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A Combined Numerical and Experimental Investigation on Deterministic Deviations in Hot Forging Processes

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Abstract

In hot forging processes, geometry of the formed workpieces deviate from the desired target geometry, due to complex interactions between tools and billets which result in inhomogeneous temperature and stress fields. The resulting deviation can only be mapped insufficiently by using numerical simulation which makes it difficult to be considered when designing the tool. Therefore, the development of forging tools requires an iterative adaptation process through a large number of revisions in the tool geometry, which escalates the resulting costs. To compensate the deviations and reduce the number of tool revisions, a holistic view of the influencing factors on the geometrical deviation is necessary. In order to address this issue, a hot forging process was developed, whose geometry is prone to high deviations, and a stress-based compensation model was applied. For this, forging experiments were carried out and a comparison was made between the actual geometry and the desired one by means of 3D coordinate measurements. The compensation methodology, which directly takes into account the complex 3D stress states during forming, allows to determine a compensating tool geometry. This opened up the possibility of validating the simulation results and testing a compensation model while eliminating deterministic deviations in hot forging processes.

Keywords: bulk forming; deviation; geometrical compensation; numerical simulation

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1. Introduction

Forging processes are carried out under extreme thermal conditions to reduce the yield stress and increase the formability of the workpiece material [1]. In spite of this, high mechanical loads occur during forming. Due to complex interactions between thermo-elastic-plastic effects and the tool-workpiece system, an accurate prediction of these processes is hardly possible [2,3]. Elastic spring back, caused by high thermomechanical stresses, occurs after forging, which in addition to the shrinkage behavior leads to deviations from the actual to the desired geometry. Because of unpredictable deviations after forming, especially in functional areas of the component, a mechanical post processing is required. In order to reduce the effort of the subsequent process stages, to limit excess material and to keep the machining allowance as low as possible, the tool contour is modified to minimize deviations. In this procedure, the geometry is generally empirically adjusted by trial-and-error to the target contour, which is only an inadequate solution to the problem of precision and causes high costs in the development phase [4]. Decision support systems, connecting forging and product specifications, to evaluate the influence of single monitored process parameters already exist [5]. To reduce iterative steps and to achieve an optimal approximation of the output geometry to the nominal geometry, deviation compensation models can be used.

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2. Method

In sheet metal forming, where the main loading conditions are represented by plane stress state, the application of deviation compensation models has already been extensively studied and validated in previous investigations [6,7]. Since higher forces and temperatures occur in bulk forming processes compared to sheet metal forming, the consequent higher load on the tools must be considered by the deviation compensation model. Although model-based approaches accounting for component variations in bulk forming exist, they are always limited to certain parameter fields or support only certain portions of the deformation. Based on the work of [7,8], the calculation of elastic spring back of solid components is carried out with a three-dimensional high-order approach, taking also into account the shrinkage and transformation behavior of the materials during cooling. The deviation compensation should also lead to a shortening of the process chain due to higher dimensional accuracy.

The conventional compensation strategy and the new approach acting directly on the CAD data are shown in Fig. 1. By identifying phenomenological relationships, the compensation model can generate a tool contour by means of surface replacement, which counteracts deterministic deviations of forged components. In order to be able to test and to adapt the compensation model, the deviations are examined on basis of the results of a sensitivity analysis. Simulation results validated by experimental investigations are used to perform an iterative compensation of occurring deviations. This process is carried out until a sufficient compensation of the deviations is reached. The model is continuously adapted to limit the iteration steps to the design stage, which is ultimately a reasonable solution with high efficiency. The compensation model in its final version expresses the updated tool CAD geometry leading to a strong reduction in the deviations of the parts.

The purpose of the current investigation is to detect deterministic deviations on forgings, arising numerically and experimentally, and to make them available in a suitable form for the validation of a deviation compensation model. In order to generate an optimized bulk formed component geometry an iterative simulation-model coupled process is introduced. The challenge here is to describe an imprecise process and to optimize it to such an extent that even the smallest deviations can be accurately represented and compensated by tool-development.

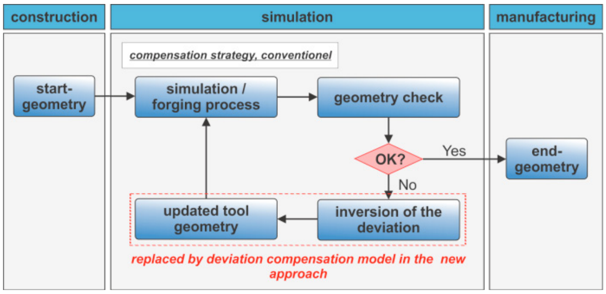

Fig. 1. Comparison of the conventional deviation compensation strategy and the new approach.

Process robustness and adaption of manufacturing tolerances are in focus when considering stochastic influences. By contrast, deterministic deviations can be eliminated by tool compensation, because of their uniform direction and systematic occurrence [9]. To investigate deterministic deviations in forging processes, a rotationally symmetric geometry using DIN 7523 "Steel Forgings" [10] has been developed which allows reducing the influence of stochastic effects. It exhibits systematic contour deviations during deformation due to the complex thermo-mechanical loads arising while forging.

Parameters like thermal changes during the forming cycle, secondary yielding caused by contracting as a result of unloading, elastic recovery of the component, elasticity of tooling and the forming machine, and the thermal contraction of the component after ejection from the forming tools show a significant influence on the geometrical stability [9]. The process parameters workpiece and tool material, forming and tool temperature are varied in this study. In case of workpiece material, research has shown that the carbon content in particular affects the shrinkage behavior [11]. Therefore, the steel 1.7225 (42CrMo4) with a high carbon content and 1.7131 (16MnCr5) steel with low carbon content are used.

The tool material is another important factor considering elastic deformation due to thermo-mechanical process control. Therefore the materials 1.2714 (55NiCrMoV7) and 1.2365 (32CrMoV12-2) were used for the forming dies. Table 1 shows the process parameters, which were investigated full factorial.

Table 1. Process parameters for the experimental sensitivity analysis.

Workpiece material	Tool material	Workpiece temperature [°C]	Tool temperature [°C]
1.7131	1.2714	1250	250
1.7225	1.2365	1050	150

The experiments were carried out with a mechanical screw press “Lasco - SPR 500”. To achieve a homogenous temperature distribution the billets were heated for 15 min in a chamber furnace to selected temperatures. The process used is forging with open die, where the flash is formed from the flange of the cup. The initially produced tool contours are based on the previously defined component geometry, which is assumed to coincide with the target geometry, shown with the tool system in Fig. 2. When the punch penetrates the billet it generates surface area while applying shear forces on the material. Simultaneously high thermo-mechanical stresses are applied, which lead to a complex stress state. During expansion of the flange area, additional tangential tensile stresses are introduced into the component, increasing the complexity of the resulting stresses. After the forging process, the parts were air-cooled. Deviations, which extend from the ideal part geometry, are marked as positive. For negative deviations, the contour appears within the target geometry.

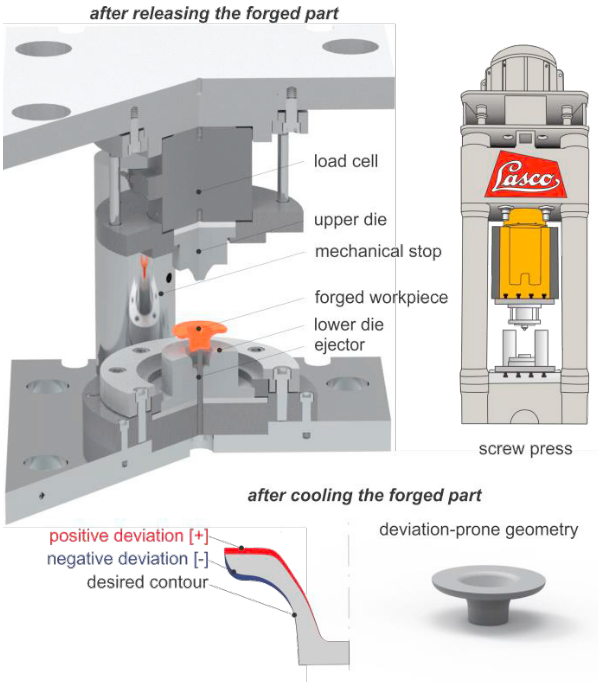

Fig. 2. Tool system with forged workpiece and deviation-prone geometry.

In order to test the dimensional accuracy, contour measurements were carried out. A holistic representation of the entire surface allows the optical measurement system “GOM- Atos 2 400” based on the triangulation principle. The measured geometry can subsequently be superimposed with the target geometry and a comparison of the surface contour can be achieved via inspection sections and following area comparison. Since the measurement uncertainty moves below 0.01 mm this measuring method can be applied. The inspection sections were determined in two levels and compared with 52 specified reference points. Fig. 3 shows illustratively a measured component of the test series with workpiece material 1.7225 at a forming temperature of 1250 °C, formed with dies of 1.2714 at a temperature of 250 °C. The location and number of reference points have been chosen so that the deviation compensation model can optimally determine the contour and further be adapted. For this purpose, the reference points were placed in the region of the radii with a higher dislocation density. The flash that forms in the flange area is not taken into account since it has an indefinable contour.

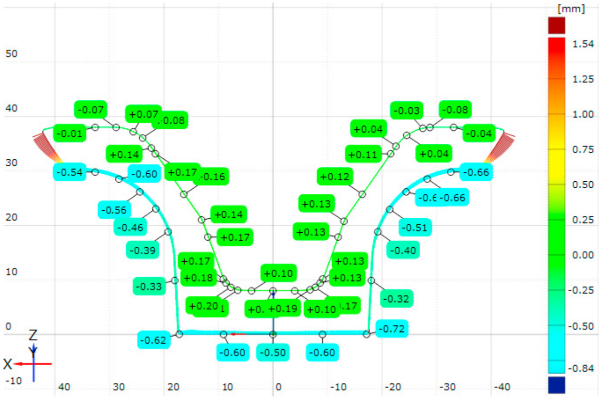

Fig. 3. Deviations measured on a forged part ($T_{1.7225} = 1250°C$; $T_{1.2714} = 250°C$) using GOM.

Within this study, the thermal and mechanical deviations were investigated in a hot forging process. Therefore, material characterization of the workpiece materials 1.7131 and 1.7225 was carried out in order to determine the flow behavior at process related temperatures and strain rates. For each run of the sensitivity analysis, relevant variables, including component deviations and elastic tool deformation, can be written out and thus the influence of the varied parameters on the overall result can be assessed. As a result, the compensation model is based on extensive experimental and numerical investigations on a broad database.

3. Results

The process runs in several stages, which must be taken into account when considering the causes of deviation. The forming process is completed as soon as the stamp is in lowest position. After completion of the forging process, the outer surface is released by the shrinkage from the lower die and the inner surface is pressed to the stamp [6]. The tool geometries were designed in a way that the material flow contributes to increase the flow resistance, which is mainly caused by small radii on the stamp in an area where a large surface generation takes place. In the part geometry, a reduction in cross-sectional area is provided which significantly increases the stress on the dies, since the flow resistance increases as a decreasing cross-sectional area is formed. Fig.4 shows the stress distribution after forming, ejection and cooling. Along these three stages, the highest stresses result at the end of the forming process and are located in the bottom area and cup transition. When considering the individual stages, all deviations can be attributed to different spring back mechanisms. The stresses are largely relieved after ejection, but subsequent cooling leads to the build-up of internal stresses in the component. These mechanisms are to be considered as the cause for the subsequent distortion of the component.

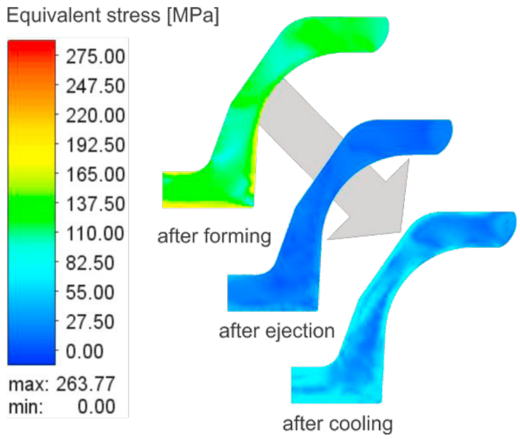

Fig. 4. Equivalent stress of the part in the process stages after forming, after ejection and after cooling to ambient temperature (tool: 1.2714 - 250°C; workpiece: 1.7225 – 1250 °C).

Experimental and numerical results show an influence of the forming and tool temperature on the arising deviations. The interaction of material configurations also shows an influence on the resulting deviations. The forming situation after completion of the forging process is different due to a higher temperature. Tool spring back rises with higher temperatures, thus the component has a more deviating geometry already at the time of ejection. The induced stress in the component and the tool hardly differ here. As the tool temperature rises, there is an increase in deviations of the component base. This is caused by a higher elastic spring back on the upper die side, and by an expansion of the diameter on the die wall on the lower die side.

In Fig. 5 the averaged deviations of the forged parts in the experimental sensitivity analysis are shown. The deviations increase significantly in the examined workpieces with higher temperature. In particular, the tool material 1.2365 shows a higher influence on the elastic spring back in the component than the tool material 1.2714 at a high forming temperature. High forming temperatures show a greater change of the component shape after ejection and cooling. At a temperature of 1250 °C the standard deviations are significantly higher than the elevated temperatures entail higher uncertainties regarding the stress distribution. According to "DIN ISO 286-1" [12], deviations occurring are classified in IT stages depending on the nominal size. For forging with open die IT range 12 - 14 is defined according to [13]. The deviations occurring with tool material 1.2365 show a high difference with changing tool temperature. It can be shown that the tool material also has a significant influence on the accuracy in forging. The deviations, which were caused by using 1.2365 and a forming temperature of 1250 °C, are outside the tolerance range that should be achieved during forging at higher temperatures. Likewise, the temperature of the investigated tool materials shows an increasing influence with rising temperatures. The comparison of the forging contour with the ideal contour shows the occurrence of small deviations. The simulative deviations are smaller than the experimental ones, since stochastic effects on the surface like scale formation and an inhomogeneous application of lubricant can hardly be simulated on the forging process. The workpieces were observed at the end of the forming process, at the bottom dead center of the die movement, directly after ejection and after cooling. After ejection a complete relaxation takes place, additional deviations caused by internal stresses due to cooling process are illustrated by the simulation and the final deviations of the workpieces. For further simulative adjustment, the test series with the workpiece ($T_{1.7225}$ = 1250 °C) and the tool ($T_{1.2714}$ = 250 °C) is considered, since it showed high contour deviations with low standard deviations within the test series.

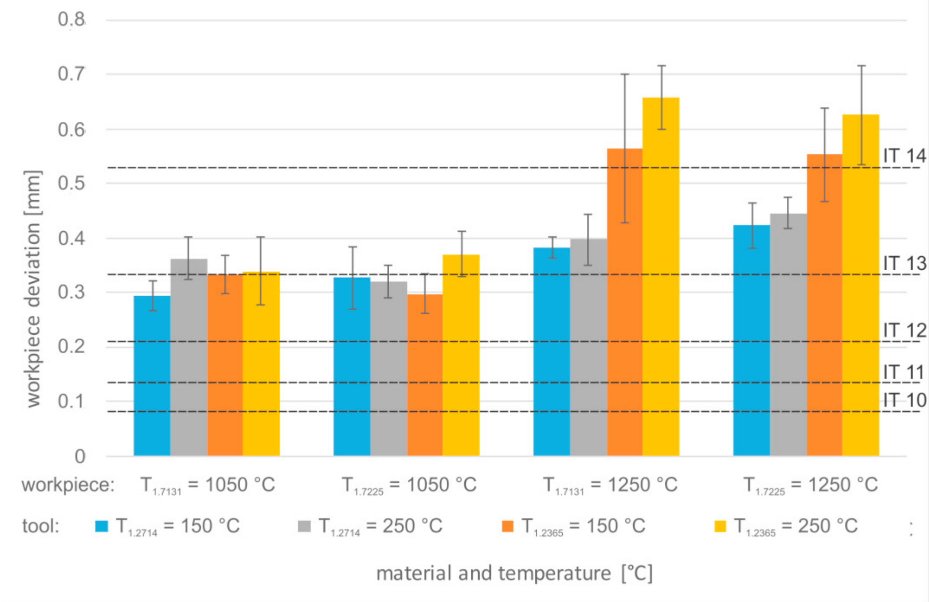

Fig. 5. Arithmetic mean of the measured deviations on forged workpieces under varied tool and workpiece material at different interacting temperatures.

The simulation-coupled compensation of the forging deviations with the iteration stages carried out is shown in Fig. 6. Here, a distinction is made between the deviations on the upper and lower edges. After the fourth iteration step, the deviations, caused by the upper die, increase again. A reduction of the determinological deviations of 65 % is achieved numerically. By adapting the tool geometry to the compensated shape, a higher mechanical and technological effort is required because the new geometry of splines is composed on the tool contour.
After the 4th iteration step overcompensation occurs and the geometries show larger deviations. Following iterations do not result in an improvement that justifies further iterative adjustments.

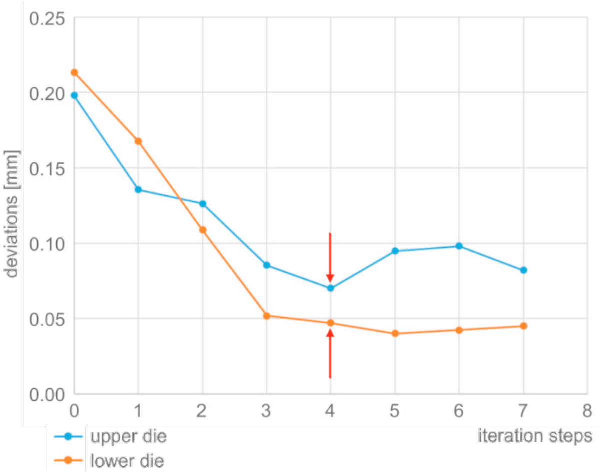

Fig. 6: Numerical contour deviations transferred by the upper and lower die after iterative adaption.

4. Discussion

The experimental results show significant influence of the forming temperature on the deviations occurring in the forming process. By increasing the forming temperature from 1050 °C to 1250 °C, significant changes in the form accuracy were detected. The strain on the tool, outside of the numerical representation, seems to be subject to fluctuations due to stochastic influences which cannot be calculated. The forming forces cause high mechanical stresses, which increase sharply during forging with open die towards the end of the forming process due to the pressure in the die. The ultimate stresses in the tool result from the superposition of mechanical and thermal loads [14]. Deviations from the ideal geometry already occur at the end of the forming process, which are caused by elastic deformation of the tools. Depending on the workpiece material and temperature conditions, these deviations are mainly due to the temperature-dependent flow stresses during forming. The spring back of the tool is detected by increasing deviations with raising tool temperature, while the other conditions remain the same. It is shown that the workpieces forged with tools made of 1.2365 show significantly higher deviations than the reference material. This can be attributed to a lower pressure resistance at higher temperatures, as this effect was only observed at 250 °C tool temperature. Tools made of 1.2714 show also a slight increase in deviations at higher base temperatures. Comparing the simulative results with the experimental forms the scale layer that forms in the experiment around the workpiece surface draws an irregular offset of the deviations. This is reflected in a high standard deviation, which increases significantly as the forming temperature rises and is responsible for irregularities in the surface condition. This also has an influence on the dimensional stability of the component in conjunction with the forming temperature parameter, since different stresses are primarily caused in the die. However, lower forming forces at higher forming temperatures do not allow for smaller deviations, but lead to increased distortion after cooling caused by the shrinkage behavior and the development of residual stresses.

With the deviation compensation model examined, a significant reduction of the occurring deviations has been numerically demonstrated. However, no surface changes such as scaling are taken into account, which leads to an additional influencing parameter.

5. Conclusion

The causes of the deviations introduced are initially triggered by the forming process itself, whereby not only the geometric conditions but also the tool material and its temperature must be taken into account in addition to the geometric conditions. The experimental results show that a significant influence of the forming temperature can be observed. Here, the heating process and the duration of heating should be considered more closely. In order to reduce the stochastic deviations, an inductive heating strategy is considered to cause a lower scaling, which has a negative effect on the friction conditions or the material flow. However, this leads to an inhomogeneous yield stress distribution in the workpiece. To achieve a higher accuracy without the offset caused by surface reactions, additional measures must be taken to reduce scaling, e.g. heating in an inert gas atmosphere. When compensating the tool geometry numerically, the range of IT 9 can be reached, which otherwise can only be achieved by complex additional measures or precision forging with closed die. For further investigations the 4. iteration step will be covered within real experiments. The production of the tools to an iteratively adapted, deviation-compensated tool contour represents a challenge in terms of manufacturing technology, since a complex contour is created and also the manufacturing deviations must be taken into account during tool production.

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