Simulation Of Phase Transformation In Hot Forging Dies During A Precision Forging Process By Means Of Finite-Element-Analysis

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Abstract. The Finite-Element-Analysis (FEA) is of major importance for the design and improvement of forging processes. In this field, FEA is traditionally used to predict die fill, residual stresses and forming forces. The intention of the work presented in this paper is the development of an advanced simulation model for the description of phase transformation processes in forging dies based on FEA. This simulation model enables the prediction of die wear, since the hardness of the surface layer could be predicted. Due to the mechanical and thermal interactions with the work piece, the temperature in certain regions of the die surface layer exceeds the austenitizing (Ac_{1b}) temperature. After the lubrication, following the forging cycle, a fast cooling of the die surfaces takes place, so that martensite is generated in the surface layer. Below this layer, the temperature is higher than the annealing one, but lower than the Ac_{1b} temperature of the forging die steel, which leads to soft annealing of this region. A precision forging process will be simulated to predcit this change of microstructure. The FEA includes the modelling of mechanical and thermal interactions between the work piece and the dies and the cooling through a lubrication medium. Finally, in order to calculate the microstructure, specific developed subroutines are implemented in a commercial FE-code.

INTRODUCTION

Drop forging in the temperature range between 900 to 1250°C has a great importance for the manufacturing of complex components. Due to high work piece temperatures, high strains caused by deformations are possible. At the same time the forming forces are lower compared to warm and cold forming. A special technology of drop forging is the precision forging as a near-net-shape technology. Components produced by this manufacturing method are characterized by high dimension accuracy and contour quality.

The high work piece temperatures and high contact pressures during the precision forging process lead to large die loadings. As a consequence of this die wear is of great significance at precision forging. The die adhesive and abrasive wear is the major failure reason of forging dies. The knowledge of the regions with a high magnitude of wear enables the optimization of forging dies. Furthermore, the calculation of die wear permits the prediction of lifetime of forging dies. In this paper the Finite-Element-Analysis is used to investigate material changes in the surface layer of dies in precision forging, which are essential for the prediction of die wear. The results can be used to calculate the wear accurately.

MATERIAL CHANGES IN THE SURFACE LAYER OF FORGING DIES AT PRECISION FORGING

Precision forging is carried out in closed dies without flash. The slug has usually a temperature of 1200°C. To reduce the risk of thermal cracks, tools are preheated to magnitude of 200°C.

Due to the mechanical and thermal interactions between work piece and dies, heating of the die surface layer occurs. The main reasons of this heating are the high work piece temperature, the large contact pressure and the friction during the forging process. As a result of heating two temperature ranges has to be distinguished **[4]**. There are layers which are heated up to

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temperatures above the austenitizing temperature of the die material. In these layers the requirements are fulfilled that phase transformations can take place. After the unloading sequence, the very thin austenitic layer, approximately 0.2 millimeters, cools down. Due to the high cooling rate new martensite is generated. The hardness of the new formed martensite is greater than the hardness of the base material of the dies. This re-hardened layer is also called white layer in literature. Furthermore, there are layers in the dies with temperatures between annealing and austenitizing temperature. These layers have also a great meaning for the die wear. In this temperature range annealing effects occur, which cause a hardness decrease and an acceleration of wear.

The measurement of temperatures in the surface layer of dies is very difficult due to the high mechanical and thermal loadings during the forging process as well as of the complex geometries. Moreover, a measurement period of only a few milliseconds causes difficulties. With the aid of the FEA it is possible to calculate the temperature at any distance from the surface of the die.

SIMULATION OF A PRECISION FORGING PROCESS USING THE FINITE-ELEMENT-ANALYSIS

The Finite-Element-Analysis is an effective tool to predict die fill, residual stresses and forming forces. Furthermore, the FEA plays a decisive role in construction and optimization of forging tools. In order to analyze the changes of the microstructure in the surface layer of forging dies by using the FEA a cycle of a precision forging process with the parameters shown in **table 1** is considered (**figure 1**).

TABLE 1. Parameter of work piece and dies

part	Material	initial temperature [°C]
work piece	42CrMo4 (1.7225)	1200
dies	X38CrMoV5-3 (1.2767)	200

The FEA is performed with the commercial Finite-Element (FE) Code MSC.SuperForm. Because of its robust remeshing and contact algorithms MSC.SuperForm is suited for this purpose. Moreover, this program have an user interface which allows the user to implement his own subroutines in order to simulate specific problems.

To analyze the interactions between the work piece and the dies a thermal-mechanical FEA with meshed tool components is carried out. Because of the rotational symmetry of the work piece and the dies a two dimensional simulation is modeled. This leads to a major reduction of the number of degrees of freedom compared to a three dimensional simulation. The result is a substantially smaller solution time. Due to the fact that the thickness of the layer where the re-hardening and annealing effects take place is approximatelay one millimeter a high level geometric discretisation is necessary.

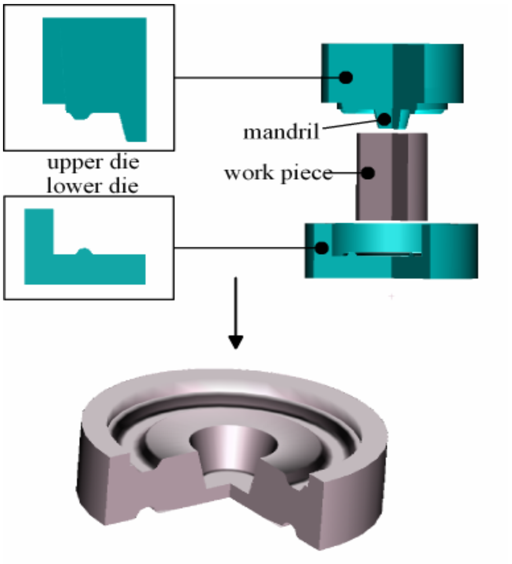

FIGURE 1. Considered precision Forging Process

To allow an accurate heat tarnsfer from the work piece to the dies, the element edge length at the work piece surface has to be smaller than at the die surface. With a local refinement of the FE mesh in this contact area, the interactions betweem work piece and dies can be simulated accurately. In **figure 2** the mesh at the region of the mandril is shown. The heat flow $\dot{Q}$ between two contact bodies with the temperature ϑ_1 and ϑ_2 is described through:

$$\dot{Q} = h \cdot A \cdot (\vartheta_2 - \vartheta_1). \qquad (1)$$

In this equation h is the contact heat transfer coefficient and A the contact surface. Since the highest thermal loadings appear in the upper die only this die is considered in the study.

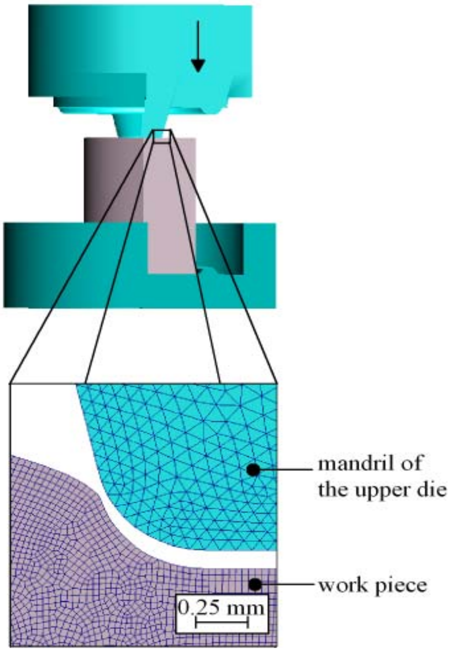

FIGURE 2. FE-mesh at the mandril

Thermal loading of the upper die

Due to the high work piece temperature and the high contact pressure between the work piece and the upper die, the surface layer of the die reaches high temperatures. **Figure 3** shows the temperature distribution of the upper die at the end of the forming process. Because of the short contact time between work piece and upper die only a very thin surface layer of the upper die is heated. The layer where significant heating takes place has an approximate thickness of two millimeters. This thin layer has a important meaning for the die wear.
As easily seen in figure 3, the highest thermal loading appears in the radius of the mandril. The long contact time of the mandril to the hot work piece and the material flow along the radius of the mandril causes great thermal loadings. At regions of the upper die without or with only short contact to the work piece there is no significant temperature rise.

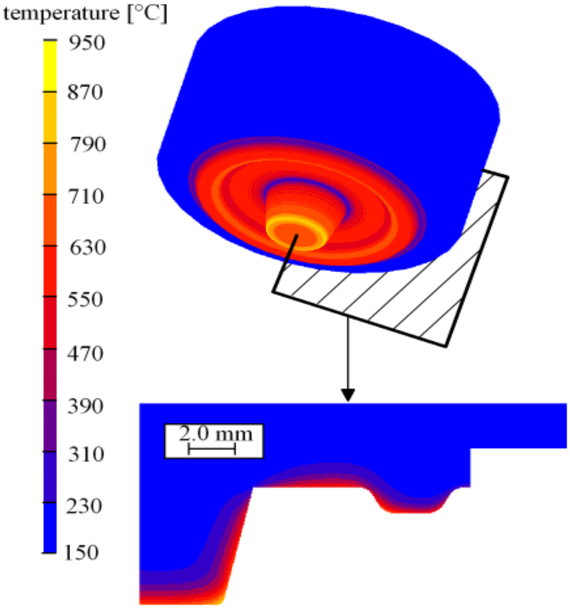

FIGURE 3. Temperature distribution in the upper die

Figure 4 shows the temperature gradient at four locations of the upper die from the edge to the inner of the die. The highest temperatures with over 700°C appear in the radius of the mandril (location 2). At the other locations the temperatures do not reach 700 °C. Temperatures above 500°C occur in a maximal edge distance of 1.2 millimeters. Layers with this temperature are exciting for die wear. Also obviously clear is that in a edge distance of maximal five millimeters the temperature falls to 200°C. In conjunction with the rehardening as a result of exceeding the austenitizing temperature the temperature distribution at the end of a forging cycle is important. To compute the temperature distribution at the end of the forging cycle the cooling of the dies during the unloading sequence have to be considered. The cooling process consists of two periods with the length of about one second. First a heat transfer between the air and the die during the unloading of the work piece takes place. The following lubrication process causes a cooling of the die surface layer. In order to simulate the heat transfer between the lubrication medium and the upper die a temperature dependent heat transfer coefficient is implemented into the simulation with the aid of a user subroutine.

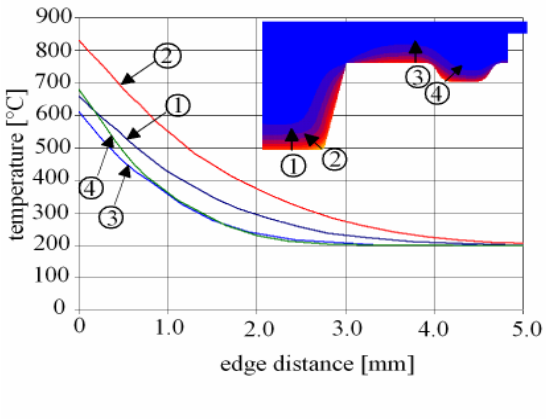

FIGURE 4. temperatures at different locations

The computed temperature distribution at the end of the forging cycle is shown in **figure 5**. At the end of this forging cycle the temperature falls bellow 300°C. Only in the core of the mandril the temperature stays above 300°C, because of the highest heating of this region during the forging process.

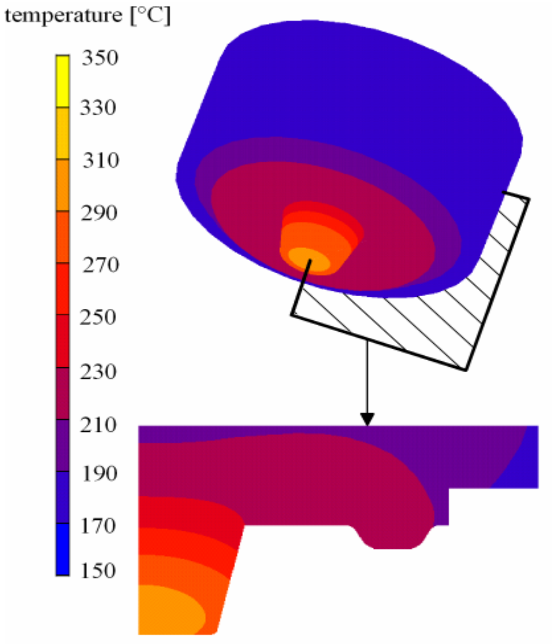

FIGURE 5. temperature distribution at the end of the forging cycle

Influence of the thermal loading on the microstructure

The high temperatures in the die surface layer at the end of the forging process causes changes in the microstructure in this layer. To understand these changes TTT (Time Temperature Transformation) diagrams and annealing diagrams have to be used. But because of the complexity of the procedures at forging these diagrams are of limited significance due to high pressure and short contact time. On the other hand the TTT and annealing diagram can be used for general statements in conjunction with the microstructure in the surface layer of dies. Because of this the hardening of the die after the manufacturing process a unbalanced microstructure is produced. For this reason the austenitizing temperature is below the austenitizing temperature of the normal material. According to **[4]** the die material 32CrMoV12-28 (1.2365) has an austenitizing temperature of 750°C after the hardening process. Due to this fact and the analogy of X38CrMoV5-3 (1.2367) to 32CrMoV12-28 a austenitizing temperature of 780°C can be assumed for X38CrMoV5-3. **Figure 6** shows the area of the upper die where an austenitizing takes place. Only in a very thin layer in the mandril radius the requirements of an austenitizing are fulfilled. At this location a re-hardening takes place since the temperarure falls below the martensite start temperature of 300°C at the end of the forging cycle (**figure 5**).

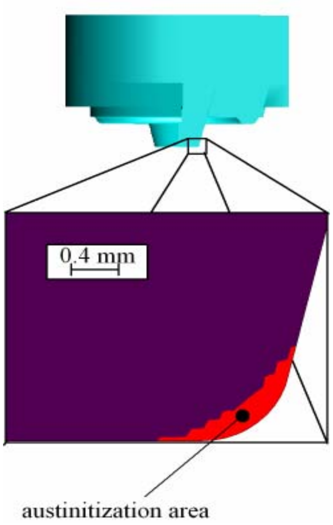

FIGURE 6. austenitizing area at the mandril

According to the annealing diagram of X38CrMoV5-3 temperatures above 500°C lead to a hardness decrease. The critical layer in which annealing effects can occur are shown in **figure 7**. This layer has an maximal thickness of 1.2 millimeter.

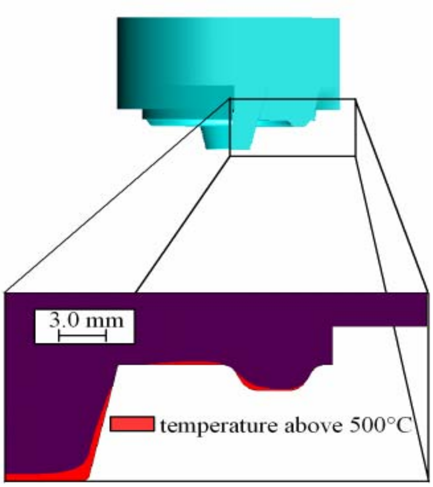

FIGURE 7. critical layer with temperature above 500°C

CONCLUSION

With the FEA a precision forging process is simulated. At this the temperatures in the dies are of particular importance. Since the highest thermal loading appears in the upper die, only this die is considered. To calculate the temperature distributuion in the surface layer of the upper die a high level geometric discretisation is used. The results show that temperatures above 500 °C only occur in a thin surface layer with a maximal thickness of 1.2 millimeters. Furthermore, in the radius of the mandril a re-hardening takes place since the austenitisation temperature is exceeded.

The abrasive wear has a great dependency on the hardness of the microstructure. On this account the knowledge of the hardness of the die surface layer is essential. By use of the developed simulation model the calculation of die wear is possible.

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