

# Grain size prediction during open die forging processes

D. Recker, M. Franzke, G. Hirt, R. Rech, K. Steingießer

*One of the most important target parameters during open die forging is the microstructure, respectively the grain size. This paper details different semi-empiric models that ultimately help to predict the microstructure properties of a forged block. As a first step, trials in industrial scale were performed by Buderus Edelstahl GmbH and attended by SMS Meer GmbH. The collected process data was used by the Institute of Metal Forming (IBF) for the numerical analysis of the open die forging process and to validate the microstructure prediction module STRUCSIM. The numerical prediction of the grain size shows a good agreement with the results obtained from the metallography. In a second step models for the core fibre of a forged block were developed at the IBF. The models use data from the online process measurement and simplified plastomechanical interrelations for the calculation of equivalent strain and the temperature in the core of the forged part during the process. With their results the microstructure in the core fibre of the workpiece can be predicted online. The models are still in development and the most recent results will be presented in this paper.*

**KEYWORDS:** open die forging, strain distribution, temperature distribution, simulation, microstructure, optimisation, model

## INTRODUCTION

Modern open die forged products with high quality properties and material require a smooth and accurate forging process. An important aspect during the open die forging of large workpieces is to pursue the right forging strategy so that the desired microstructure can be achieved and possible casting defects can be removed from the core of the workpiece. To guarantee the desired microstructure and mechanical properties within the workpiece it is of high interest to be able to predict the microstructure within the workpiece during the forging process [1].

Generally, a minimum true strain of the workpiece is required to accomplish a workpiece with the desired quality. As the local strain is highly inhomogeneous within the workpiece, the accomplishment of a minimum true strain can not always avoid defects caused during forging. For large workpieces, this can lead to extensive waste and economical loss, since large workpieces usually represent a high value. Present trials to avoid these problems with programmed forging through pre-calculated forging plans failed due to differences between reality and calculation which were adding up during the process. Aside from that, the pre-calculated plans do not consider unpredicted interventions by the forging press operator. This leads to a less reproducible process and is therefore not satisfactory.

Since there is the desire for reproducible processes and gua-

ranteeing the expected microstructure inside of the workpiece, the project "Entwicklung eines Prozessmodells zur Online-Optimierung von Freiformschmiedungen großer Blöcke" ("Development of a process model for online-optimisation of open die forging of large workpieces") which is supported by the DFG through SPP1204 "Algorithmen zur schnellen, werkstoffgerechten Prozesskettengestaltung und -analyse in der Umformtechnik" ("Algorithms for a fast, material-suitable design of a process chain in metal forming") [2], aims at developing fast simulation models. These models shall be the basis for realising a numerical assistant system, which is able to suggest the best continuation of the forging sequence at any time during the forging process. A fundamental, semi-empiric model was developed, which is able to calculate the equivalent strain and temperature for the core fibre of a forged block. By connecting its results to the microstructure model STRUCSIM [3, 4], prediction of the expected grain size can be made.

The models for the equivalent strain and the temperature are derived and verified with a reference solution. As a reference solution the Finite Element Analysis (FEA) simulation is chosen since more cognition can be gathered easier and faster from the FEA than from real processes, at the moment. As evaluation of the FEA and STRUCSIM a forging process was carried out at Buderus Edelstahl GmbH and the metallographic examination of the workpiece was compared with the FEA results.

## OPEN DIE FORGING EXPERIMENTS

Open die forging experiments were carried out at Buderus Edelstahl GmbH and were attended by SMS Meer GmbH to evaluate FEA simulations and the integrated microstructure calculation (STRUCSIM). The material of the workpiece was 26NiCrMoV. The ingot had an initial diameter of around 700 mm and was forged to a diameter of around 500 mm using a total of four passes. The forging temperature was 1170 °C and a total of 65 strokes were carried out. The initial average grain size of the ingot was 1000 µm (Fig. 1, left) [5].

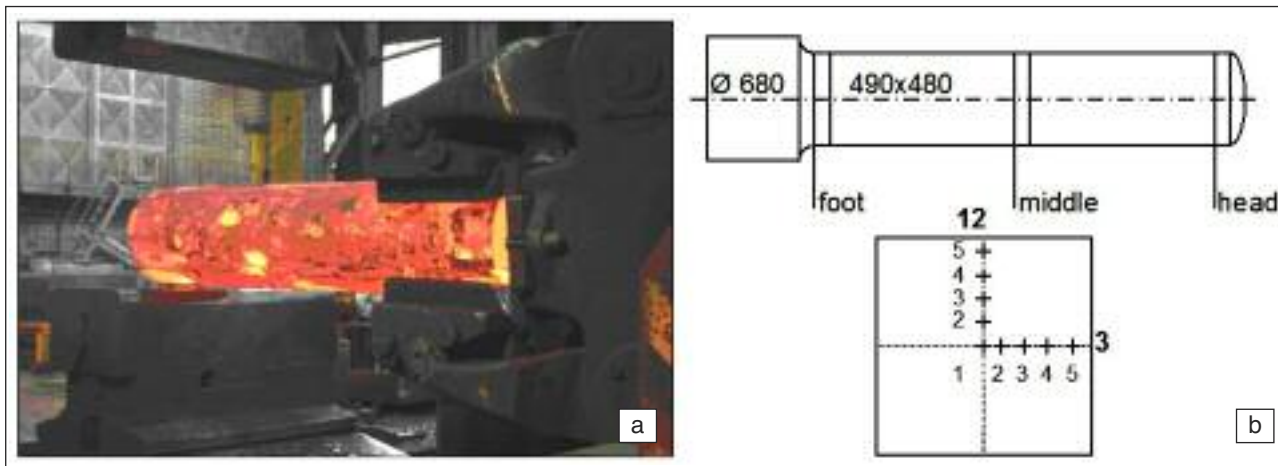
For metallographic examination discs were cut out of the forged

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**FIG. 1** Open die forging at Buderus Edelstahl GmbH (a) and positions for metallography (b).

*Forgiatura a stampo aperto presso la Buderus Edelstahl GmbH (a) e posizioni degli esami metallografici (b).*

Position =	Average Grain Size $\mu\text{m}$
M-12-1	150 - 250
M-12-2	100 - 200
M-12-3	100 - 300
M-12-4	150 - 250
F-12-1	150 - 250
F-12-2	150 - 300
F-12-3	150 - 300
F-12-4	100 - 200

**TAB. 1** Results of metallography at some selected locations.

*Risultati della metallografia in alcuni dei punti selezionati.*

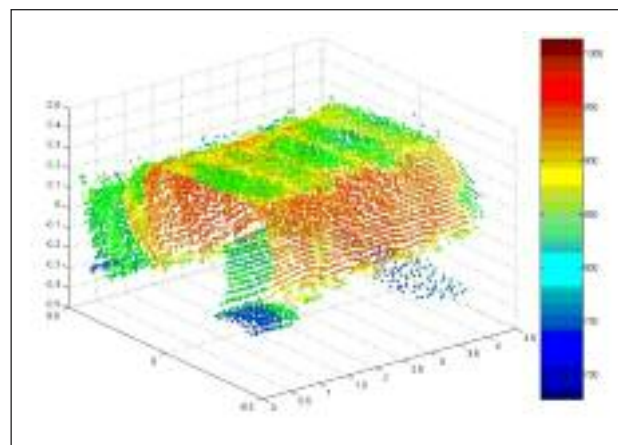
ingot at three different positions after the forging process (Fig. 1, right). From each disc nine samples were taken from defined positions. The average grain size for each sample was determined and some results are shown in Table 1.

#### THE MEASURING SYSTEM LACAM FORGE®

During the whole forging process all mechanical data was recorded and the process was recorded per video as well. Aside from that, the measuring system LACAM® [6] which is installed at Buderus Edelstahl GmbH delivers relevant process information online [7]. The LACAM® system which is developed by Ferrotron Technologies GmbH provides information about

- length of the workpiece
- surface temperature of the workpiece
- stroke protocol and saddle position

in a uniform coordinate system through laser scanning the forged workpiece during the forging process (Fig. 2). The distance measurement is based on a time-of-flight measurement using a pulsed semiconductor laser deflected in two directions. The heat radiation is measured and provides the possibility to measure the surface temperature distribution of the workpiece [6]. With this data the process can be simulated in detail. Fig. 2 shows the surface temperature distribution recorded by LACAM® for the first stroke. The temperature of the contact surface of the tool and the higher temperatures of the ingot side are clearly visible.



**FIG. 2** Temperature measurement with LACAM® after the first stroke.

*Misurazioni della temperatura mediante LACAM® dopo il primo passaggio.*

#### NUMERICAL SIMULATIONS

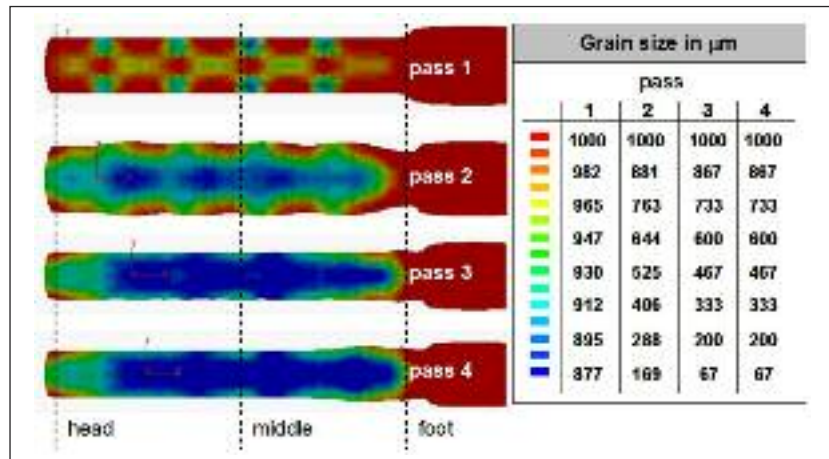
The measured and recorded information was used to create the models for the numerical simulations. The models were created with the software PEP [8] and the simulations were calculated using the FEA system LARSTRAN [9]. The microstructure was calculated using the module STRUCSIM which is directly coupled to LARSTRAN. The four passes of the reference open die forging process were simulated. The initial average grain size was set to 1000  $\mu\text{m}$ , according to the original process. The calculated distribution of the average grain size in the longitudinal sections for all four passes is shown in Fig. 3. At the head and foot of the ingot the results show a coarse microstructure (between 500  $\mu\text{m}$  and 1000  $\mu\text{m}$ ). In the middle of the forged part the microstructure is finer (between 60  $\mu\text{m}$  and 300  $\mu\text{m}$ ) while the grain size increases from the core towards the surface. The calculated microstructure results were compared with the microstructure determined from the experiment. This comparison is shown in Table 2 exemplary for the position 3 (see Fig. 1) of the middle and foot disc.

As Table 2 shows, the experiment and the simulation show a good correlation. Regarding the comparison between the experiment and simulation, the experiment validates the FEA, so that in the next steps the different models could be derived and verified from FEA reference solutions.

FIG. 3

**Simulated grain size distribution in the core plane for the four forging passes.**

Simulazione della distribuzione delle dimensioni dei grani nel piano centrale per i quattro passaggi di forgiatura.



Position =	Average Grain Size Experiment µm	Simulation µm
M-3-3	150 - 300	173
M-12-3	100 - 300	318
F-3-3	150 - 300	289
F-12-3	150 - 300	295

TAB. 2 Comparison of experiment and simulation for the grain size.

Confronto tra dati sperimentali e simulati, relativamente alla dimensione dei grani.

### CONCEPT OF AN ASSISTANT SYSTEM FOR OPEN DIE FORGING PROCESSES

The LACAM® system is a first step to a more reproducible forging process. The vision of the Institute of Metal Forming is to set up an intelligent assistant system that uses the provided data of LACAM® to predict the microstructure distribution within the workpiece and finally to assist the forge during the process.

According to the present works at the Institute, a concept for the assistant system could comprise the modules as shown in Fig. 4. The process provides current data about the change in length, position of the tools and the surface temperature of the workpiece. With the change in length of the workpiece a strain model calculates the equivalent strain in the workpiece. Respectively, the surface temperature is used by a temperature model to calculate the temperature in the workpiece. The results are processed subsequently by the microstructure model STRUCSIM to predict the microstructure in the workpiece.

In long-term work the assistant system is to be developed. Aside from the already mentioned models, a visualisation-tool has to be derived. This tool shall display the current distribution of microstructure in the workpiece. In combination with this and different optimisation methods [10], the numerical assistant system shall suggest and display the optimal continuation of the current forging pass.

### STRAIN MODELS

The main criterion for the models is a fast working algorithm so that e.g. the strain can be calculated during the process. As shown above, FEA simulations can be used to calculate several technical values rather precisely. In the case of open die forging the disadvantage of the FEA is that the numerical calculation of the process takes more time than the actual real process itself. Therefore the FEA is inappropriate to compute e.g. the strain (online)

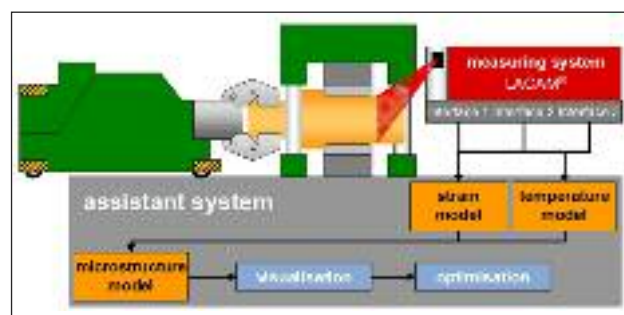


FIG. 4 Possible concept of the intended assistant system for open die forging processes.

Possibile impostazione del sistema di monitoraggio nel processo di forgiatura a stampo aperto.

during the forging process. Thus, a fast and online capable model has to be derived.

In a first step a one dimensional model for calculating the equivalent strain was developed for the core fibre of the forged block. The basic idea is that the equivalent strain can be calculated on the basis of global values, such as the change in length of the workpiece. The strain model calculates the equivalent strain through the change in length of the workpiece during one stroke of a forging pass. The functionality of this approach was described previously in different publications [11, 12].

So far the model for the core fibre showed good results for forging process consisting of only one forging pass. Thereby the main problem was to superimpose the model results for the first pass and following passes [12]. In recent trials a method for superimposing the strain distribution for several forging passes was developed. In this method the stretching of the strain distribution due to the stretching of the forming zone is considered. Hence, the strain distribution for several following forging passes can be simply added to the total strain distribution:

$$\epsilon_{total} = \sum_{i=1}^n \epsilon_{pass,i} \quad (1)$$

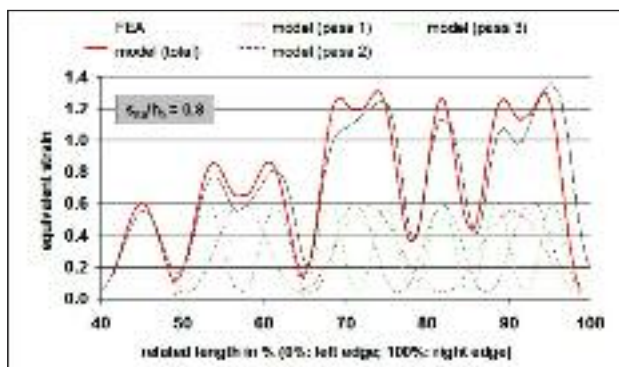
As evaluation of the model a two-dimensional FEA reference process was created. The main simulation parameters can be found in Table 3. After every simulated stroke the change in length of the core fibre is measured and put into the strain model and it calculates the strain distribution for the core fibre in the forming zone for this stroke. Finally the calculated strain distributions for each pass are added up and so the total strain distribution in the core fibre of the workpiece is determined.

Parameter	Value	Unit
$l_0$	650	mm
$h_0$	100	mm
saddle width	200	mm
saddle radius	20	mm
$\mu$	0.3	-
$\vartheta_{\text{Start}}$	1200	°C
$\vartheta_{\text{Environment}}$	25	°C
$\vartheta_{\text{Tool}}$	300	°C

**TAB. 3** Simulation parameters for the two-dimensional FEA model.

*Parametri di simulazione per il modello FEA bidimensionale.*

For an initial bite ratio of  $s_{B0}/h_0 = 0.8$  Fig. 5 shows the results for the equivalent strain in the core fibre of the reference simulation at the end of the process. The calculated total equivalent strain is shown as well as the strain distribution for each forging pass. As the results show, there is a good correlation between the calculated total equivalent strain and the FEA results. Only small differences between FEA-solution and model-solution can be observed. The differences may be explained by the half-empirical character of the model. In the FEA-calculation material flow varies in each stroke and thus the distribution of equivalent strain in the core fibre also varies in each stroke. Since the model uses the change in length of the workpiece to calculate the equivalent strain it does not consider different material flow behaviours within the workpiece. However, the results show that the model can be used for a fast estimation of the equivalent strain distribution in the core fibre of the workpiece during the open die forging process. The same model was applied to a bite ratio of  $s_{B0}/h_0 = 0.5$ . Fig. 6 shows the results for the FEA and the model. In this case the model does not deliver as accurate results as for a bite ratio of 0.8. Especially at positions where a forging pass ends ( $x = 65\%$  and  $x = 75\%$ ), the model shows unusual peaks. Methods to smooth the distribution in these zones have to be developed in the further progress of the project. Furthermore, in the areas where single strokes overlap, a better method to superimpose the strain distributions has to be developed as well.



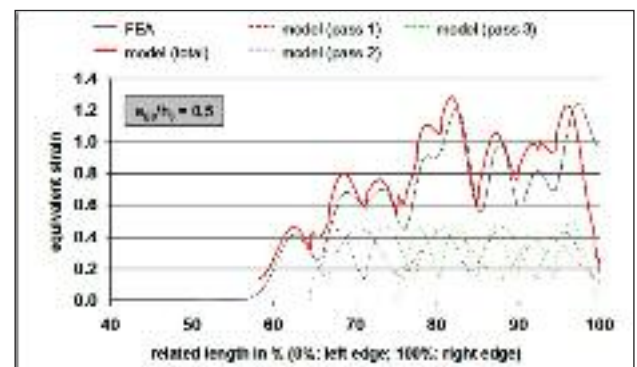
**FIG. 5** Comparison of the equivalent strain in the core fibre calculated by the strain model and by FEA simulation after three forging passes. The bite ratio is  $s_{B0}/h_0 = 0.8$ .

*Confronto della deformazione equivalente nella fibra centrale calcolata mediante modello di deformazione e mediante simulazione FEA dopo tre passaggi di forgiatura. Il "bite ratio" è  $s_{B0}/h_0 = 0.8$*

Nevertheless, considering that the model is based on very simple assumptions [11, 12] and calculates the equivalent strain distribution of the core fibre by only using the change in length between to passes, it delivers good results for the examined bite ratios. For the small bite ratio the accuracy might be reduced but the principle of the distribution is similar to the one of the FEA. The comparisons show that the principle of the model works. The results are in good agreement with the FEA reference solution. Aside from that, the model works fast. In the next steps the model has to be evaluated with three dimensional reference solutions. Furthermore it has to be implemented in a module so that interfaces to the LACAM® system can be derived.

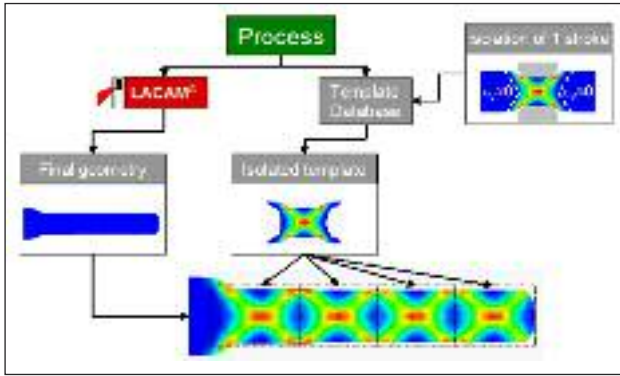
A different approach is to accelerate the FEA simulation so that the results can be used during the process. In general, one forging pass consists of several similar strokes. The idea of the IBF is to simulate one forging stroke and then isolate the computed strain distribution. Thereby all elements of the FEA results with an equivalent strain of  $\epsilon_V \approx 0$  are deleted. The isolated strain distribution is then transferred to the final shape of the workpiece as many times as strokes were performed so that the strain results of one stroke are superposed resulting in the total equivalent strain distribution after one forging pass (Fig. 7).

Combined with the LACAM® system the principle of the superposition could work as follows: The system measures the workpiece. With the measured point cloud a net of the final shape of the workpiece is generated. Combined with the input of required parameters (bite ratio, tool speed, material, etc.) a database delivers the "template" for one stroke. The database can be generated from FEA simulation results which were performed for different conditions prior the forging process. This template is then superposed to the total strain distribution within the workpiece. The basic idea of the superposition had to be evaluated. Therefore the superposition was used on a FEA reference process. For a certain bite ratio one pass of a forging progress was completely simulated. Aside from that, one stroke with the same bite ratio was simulated as well. The results were isolated and transferred to the final shape of the workpiece of the complete simulation. For a bite ratio of  $s_{B0}/h_0 = 0.8$  the results are shown in Fig. 8. The left part shows the graphic results of the FEA simulation and the superposition. Both pictures show a similar distribution of the equivalent strain throughout the whole workpiece. The core fibre shows slight differences between the FEA results and the results of the



**FIG. 6** Comparison of the equivalent strain in the core fibre calculated by the strain model and by FEA simulation after three forging passes. The bite ratio is  $s_{B0}/h_0 = 0.5$ .

*Confronto della deformazione equivalente nella fibra centrale calcolata mediante modello di deformazione e mediante simulazione FEA dopo tre passaggi di forgiatura. Il "bite ratio" è  $s_{B0}/h_0 = 0.5$*



**FIG. 7** Principle of the superposition method for an open die forging process.

*Principio del metodo di sovrapposizione per un processo di forgiatura a stampo aperto.*

superposition which increase towards the surface. A more precise comparison for the core fibre and the surface fibre of FEA simulation and superposition is shown in the right part of Fig. 8. In addition, the difference between the FEA and superposition - related to the FEA distribution - is plotted in both graphs. For the core fibre both strain distributions match each other quite accurately for the chosen bite ratio. For the forged part of the core fibre the biggest differences can be observed at the edges of the different forming zones (25 % up to around 75 %). For the centre of the forming zones the difference is around 0 % to 15 %. In the lower right part of Fig. 8 the comparison of the surface nodes is shown. While the relative difference between superposition and FEA is rather small for the core fibre, the comparison for the surface shows much bigger differences. For the whole forged part the relative difference is around 25 % up to 75 %.

Overall, it can be seen, that the superposition delivers good results for the core fibre for the examined bite ratio. However the differences for the surface can not be neglected. For a two dimensional application of this method an appropriate superposition algorithm has to be developed so that the surface and the areas between the core fibre and surface deliver more accurate results. Nevertheless, the results show that the principle of this method works.

## TEMPERATURE MODEL

As in every other hot forming process the temperature of the workpiece plays a very important role during the open die forging pro-

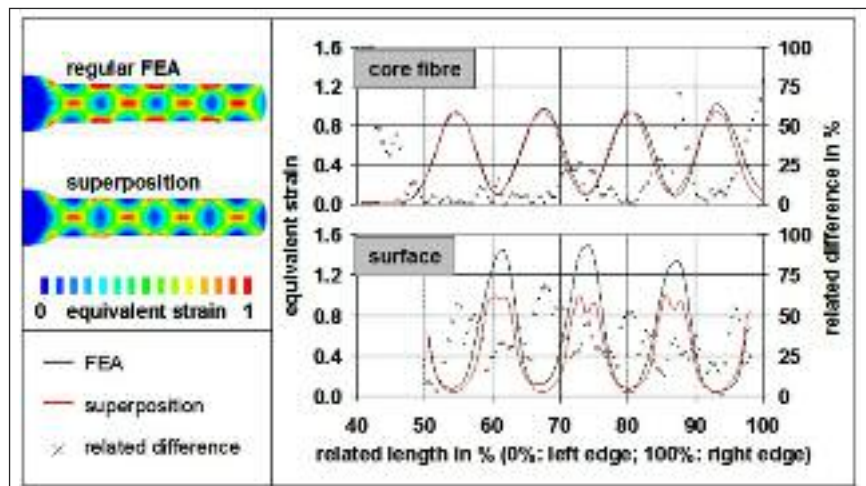
cess. The temperature field within the workpiece occurring during the process influences directly or indirectly many important parameters such as local flow stress, local forming capacity, strain and stress condition, force and work requirements. Another important aspect is the microstructure. Especially during thermo-mechanical forming, the thermal conditions determine the microstructure which directly influences the mechanical properties and the quality of the final product [11, 13]. Knowing the temperature distribution, in particular in the core of the workpiece is therefore of high significance to the forging process. Thus, the target is to develop a fast model which calculates the temperature distribution within the workpiece on basis of online measurements of the surface temperature of the forged block. This model is being developed at the Institute of Metal Forming. In the first stage the model calculates the temperature distribution in the core fibre of the workpiece. As the functionality of this model is described precisely elsewhere [11], only a short overview of the model is given. The workpiece is divided in three sections, in which different thermal conditions exist (Fig. 9). Since the model is derived from a two-dimensional FEA-reference-simulation, there can be only heat flow in x- or in y-direction. It is assumed that only one-dimensional heat flow in the y-direction occurs in section 1 (forming zone). For the duration of one stroke, heat transfer occurs from the workpiece surface into the tool. Aside from that, an increase in temperature (dissipation) due to the deformation work may occur in the core fibre. For section 2, heat loss by radiation to the surroundings causes a one dimensional heat transfer in y-direction. In section 3, it is assumed that heat flows only in x-direction. According to the direction of heat transfer, one dimensional finite Difference (FD) models are placed in each section. Based on a known temperature of the surface node, each FD-model calculates the temperature of the respective node in the core fibre after the current stroke. The dissipation in the forming zone is thereby approximated through the equivalent strain given by the strain model (see above).

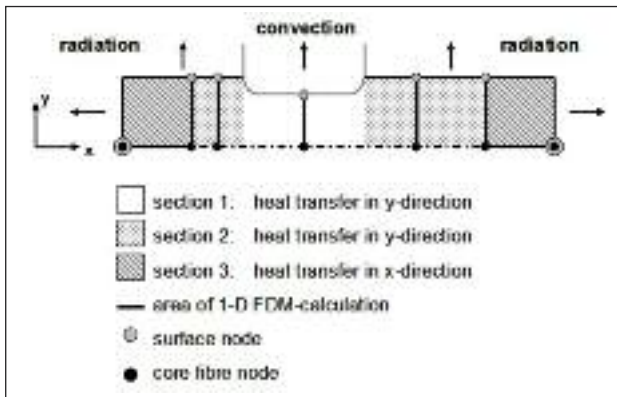
The temperature model was applied to the same two dimensional FEA simulation as it was used for the strain model. For the second pass the temperature distribution was calculated for the core fibre and is shown in Fig. 10 (left part) as well as the temperature distribution calculated by the FEA. For a more detailed view of the block edges, the temperature distribution of model and FEA is shown in Fig. 10 (right part) exemplary for the right block edge. Overall the temperature distribution of the model shows a good agreement with the results of the FEA. In the formed area (between 40 % and 100 % of the related length of the core fibre) the maximum difference between model and FEA is around 5 °C. Re-

**FIG. 8**

*The left part shows the graphic results of FEA and superposition method. The right part shows the results of both methods for the core fibre and the surface, as well as the related difference between both (FEA and superposition).*

*Il grafico della parte sinistra mostra i risultati dei metodi FEA e di sovrapposizione. La parte destra mostra i risultati di entrambi i metodi per la fibra centrale e per la superficie, e le relative differenze fra i due (FEA e sovrapposizione).*





**FIG. 9** Subdivision of the workpiece in three different sections with different thermal conditions in each area.

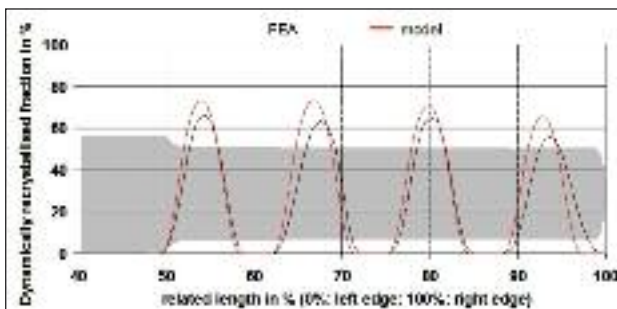
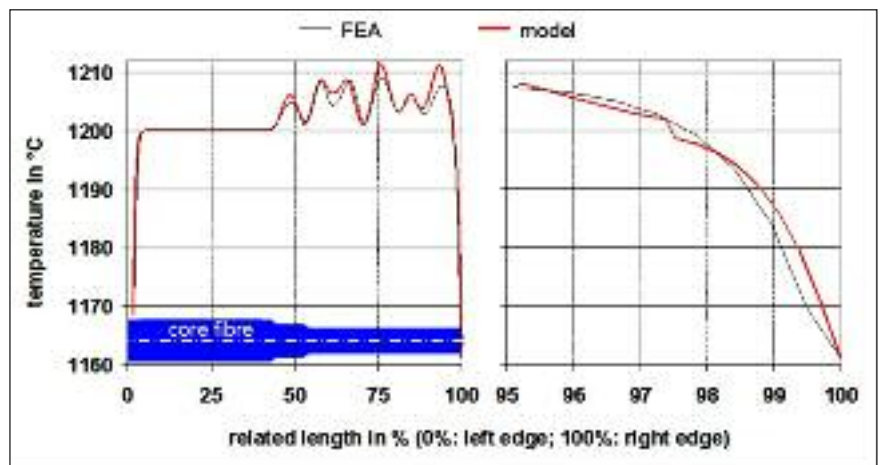
*Suddivisione del pezzo in tre diverse sezioni con differenti condizioni termiche in ogni area.*

lated to the overall start temperature of 1200 °C, this difference is rather small. Similar results can be observed for the block edges (figure). The differences between model and FEA are not higher than 10 °C in this area.

The results show that the presented model approximates the FEA results for the temperature distribution of the core fibre of a forged block quite well. Considering that the FEA represents a real life forging process, the model delivers the possibility to give a fast estimation of the basic temperature distribution inside the

**FIG. 10** Comparison of the temperature distribution in the core fibre calculated by the temperature model and by FEA simulation after two forging passes. The bite ratio is  $s_{B0}/h_0 = 0.8$ .

*Confronto della distribuzione della temperatura nella fibra centrale calcolata con il modello di temperatura e mediante simulazione FEA dopo due passaggi di forgiatura. Il "bite ratio" è  $s_{B0}/h_0 = 0.8$ .*



**FIG. 11** Dynamically recrystallised fraction of the core fibre calculated by STRUCSIM for model-values and FEA-values.

*Frazione ricristallizzata dinamicamente nella fibra centrale calcolata mediante STRUCSIM per i valori del modello e i valori FEA.*

workpiece. However, more FEA trials have to be run so that material with e.g. a higher dissipation can be tested. This would give the opportunity to test if the differences between model and FEA are still as low as described above. Furthermore trials of real forging processes have to be run to validate the model in real life.

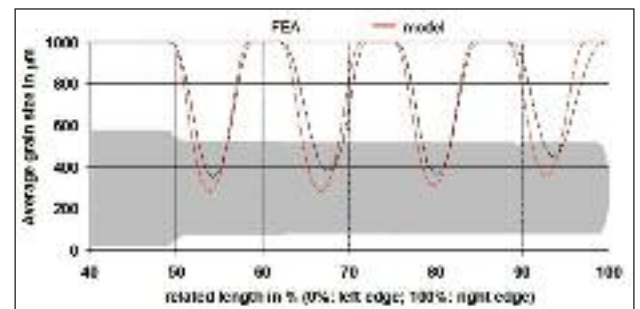
## MICROSTRUCTURE MODEL

Once the data for the temperature and the equivalent strain inside of the workpiece is available, the microstructure model STRUCSIM can calculate the microstructure properties of the workpiece. The exact functionality of STRUCSIM is described in detail elsewhere in different literature [3, 4]. Therefore, only the results will be presented in the following paragraphs.

The calculated strain and temperature distribution in the core fibre of both, model and FEA, is used as input for STRUCSIM. In this specific case the temperature and strain distribution after one forging pass is used. As initial grain size the fictional value of 1000 μm is used. The STRUCSIM results for the dynamically recrystallised fraction of the core fibre after one stroke are shown for model and FEA values in Fig. 11.

Fig. 11 shows that there are some discrepancies between the FEA and the model values for the dynamically recrystallised fraction. The differences are around 10 % reaching up to around 20 % in the area of the right edge of the block (90 % - 100 % of the core fibre). These differences might be explained by the differences between the input data. As described above, there are differences between the strain distribution calculated by model and by FEA. The same applies to the temperature distribution.

Fig. 12 shows the calculated grain size in the core fibre after one



**FIG. 12** Grain size distribution in the core fibre calculated by STRUCSIM for model-values and FEA-values.

*Distribuzione della dimensione dei grani nella fibra centrale calcolata mediante STRUCSIM per i valori del modello e i valori FEA.*

forging pass for model and FEA. As well as for the dynamically recrystallised fraction, the model values do not match the FEA values exactly. The differences are around 100  $\mu\text{m}$  throughout the forged part. Nevertheless, the grain size distribution calculated using the model values shows a similar character to the FEA distribution. This means that the model values can be used by STRUCSIM to give a fast estimation of the microstructure of the core fibre during the forging process. Improving the models for strain and temperature will lead to a more accurate calculation of the microstructure properties of the workpiece.

## CONCLUSION

Summarizing the presented work, the following aspects can be highlighted:

- The trials carried out show that the finite element analysis can be used to predetermine the microstructure inside the workpiece. Additionally, the trials show that the FEA can be used as a reference instead of a real forging process if appropriate material data is available.
  - Two different models for calculating the strain in the core fibre of the workpiece during the forging process were presented. Both models work fast and deliver quite accurate results. The different inaccuracies in predetermining the equivalent strain shall be avoided in the future so that the results can be improved.
  - The presented temperature model is able to predict the temperature distribution in the core fibre in principle using measured surface temperatures. Some inaccuracies can be observed. Nevertheless, the model can be used to approximate the temperature distribution of the core of the forged block during the process.
  - Connecting the model for temperature and equivalent strain distribution to the microstructure model (STRUCSIM) shows that the grain size of the core fibre can be predicted during the forging process. The estimation of the grain size can be improved by improving the accuracy of the strain and temperature model.
- In future the models have to be implemented in a compiler language so that a fast and automatic work of the models is secured. Aside from that, algorithms which process the measured data for the models will be developed. Another important step is to implement the different models in the assistant system. Furthermore, optimisation methods and algorithms have to be implemented in the system. These will deliver an online support for the forging press operator and will suggest the optimal continuation of the current forging pass.

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## Abstract

### Previsione delle dimensioni dei grani durante i processi di forgiatura a stampo aperto

**Parole Chiave:** acciaio, forgiatura, metallografia, simulazione numerica

Uno dei parametri più importanti da seguire durante la forgiatura a stampo aperto riguarda la microstruttura e, più propriamente, la dimensione del grano. Questo studio fornisce una descrizione dettagliata dei diversi modelli semi-empirici che possono contribuire a predire le proprietà microstrutturali di un blocco forgiato. Come primo passo, sono state eseguite prove su scala industriale presso la società Buderus Edelstahl GmbH e presenziate dalla SMS Meer GmbH. I dati di processo raccolti sono stati utilizzati dall'Institute of Metal Forming (IBF) per condurre l'analisi numerica del processo di forgiatura a stampo aperto e per convalidare il modulo STRUCSIM di previsione della microstruttura. La previsione numerica della granulometria mostra una buona concordanza con i risultati ottenuti con la metallografia. In una seconda fase sono stati sviluppati, presso la IBF, modelli per la fibra centrale di un blocco forgiato. I modelli utilizzano i dati delle misurazioni rilevati durante il processo e le interrelazioni plasto-meccaniche semplificate per il calcolo della deformazione equivalente e della temperatura durante il processo, a cuore della parte forgiata. Con questi risultati è possibile prevedere in linea la microstruttura della fibra centrale del pezzo. I modelli previsionali sono ancora in fase di sviluppo e in questo documento vengono presentati i risultati più recenti.