination of the geometry of the backward can extrusion process takes place regarding the required forming load of the process. Thereto, first a two dimensional rigid-plastic FE-model of the backward can extrusion is generated, shown in Fig. 4.

![Fig. 4: Two dimensional FE-model with rigid tools](image)

The maximum possible forming load of the forming machine is 8000 kN. Hence, this value is the upper boundary for the forming load of the process. As a result of the variation of the tool and work piece geometry in the simulation model the construction of the process has been realized. The resulting forming loads over the time in the simulations are shown in Fig. 5 for several punch diameters.
4.1. Construction of the lower die

Strain gauges are fixed in the bore for the measurement of elastic strains in the horizontal bore of the lower die. Hence, to obtain meaningful measurement results the distance between the bore and the intermediate layer on the surface of the lower die have to be as small as possible. On the other side, with decreasing the distance between bore and surface of the lower die the mechanical strength of the die decreases, too. This means that the die would be plastically deformed during the forging process. The optimal distance of the bore to the die surface is determined in a three dimensional FE-model with a deformable lower die. A simulation of the backward can extrusion with the FE-model is shown in Fig. 6.

The two symmetry axis of the process have been used to reduce the FE-model to a quarter of the backward can extrusion. A further simplification is the rigid modelling of the punch and upper die.

The maximum forming load is reached at the end of the forming process. Hence, the loading of the lower die at the end of the forming process have been investigated. The simulation results for a quarter of the lower die are shown in Fig. 7 and 8.
Fig. 7: Von Mises stresses in the lower die at the end of the forming process

Fig. 8: Elastic strains in the lower die at the end of the forming process

For the lower die the material X 38 CrMoV53 (1.2367) with a tensile strength of 2,000N/mm$^2$ has been chosen. Therefore, for the lower die an elastic limit of 1,800N/mm$^2$ is assumed which is to be the maximum allowed von Misses stress in the die. The punch diameter in the process is 90mm. The simulation results show that the maximum von Mises stresses appears in the middle of the bore. The maximum values of the stresses are in a range of 1500N/mm$^2$ to 1800N/mm$^2$.

The maximum for the elastic strains in the x-direction are at the middle on the side of the bore and have a value of $\varepsilon_{xx} = -9^{0}/00$. The local maximum for the strains in y-direction are at the middle on the upper side of the bore and have a value of $\varepsilon_{yy} = 3^{0}/00$.

4.2. Analysis of the sensitivity of the elastic strains with regard to the contact normal stresses

For the investigation of the significance of the strain measurements in the lower die another FE-model has been created. The model comprises only a quarter of the lower die of the backward can extrusion process. On the die there are three areas of surface loads in form of boundary conditions like in Fig. 9 shown.
Fig. 9: Lower die with horizontal bore and the fixed loads

In a simulation employing this model the dependency of the elastic strains at the bore wall on the surface loads has been investigated. Every load area includes 22 surface nodes and 22 loads respectively.

The elastic strains in the die caused by different loads are shown in Fig. 10 and 11. In the figures the elastic strains in $\xi$-direction over the $\eta$-axis are graphed. The $\eta$- and $\xi$- axis are shown in Fig. 9. The different load cases with each different load in the three areas are also graphed.
Fig. 10: Simulation results for the load cases 1 to 4
Fig. 11: Simulation results for the load cases 5 and 6

The result is that every individual profile of the surface load on the die has its own individual elastic strain conditions in the die. The to be measured strains are directly proportional to the contact normal stresses on the surface of the die. The contact normal stresses again are dependent on the friction in the process. This means that the measured strains are well suitable for the numerical identification of a new and local friction law. This circumstance is also shown in Fig. 12:

Fig. 12: Profile of the elastic strains for the load cases 4 and 6

The load profile 4 and 6 are very similar to each other and have in summation the same total surface load but anyhow the run of the elastic strains are still different. This shows that different local distributions of the load faces cause different local elastic strain conditions in the die. This permits the local determination of the friction in dependency to the contact normal stress.
4.3. Influence of friction on the forming process

In the following investigation again a two dimensional FE-model of the backward can extrusion with rigid forming tools is used to examine the influence of friction on the forming process. Fig. 13 shows the profile of the forming load in dependency of friction.

![Graph showing forming load vs time for two friction factors](image)

*Fig. 13: Profile of the forming load for two friction factors*

It is seen that the friction has a significant influence on the forming load especially for higher contact pressures.

The influence of the friction law on the flow of material is shown in Fig. 14.

![Diagram showing flowlines for different friction laws](image)

*Fig. 14: Visualisation of the flow of material with flowlines*

A feature of MSC.Marc AutoForge [1] is the possibility to use flowlines to visualise the material flow during the forming process. On the left side of Fig. 14 the undeformed work piece in a FE-model is shown. On the right side two simulation results using one time the Coulomb friction law and one time the friction factor model are shown. The results show that with the Coulomb friction law there is a small movement of material at the outer zones of the work piece and a higher movement in the inner zones. Hence, the two friction laws results two characteristic fibres in the work piece.

The displacements and the velocity field in the work piece for two points of time of the forming process are shown in Fig. 15 and 16. In the simulation the friction factor...
model has been used. These figures show that in the intermediate layer between work piece and lower die there are high values for the sliding way and sliding velocity.

\[ \Delta y \text{ [mm]} \]

Fig. 15: Vertical displacements

\[ v_y \text{ [mm/s]} \]

Fig. 16: Vertical velocities

5. CONCLUSIONS

In this paper a new method for the development of intermediate layer laws is presented. A new indirect measurement device has been developed which has no influence on the intermediate layer conditions and which is suitable for meaningful measurements. The Numerical Identification method is presented for the determination of local intermediate layer laws. The intermediate layer laws which permit the local determination of the intermediate layer quantities are suitable for the implementation in FE-simulation models.

This work shows the MSC software users the possibilities of the MSC.Marc AutoForge software: The use of the interfaces for the implementation of
advanced physical models and a systematic for the determination of more accurate process data with the help of MSC.Marc AutoForge.

6. ACKNOWLEDGMENTS

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7. REFERENCES

