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FEM simulation of open die forging of a plate from material NIMONIC 80A in DEFORM 3D

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ABSTRACT

Purpose: This article presents results of a three-dimensional FEM-simulation of open die forging of a plate from material NIMONIC 80A. The FEM-simulation was carried out in DEFORM 3D Multiple Operation.

Design/methodology/approach: The open die forging simulation contains many sequence operations, each single stroke and displacement of dies had to be modelled. The FEM-simulation of the open die forging process was set in accordance with real process conditions.

Findings: The main effect on the crack initiation was the decrease in temperature on a edge of the plate. The real forgings show transverse cracks on the surface which starts on edges of the plate during forging. A good agreement between the simulation and experiment results was observed.

Research limitations/implications: The plastic behaviour of material NIMONIC 80A was defined by means of strain hardening data which was obtained on the basis of measured data from Rastegaev compression test. The desired final thickness of the plate was reached by two procedures to study the effect of an amount of a reduction. The first procedure comprised 8 reduction passes with three reheatings, and second procedure comprised 10 reduction passes with four reheatings. The data evaluation of crack initiation in the FEM-simulation was carried out by tensile tests on the specimens.

Originality/value: This article describes the FEM-simulation of open die forging process that was set in accordance with real process conditions. The aim of this simulation was to analyze the effect of an amount of a reduction on crack initiationon a real plate and to suggest the optimization of the process.

Keywords: FEM-simulation; Open die forging; Strain hardening

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METHODOLOGY OF RESEARCH, ANALYSIS AND MODELLING

1. Introduction

The open die forging process enables production of forged, homogeneous, high strength and long life components. In open die forging, a workpiece is repeatedly deformed between two dies. The FEM-simulation of open die forging contains many sequence operations, where each single stroke of dies had to be modelled. This article describes the FEM-simulation of open die forging process that was set in accordance with real process conditions. The aim of this simulation was to analyze the effect of an amount of a reduction on crack initiation on a real plate and to suggest the optimization of the process.

The temperature region of the plastic deformation is very important for achieving the best formability of NIMONIC 80A. The correct temperatures simultaneously with correct reductions in the open die forging process influence final properties of a product. It is optimal for formability and a final structure of a material when a complete recrystallization occurs during the forming process. Then, it is reached refinement of the grain, but it is also prevented from propagation of micro-cracks along grain boundaries [1]. It is important to keep in mind that NIMONIC alloys have minimum recrystallization ability. Recrystallization of these alloys occurs at temperatures up to 1100°C [2]. As it is also noted in [3], the carbides rearrangement process did not occur at the lowest temperature 950°C, but is clearly visible at higher temperatures.

2. Numerical model

The FEM-simulation was carried out in DEFORM 3D Multiple Operation. The simulation and optimization of industrial forming processes demand accurate knowledge of data that describes material behaviour. The elastic, plastic and thermal data for material NIMONIC 80A were found in the extensive material library of the software DEFORM 3D. Additional experimental measurements were performed in order to obtain correct data of plastic behaviour of the forged material.

2.1. Material properties

The plastic behaviour of the material NIMONIC 80A was defined by means of strain hardening data which were obtained on the basis of measured data from Rastegaev compression test. A uniaxial compression test according Rastegaev was proposed to minimize friction during the measurement and therefore to prevent barrelling of the samples. In this test, the dies and the cylindrical sample are maintained at the same temperature so that die chilling, with its influence on thermal flow, is prevented. In order to maintain nearly isothermal and uniform compression conditions, the test was conducted in the furnace. The compression test was carried out using the testing equipment MTS 810. The tested temperatures were 1000, 1050, 1100 and 1150°C at the constant strain rates 1, 10 and 100 s^{-1}.

The plastic model so-called flow stress data was created from the measurement test and used in simulation. The advantage of this method is the possibility of calculating the flow stress directly from the force measured during compression test. Flow stress data are influenced by deformation temperature, strain and strain rate [4].

In order to guarantee that the calculated flow stress data are “acceptable”, it is necessary to prove that results of the simulation of the compression test with these data correspond to experimental results. Forces and shapes of the samples obtained from the simulation can be compared to experiment and then modify data to fit the process. The essential is to obtain accurate flow stress data that properly describes the plastic material behaviour.

2.2. Process parameters

Simulation parameters for the open die forging were set in accordance to the real process condition. Inputs include the forging temperature range, the number of heatings, the transport time from the furnace to the press, the pass reduction and the displacement of the plate for each pass. The setting up all this information to the software DEFORM 3D Multiple Operation enable to carry out the numerical simulation through defined forming sequence.

The shape and the dimension of the plate and the dies were imported from CAD files. The dimension of the plate was 950 x 650 x 220 mm, and the dimension of the die face was 200 x 1000 mm with the edge radius R80 mm. The forged reduction was from 10 to 5 mm and the displacement of the plate between reductions was 150 mm. The open die forging of the plate was simulated in two procedures, with a different reduction to reach the final desired thickness 155-160 mm of the plate, see Table 1. The first procedure comprised 8 reduction passes with three reheatings, and the second procedure comprised 10 reduction passes with four reheatings.

Table 1.
Forged reduction during open die process

First procedure			Second procedure		
Reduction, mm	Reduction, mm	Furnace	Reduction, mm	Reduction, mm	Furnace
10	8	Reheating	8	6	Reheating
8	8	Reheating	6	6	Reheating
8	8	Reheating	6	6	Reheating
8	8		6	6	Reheating
			6	6	

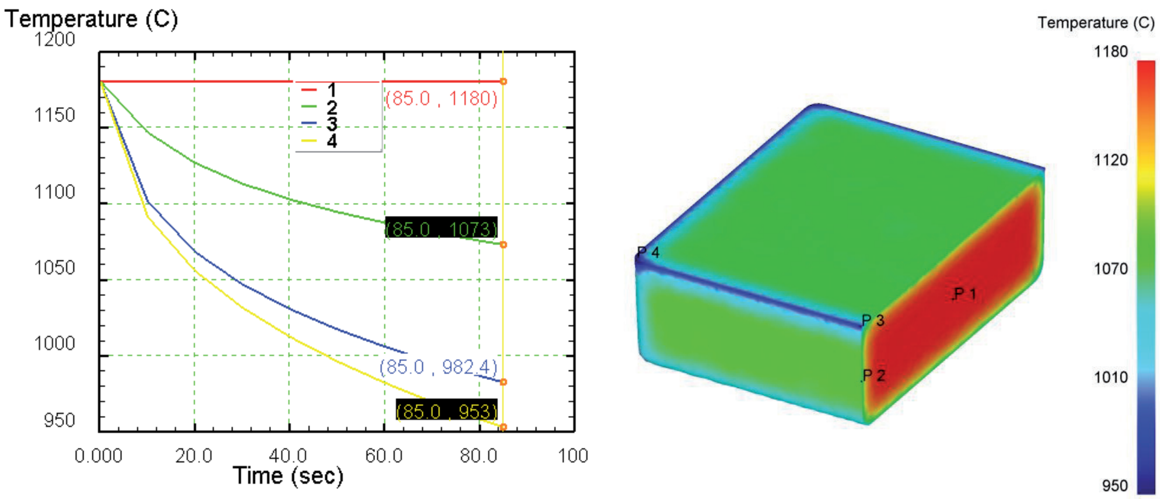

Fig. 1. Temperature drop in the cut plate before start forging

The available load of the forging press was 1600 t and the stroke takes 0.5-1 s. The delays according to the real process are 20 s for the exit from the furnace, 35 s for the grasping and the transport to the manipulator, 30 s for the forging manipulator grip before open die forging starts and 25-30 s for the forging manipulator grip during the plate rotation.

The plate before the open die forging is homogenized at 1180°C and then air-cooled for 85 s which correspond to the transport time from the furnace to the press in real process conditions. The temperature of the dies was estimated at constant value of 350°C which was based on the assumption that the dies will be heated during forging from the workpiece. The temperature gradient in the dies was neglected in the FEM-simulation. The temperature changes were calculated only in the forged plate, it means heat loses to environment, the heat transfer from plate surface to the dies at the contact time, and the heat generation inside workpiece produced both plastic deformation and friction [1]. The ambient temperature was 20°C. The temperature region for NIMONIC 80A is recommended in the range of 950-1120°C in literature [3] or in the range of 1050-1200°C in the data-sheet. The prescribed minimum forging temperature was 950°C. The intermediate heating of the plate between passes was at 1180°C again.

3. Results

First the temperature drop was calculated in the plate due to the transport from the furnace to the press, see Figure 1, where the temperature behaviour in the selected points on the plate is seen. As mentioned before, the prescribed minimum forging temperature was 950°C, but this temperature is reached in the corner of the plate before the forging even start.

The strain of the plate increases in each reduction. The strain occurs particularly at the edge of the die face which is shown by developing local strain areas on the surface of the plate. The following Figure 2 and Figure 3 illustrate a total increase of the strain for the both procedures during open die forging in the last pass, as was described in the Table 1.The total strain in the second procedure is only slightly lower than in the first procedure. The red arrow indicates the displacement of the plate during forging.

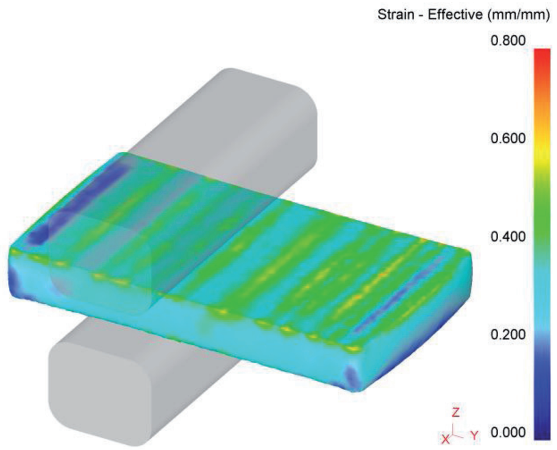

Fig. 2. Last pass in the first procedure

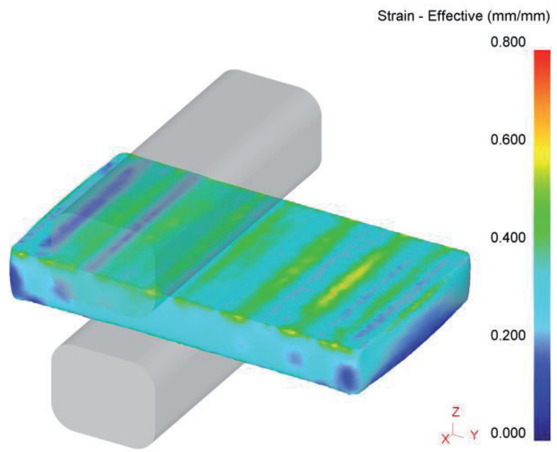

Fig. 3. Last pass in the second procedure

Another important value is the damage of the plate. The damage factor in the simulation can be used to predict the places of the initiation of cracks in the forged plate. The crack occurs when the damage factor has reached its critical value. The critical value of the damage factor must be determined through a physical experiment. The damage factor was calculated using a standard Cockroft-Lathammodel [5]:

$$\int \frac{\sigma^*}{\bar{\sigma}} d\bar{\varepsilon} \tag{1}$$

where: $d\bar{\varepsilon}$ is the effective strain increment, σ^* is tensile maximum principal stress and $\bar{\sigma}$ is effective stress.

The calculated damage of the plate increases in each reduction. The damage peaks are concentrated near the edge of the plate and along its sides, as presented in Figure 4 and Figure 5. There is seen no significant difference in the damage between the two procedures. The distribution of the damage in the first procedure (Figure 4) shows the slightly greater possibility of the crack initiation at the edge of the plate. The photo in Figure 6 shows real cracks in the open die forged plate, which corresponded to the first procedure.

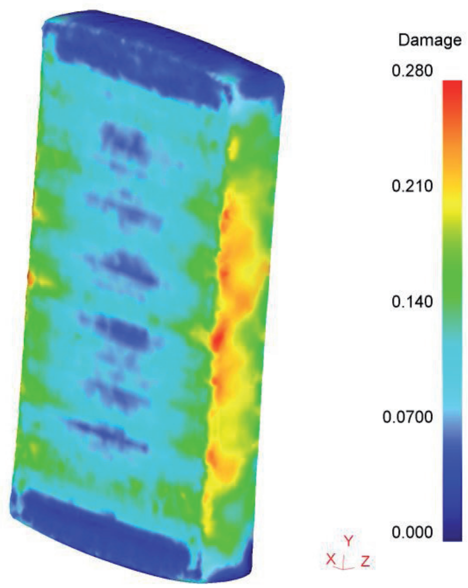

Fig. 4. The distribution of damage at the end of the first procedure

The critical value of the damage factor was obtained using tensile tests. The tests were carried out on the samples at temperature range 950-1050°C and at the constant strain rates 0.1 and 1. The tested temperatures and strain rates were chosen according to the calculated values in the area of the crack initiation. The tensile test was then simulated in the DEFORM 2D to determine the critical value of the damage. The final calculated value for the critical damage factor was in the range of 0.28-0.34 for the most tensile tests, only for the samples tested at 950°C and strain rate 1 s^{-1} was the critical damage factor 0.18. It is important to realize that this value correspond to the minimum prescribed temperature. It means that the probability of the cracks is really large, when the plate is forged near the temperature of 950°C.

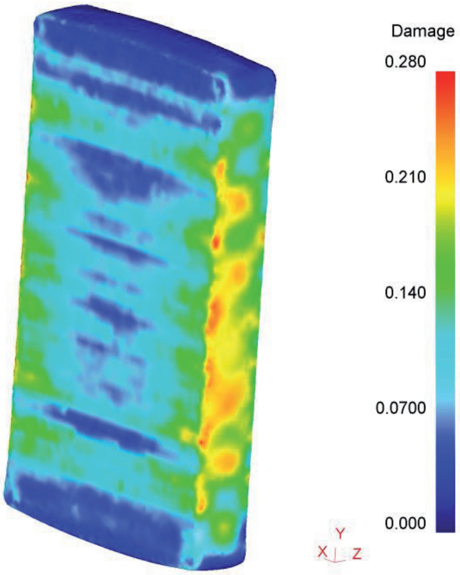

Fig. 5. The distribution of damage at the end of the second procedure

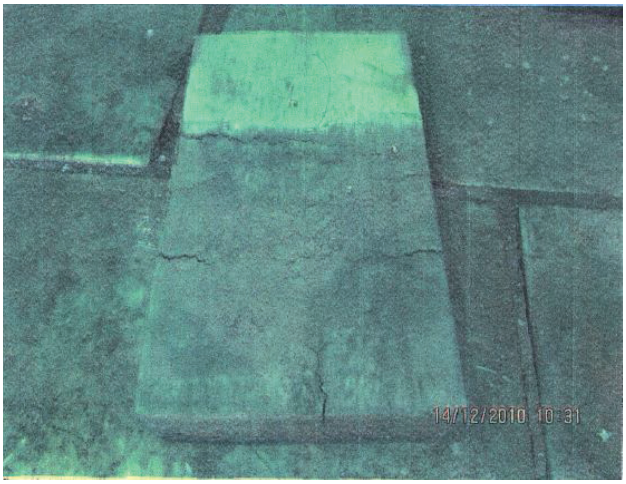

Fig. 6. The cracks on the real plate

As shown in the figures before (see Fig. 4 and Fig. 5), the final calculated value of the damage is on the lower limit of the critical damage factor. The calculated value of the damage peak in the first procedure was 0.27 and the value of the damage peak in the second procedure was 0.26. When the temperature on the edge of the plate is lowered to 950°C, the probability of the cracks will be significantly greater. The calculated temperatures on the edge of the plate were between 1000 and 950°C in the pass after the reheating and between 980°C and 930°C in the pass before the reheating. The temperature drop is caused by the heat exchange with environment and particularly by the chilling of the surface under the pressure contact. There was calculated temperature in the corner of the plate even 900°C before the reheating.

4. Conclusions

The numerical simulation of the open die forging was carried out in DEFORM 3D Multiple Operation. The results of FEM-simulation are strongly dependent on the proper material model of nickel alloy NIMONIC 80A. The material was tested by the Rastegaev compression test. The data obtained from experimental testing was adapted to the simulation as flow stress data.

In this paper, two procedures for prediction of the crack initiation was described and analysed. The first procedure comprised 8 reduction passes with three reheatings, and second procedure comprised 10 reduction passes with four reheatings. There was seen no significant difference in the calculated strain and the damage between these two procedures. The load required by the forming process was smaller than the load available at the press.

In the real process, it is necessary to keep recommended forging temperature to avoid crack formation. The prescribed minimum forging temperature was 950°C in this calculation. The FEM-simulation demonstrated the large temperature drop in the plate at the beginning of the process during the transport plate from the furnace to the press. The prescribed minimum forging temperature was reached in the corner of the plate before the forging even start. Shortening transport times and manipulation times would significantly help to reduce the possible cracks.

The good agreement was found in the prediction of the places of the crack initiation on the forged plate. The cracks at the edge of the plate can be explained by excessive chilling of the surface during forging. The heat transfer between the plate and the dies causes the temperature drop below the prescribed minimum forging temperature.

The critical value of the damage factor was obtained using the additional tensile tests. The simulation of the tensile tests was fitted according to measured data and consequently the critical value of the damage factor was determined. The calculated value of the damage for the both procedures was close to the lower limit of the critical damage factor. Seeing that during simulation was calculated temperature close to the minimum prescribed temperature, it is likely, that there will be cracks on the plate, because the critical value of the damage factor at the temperature of 950°C was significantly lower than at higher temperatures. In the real process, the cracks appeared by both procedures, however, the second procedure shows smaller cracks.

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