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Two-step electromagnetic forming: A new forming approach to local features of large-size sheet metal parts

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ABSTRACT

A new two-step electromagnetic forming (two-step EMF) which combines electromagnetic forming (EM forming) with electromagnetic calibration (EM calibration), is proposed for local features of large-size sheet metal parts, such as an oblique hole-flanging. During the process, the workpiece is firstly electromagnetic formed by a flat spiral coil and then electromagnetic calibrated by a helix coil with a similar shape to the final profile of the workpiece. To develop the process, an efficient geometric design method is established, the effects of key process parameters on forming quality are investigated, and the deformation behavior of the workpiece is revealed. The feasibility of two-step EMF is validated by the accurate oblique hole-flanging with a maximum die-fitting gap less than 0.2 mm. Moreover, experimental results show that there are critical discharge voltages for both EM forming and EM calibration which lead to the minimum die-fitting gap. Furthermore, EM calibration can reduce the die-fitting gap to 0.24~1 times of that for EM forming with more uniform distribution. In addition, simulation results show that during EM calibration, the stress distribution of the workpiece is improved, the bending moment is reduced which is responsible for the shape and size errors, then the rebound is restricted. Consequently, the fittability and forming accuracy are significantly enhanced.

1. Introduction

Large-size aluminum sheet metal parts with a characteristic size larger than 1.5 m are broadly applied in many fields such as aerospace, aviation, and automotive industry, due to the low density, high strength and excellent overall performance of aluminum alloy [1,2]. Complex features need to be formed in local regions of large-size sheet metal parts which were integrally manufactured [3] to meet some specific requirements. For example, it is necessary to form some local hole-flangings on the bottom part of a propellant tank for pipe connections. As shown in Fig. 1, the local axis of the hole-flanging is usually parallel to the global axis of the component, so there is an angle between the local normal direction and global axis.

Because of the relatively low formability of aluminum alloy at room temperature [5], the large stretching and bending deformation in forming regions [6], as well as the difficult metal flow caused by strain hardening [3], the workpiece tends to crack or tear along the circumference at the flanged edge, when a local oblique hole-flanging of large-size sheet metal part is formed by conventional stamping [7]. In order to avoid this problem, a general approach is forming the workpiece by small deformation with multi-pass methods and annealing the strained local regions between the passes. However, the compromised conventional solution results in more complex processing, worse flexibility and longer forming periods. Meanwhile, for large-size sheet metal parts, conventional stamping requires the press machine with large-size workbench, complicated forming tools, precise assembly and strict motion control, which all raise the difficulty and cost [8]. Furthermore, the springback of the workpiece formed by conventional stamping is quite severe due to the high strength to weight ratio of aluminum alloy [9,10], which undermines the forming accuracy. To sum up, it is a costly task to form the local features of large-size sheet metal parts by conventional stamping while the forming quality is not guaranteed. Therefore, forming processes with lower complexity and higher efficiency should be explored. Electromagnetic forming (EMF) technology is one of the potential alternatives due to its high precision, high repeatability, contact-free and environmentally friendly, which has been widely used in metal forming [11].

EMF is a high-speed forming technology using electromagnetic body

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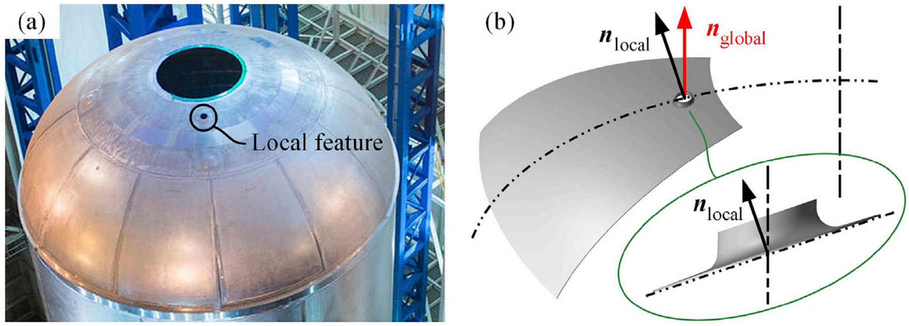

Fig. 1. A typical large-size aluminum sheet metal part (a) a dome-shaped component extracted from Ref. [4], (b) illustration of global and local axes.

forces to deform metallic workpieces [12], which is prominently applicable for metals with a high electrical conductivity such as copper, aluminum, magnesium [11]. Many studies show that the formability of metals with low ductility is significantly enhanced by EMF [5,13,14]. Therefore, the plastic flow in forming areas of workpieces can be promoted and the risk of material failure during the process can be reduced by EMF. In addition, the springback of the workpieces is reduced or eliminated by EMF [15,16], then the forming accuracy will be improved. What's more, compared with conventional stamping, the local features of large-size sheet metal parts can be fabricated by EMF by relatively simple tools to assemble the forming coils (instead of punches), workpieces and dies, which diminishes the requirements of forming equipment and process control, hence enhances the flexibility of the forming process.

EMF process can be classified into two categories: electromagnetic forming (EM forming) and electromagnetic calibration (EM calibration), and EM forming can be divided into integral forming and local forming. Noh et al. [17] formed a conical sheet part with middle hollow by a flat spiral coil and an optimized discharge voltage. Electromagnetic incremental forming was proposed by Cui et al. [18], which forms large parts by the accumulation of local deformations caused by discharges of a small coil along desired paths. Similarly, electromagnetic superposed forming was developed by Long et al. [19] which expanded the application of EMF into aircraft skin manufacturing. Electromagnetically assisted sheet metal stamping (EMAS) was developed by Shang et al. [20], which stretches local regions of workpieces by coils embedded into conventional tools. Okoye et al. [21] combined EMAS with incremental sheet metal forming to form some difficult-to-form contours and successfully applied it to a car door. Imbert et al. [22] remarkably reduced the local radius of a pre-formed V-shaped part which couldn't be realized by conventional stamping. The above researches broaden the application scope of EMF and indicate that EMF is especially suitable for sheet metal parts with large size and deformation. On the other hand, the most important advantage of EMF is enhancing the formability of lightweight metal materials, and then expanding the allowable design and application range of workpieces.

EM calibration reduces the springback of workpieces in two ways. One is to decrease the residual strain, because the high-speed impact between the workpiece and die generates plastic wave front running through the workpiece [23]. The other is to relieve the internal stress because the magnetic pressure pulse results in elastic wave running through the thickness of the workpiece back and forth [16]. Golovashchenko [15] demonstrated that the residual stress can be eliminated by subjecting the workpiece to the pulsed electromagnetic field during EM calibration. Woodward et al. [24] achieved significantly improved forming accuracy by EM calibration. They calibrated the pre-formed parts by disposable actuators and restricted the shape deviation to ±0.5 mm for most test points. The above researches show that the springback of workpieces can be reduced, and then the forming quality can be improved by EM calibration.

It is now well-known that EMF is widely used in both forming and calibration. However, the conventional local EM forming using one coil cannot well form local features of large-size sheet metal parts with satisfyingly high accuracy, due to the complexity of material flow as well as the difficulty in the control of the die-fitting gap and shape accuracy. For this reason, based on the principle of EMF and taking the forming of an oblique hole-flanging as an example, a two-step electromagnetic forming (two-step EMF) process is proposed which combines EM forming with EM calibration. On the other hand, for hole-flanging, current studies mainly concentrate on the forming process for normal flangings [25–27], but rarely involves the oblique ones. Thus, the geometric design for workpieces and tools that is vital for the oblique hole-flanging still remains unresolved, as well as the determination of process parameters, in particular. Moreover, as the base of the process control and quality improvement, it is significant to understand the deformation behavior of the workpieces and the influencing mechanism of the process on forming quality.

In this study, a geometric design method is established to determine the shape and key dimensions of the workpiece and the die firstly. Then the geometric design method and the two-step EMF process are validated by experiments. Furthermore, effects of key process parameters, i.e. the shape and dimensions of the workpiece, the discharge voltages of EM forming and EM calibration, on forming quality are revealed experimentally. In addition, the deformation behavior of the workpiece and the mechanism of improved forming accuracy are analyzed by simulations.

2. Process principle and geometric design

2.1. Process principle

Two-step EMF is proposed to form local features of large-size sheet metal parts. During the process, the workpiece is firstly formed to intermediate shapes which are close to the target one, by coils which have general profiles similar to the current shape of the workpiece. Then the intermediate workpiece is calibrated by a coil with a general profile similar to the target shape of the workpiece. For EM forming, one or several discharges can be chosen, according to the shape and thickness of the workpiece, the deformation degree, the maximum energy of the pulse generator, the coil structure and so on. Moreover, different forming coils with different profiles can be used to form, for instance, thick or large workpieces that cannot be formed by just one discharge.

Taking the oblique hole-flanging as an example, the principle of two-step EMF process is illustrated in Fig. 2. Firstly, a flat spiral coil is used to drive the workpiece to the die cavity (see Fig. 2(a)). Thus the workpiece obtains an intermediate shape with huge deviation from the die (see Fig. 2(b)). The forming coil is then replaced by a helix coil to calibrate the workpiece (see Fig. 2(c)), and subsequently, the workpiece gains an accurate final shape (see Fig. 2(d)).

2.2. Geometric design

Some analytical methods were provided by the studies of Hu et al. and Yeh et al. [28,29] and the cited herein, to inversely calculate the profile