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New method for the manufacturing of curved workpieces by open-die forging

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A R T I C L E I N F O

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A B S T R A C T

Open-die forging is an incremental bulk metal forming process usually applied for the production of straight workpieces with a symmetric cross-section. A new approach for the integrated open-die forging of curved workpieces is presented, in which the material flow is actively controlled by manipulator displacements. When these displacements are performed during forging strokes, a significant reduction of the bending force compared to conventional bending is achieved. This paper presents the integrated forging and bending process combining several individual forming steps to a forging pass. Based on numerical and experimental investigations, the influence of various process parameters on the workpiece curvature and geometry is discussed.

1. Introduction

Open-die forging is an incremental bulk metal forming process which is mainly applied for the production of long and straight workpieces. Besides achieving the intended final geometry, one main objective of open-die forging is to improve the workpieces' mechanical properties so that forged workpieces are often used for safety-relevant or highly loaded parts. Especially in aerospace industry, a significant demand for complex open-die forged parts exists. Since common open-die forging does not allow a process-integrated near-net shape production of complex workpieces without using special tools, usually a high amount of machining is required to achieve the desired geometries.

One common approach in metal forming to increase the range of producible geometries is based on stress superposition as shown for bending of tubes in [1] and curved extrusion in [2].

In [3], this principle was firstly transferred to open-die forging and generally validated both regarding the force reduction compared to conventional bending processes and the possibility to actively control the material flow during a forging stroke. Since the principle was generally proven in a small scaled model experiment and for one single forming step [3], the aim of the study presented within this paper is the investigation of a new kind of open-die forging process by developing a suitable kinematic procedure for an industrially scaled forging plant. This new kinematic concept is developed and evaluated using an open-die forging robot.

2. Open-die forging of curved workpieces

Regarding open-die forging, the methods for the production of curved workpieces are generally summarized in [4] and [5].

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In [4], Groche et al. present different kinds of methods for the flexible production in bulk metal forming like ring rolling, swaging and forging. Allwood et al. summarize in [5] different approaches for flexible forging like intermittent partial forging and forging using wedge-shaped dies.

One approach using simple tools and simple preform geometries was realized in the so-called "transverse stretch forging" [6] as shown in Fig. 1a. This process approach is based on the idea that in contrast to the common open-die forging the workpiece is aligned under a certain angle α related to the forging dies leading to a trapezoidal compressed area. Due to this, the material shears toward the side, leading to the formation of a curvature. The main disadvantages are the required very large height reductions and alignment angles. To achieve a bending angle of 15°, the workpiece needs to be forged with an alignment angle α of 45° and a height reduction of 50%. This approach is rarely used in industrial production, since common open-die forging manipulators are limited to a small movement range and usually cannot achieve alignment angles larger than 10°.

One approach using simple tools and complex preform geometries was investigated for the forging of workpieces with a profiled cross-section [7] as shown in Fig. 1b. It is following the principle that a non-constant thickness in width direction effects an inhomogeneous material flow during the forging stroke. Depending on the chosen cross-section, significant workpiece angles and small radii can be realized. The main disadvantage of this approach is given by the preform geometries, since the production of the preforms requires an additional manufacturing step. Furthermore, the formation of the curvature is strongly depending on the preform, so that during the actual forging process the geometry can hardly be influenced.

Nakamura et al. [8] developed the so-called "intermittent partial forging", where the workpiece is partially forged in width direction using a narrow forging die, resulting in a curvature of the workpiece. In [9] a modified process concept was presented where the bending was additionally realized by different scaled contact areas at both forging tools.

For in-plane bending, where the material flows on a plane perpendicular to the forging direction, as defined in [10], Jin and Murata proposed in [10] and [11] a new process concept which is based on the application of wedge-shaped forging dies as a special tool. Due to the wedge-shaped dies, a linear distribution of the thickness reduction along the cross-section of the die is achieved, leading to a curvature of the workpiece.

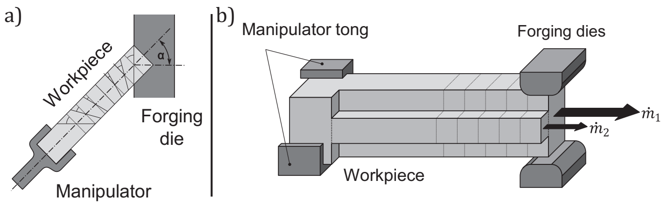

Fig. 1. (a) Transverse stretch forging [6] and (b) forging of a workpiece with profiled cross section according to [7].

As described, different methods for the open-die forging of curved workpieces have been developed in the past. They have in common that they either require special forging robots with a large movement range (transverse stretch forging), additional forming steps (forging of profiled cross-sections) or special tool setups (intermittent partial forging, forging with wedge-shaped dies). The known methods are limited regarding the achievable geometries and lacking flexibility. Therefore a new method which allows the integrated production of curved workpieces by open-die forging through superimposed stresses could be a promising approach to realize a new and cost-efficient production method for curved workpieces with excellent mechanical properties.

3. New process principle

3.1. Physical principle and process setup

The new process concept was firstly proposed in [3] and is following the idea that the plastic stress state during an open-die forging stroke is utilized to form the material toward a curved geometry by using the manipulator.

The physical principle leading to the force reduction in the case of superimposed stresses compared to pure bending can be explained as follows: In pure bending the bending stresses must necessarily be high enough to reach the yield criterion, while during a forging stroke, the deformed material is fully plasticized, so that the equivalent stress has already reached the yield stress due to the moving forging die. In this condition the direction of plastic flow is determined by the Levy–Mises flow rule:

$$\dot{\epsilon}_{ij} = \dot{\lambda}_{ij} \cdot s_{ij}$$

($\dot{\epsilon}_{ij}$: strain rate; $\dot{\lambda}_{ij}$: proportionality factor; s_{ij}: deviatoric stress.)

Following the Levy–Mises flow rule, in a plastic state of stress any deviatoric stress component will cause a correlated strain rate, so that superimposed stresses below the flow stress can be used to modify the material flow direction. In this sense a controlled displacement of the manipulator during the forging stroke superimposes bending stresses as schematically shown in Fig. 2b and forms the workpiece toward a curved geometry. The material between the manipulator tong and the forging dies is not plasticized, since the superimposed stresses do not reach the flow stress. Thus, only the material in the plasticized zone is formed, whereas the part between manipulator tong and dies is not bent. Because already small forces are sufficient to bend the workpiece, the process can be realized using common forging manipulators.

Fig. 2 shows a comparison of conventional open-die forging (Fig. 2a) and the new process approach (Fig. 2b). The general setup of these two process types is similar, since two forging dies and a manipulator are required. The main difference is that the

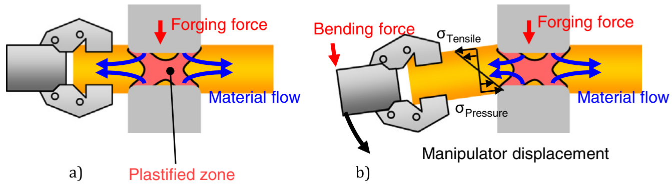

Fig. 2. (a) Conventional open-die forging and (b) open-die forging with superimposed manipulator displacements.

manipulator, which is commonly used as holding device, is used to actively control the material flow toward the desired geometry. Using common forging manipulators, which are often rail-bound and strongly limited in their movements, generally two variations of the process exist.

1. Out-of-plane bending or vertical bending: The bending displacement of the manipulator is parallel to the forging direction and thus performed in a vertical plane.
2. In-plane bending or horizontal bending: The bending displacement is perpendicular to the forging direction and thus performed in a horizontal plane.

Fig. 3 shows a schematic close-up of the bending in vertical direction with the corresponding main process parameters. The process can be characterized by the following parameters:

- Bite ratio: ratio of bite length s_B and height h
- Relative height reduction $\varepsilon_h = (h_0 - h_1)/h_0$
- Bending angle α

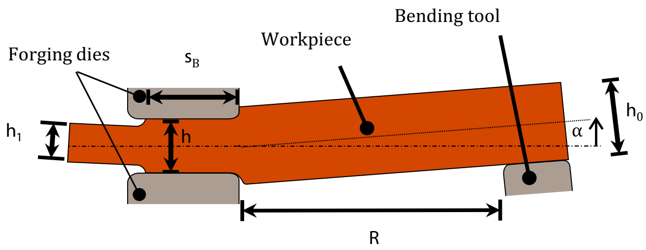

Fig. 3. Detailed view of the vertical bending process [3].

3.2. Transfer to an industrial setup

To investigate the concept and validate the applicability for open-die forging in an industrial scale, the concept was transferred to the open-die forging center at the IBF. The setup consists of a 6.3 MN hydraulic open-die forging press by SMS group GmbH and a six axis heavy-duty hydraulic forging robot by GLAMA Maschinenbau GmbH with a maximum lifting weight of 300 kg. Commonly, the robot is only used to position the workpieces during open-die forging. In order to realize the intended process, the movement of the robot needs to comply with the following requirements:

1. During the forging stroke, the manipulator tong needs to move on a path similar to a circle, since a circular-shaped geometry should be achieved.
2. The tool center point needs to be continuously oriented toward the center point of the circle at the edge of the forging die.
3. The manipulator may not impede the material flow in longitudinal direction, since in open-die forging the main material flow is occurring in longitudinal direction.

Fig. 4 visualizes the required movement for horizontal in-plane bending (Fig. 4a) and vertical out-of-plane bending (Fig. 4b). Open-die forging robots and manipulators are not designed to move along specified paths. Usually they are equipped with a simple “Point to Point” movement control, which does not allow the