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Formability of micro-gears fabrication in laser dynamic flexible punching

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ABSTRACT

A novel laser dynamic flexible punching process is employed to fabricate micro-gears to address the difficulties in punch-to-die alignment in the conventional micro-punching process. In this process, induced shockwaves act as micro-punches and soft punch acts as the media to transmit pressure. The influences of laser intensity, foil thickness and grain size on dimensional accuracy and rollover diameter have been investigated experimentally. In addition, the changes in the hardness and elastic modulus of the workpiece after the laser shock effect are characterized by nano-indentation experiments. It is revealed that the dimensional accuracy is optimal when the laser intensity is 5.6 GW/cm^2, but the laser intensity has little effect on the rollover diameter. Punched gears of thicker foils result in worse dimensional accuracy and larger rollover diameter. Foils annealed at 350 °C achieve the best punching accuracy but compromise with regard to the maximum rollover diameter. Furthermore, both the nano-hardness (9.92%) and elastic modulus (14.37%) are improved after the laser shock effect, as the evidence of an increase of surface strength and material stiffness. The proposed method, laser dynamic flexible punching, will potentially lead to new methods for micro-gears fabrication in the future.

1. Introduction

In recent years, researchers have paid increasing attention to the fabrication of high-quality micro-parts, especially micro-gears used as indispensable actuating components in micro electro mechanical systems (MEMS). It is worth noting that an efficient and economic approach has become a common goal for many researchers in the modern society. Currently, LIGA (Lithography Electroforming Molding) is one of the well-known precise techniques to fabricate micro-components, especially for larger depth-diameter ratios. Kim et al. (2002) selected micro-gears as the LIGA test pattern and the aspect ratio for the gears was 15:1. However, the photoresist and X-ray mask used in this process are expensive and it is time-consuming, so its wide application is limited. Horiuchi et al. (2006) fabricated micro-gears with pitch diameters of 760–1100 μm successfully via UV-LIGA (Ultraviolet Lithography Electroforming Molding), which is similar to the LIGA process. In the process, X-rays were replaced by less costly ultraviolet radiation and SU-8 acted as the photoresist, reducing the cost compared with LIGA. However, it is undeniable that UV-LIGA is still a very complex process. Micro wire electrical discharge machining (WEDM) is another popular method to fabricate micro-components. Gupta and Jain (2014) fabricated miniature spur gears via WEDM and analyzed the effects of voltage, pulse-on time, pulse-off time and wire feed rate on the total profile deviation 'Fa' and accumulated pitch deviation 'Fp'. The principle of the process is that the discharge reaction between the wire electrode and the components melts local material. The desired shape is obtained by controlling the movement of the wire electrode. In the process, wire electrodes must be changed because of the problem of wear. In addition, the wire is prone to fracture owing to insufficient stiffness, reducing the accuracy of the sharp narrow groove and other features of the gear. Micro-extrusion experiments were conducted by Kim and Sa (2006) to fabricate micro-gears. In the process, N_2 gas was purged into a chamber and boron nitride served as lubricant to reduce the friction between the sample and container and between the sample and the microdie. The sample was loaded into a container, heated to 533 K and 537 K and then extruded into the gear die after a holding time of 10 min. In addition, AZ31 Mg alloys that undergo ECAP (fine-grained equal channel angular press) process are more suitable for the process because of the large drop in yield stress after ECAP, so the process is also relatively complicated. Gupta and Jain (2014) proposed that conventional processes, such as hobbing, die casting, extrusion and powder metallurgy, are the

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most common methods used for manufacturing miniature gears. They think those process have certain limitations. For instance, high-quality gears require subsequent polishing and long set-up time for the hobbing process; die casting cannot be used in case requiring extreme accuracy, and subsequent trimming operations are necessary after the gear has been removed from the die; wear of die is a major problem for the extrusion process and requires secondary drawing operation to improve the accuracy of gears; for powder metallurgy, it is difficult to de-bind of the parts from mold and arrange the fine metal powder of all types.

Impulse forming, particularly electromagnetic forming, is a high-speed forming technology. Psyk et al. (2011) conducted comprehensive review of the electromagnetic forming technology and concluded that it is superior in terms of repeatability, throughput, and formability. In 2008, the International Impulse Forming Group (I^2FG) was founded to provide a platform for knowledge exchange and discuss the state of the art and future goals in the field of impulse forming. In 2011, the Journal of Materials Processing Technology released a special issue on impulse forming to summarize recent progress. Vivek et al. (2014) used the rapid vaporization of thin conductors driven electrically to produce short pressure pulses to form or emboss thin metal foils. Polyurethane was used as a medium to transfer pressure from the aluminum foil to the workpiece. Finally, pure titanium foils were fully formed into a cell phone case die and AA2024-T3 aluminum alloy foils were embossed into a die with various depths. Golovashchenko (2006) used electromagnetic forming to expand the capabilities of conventional forming technologies applied to the corner filling operation, springback calibration and joining of closed frames with an assembled coil experimentally. In addition, electromagnetic forming can also achieve the cutting process. Maier-Komor et al. (2010) used an electromagnetic field in three ways (expansion, compression and compression with the use of a field former) to cut a hollow profile and investigated the cutting energies to complete the separation of the material. The cutting surface consists of a large rollover and a fracture zone free of cracks, but there is no burr at the end of the surface. Additionally, Maier-Komor et al. (2010) believed that the trimming of the work piece, the abscission of the circle tube profiles, the separation of multiple parts or the punching and coping of profiles could be realized.

Laser processing technology is also an ultrafast process with an ultrahigh strain rate typically up to 10^6–10^7 s^{-1}. It is usually completed in the range of nanoseconds to milliseconds as an alternative of impulse forming. It has been applied rapidly in the fields of biomedicine, communications and industrial production owing to its high efficiency, flexibility and accuracy. Zhou et al. (2002) carried out a series of laser shock forming experiments to bulge metal sheets, with compressive residual stress on the surface of the workpiece. It demonstrated the potential of the process as a flexible manufacturing process with excellent reproducibility and very short manufacturing time. In recent years, the research team led by Cheng has carried on the thorough study to the laser dynamic forming (LDF) and micro laser dynamic forming (μLDF). Yu et al. (2009) extends LDF to functional and brittle materials sandwiched by elastomeric polymers on patterned 3D surface. The elastomeric polymers avoid the fracture and minimize the degradation of the materials and the patterned surface leads to controllable plasticity on the materials. Gao et al. (2009) introduced complex 3D profiles in thin films with a microsized mold in μLDF. A series of numerical simulations were conducted to investigate the effects of the ratio of the fillet radius to film thickness, the aspect ratio of mold as well as laser intensities on deformation behaviors with the verified simulation model. To investigate the forming limit and fracture of aluminum foils in microscale LDF, Li et al. (2010) increased the laser intensity until fracture was observed in the samples. It was found that the foils can deform very deeply up to more than four times of the foil thickness before failure occurs because of the ultrahigh strain rate generated in the LDF process. To keep the forming velocity below the critical forming velocity of the ultrathin aluminum foils, Li and Cheng (2010) employed the multiple-pulse in LDF. The effects of the multiple-pulse LDF on the deformation depth and thickness variation distribution of the formed 3D features were characterized. It was found that the maximum attainable deformation depth can be increased and the thickness distribution of material was more uniform, indicating an improvement forming capability of LDF. μLDF experiments were conducted by Gao and Cheng (2011) to fabricate grid microstructure. They proposed that strain rate and sample size play important roles in determining the dynamic plasticity and final results of μLDF. A multiscale modeling methodology was adopted to characterize the microscale dynamic plasticity considering the evolutions of nano-to-submicron dislocations avalanches under shock loading. Gao et al. (2013) demonstrated capability of laser dynamic forming to direct integration of functional structures on 3D microscale surfaces on three substrates. They encapsulated functional materials in a soft polymer material as cushion layers and controlled laser pulse intensity in order to integrate them onto the 3D surfaces. They also investigated the process conditions on these structures by experiments and numerical simulations and found that the ability of direct transfer is affected by the laser intensity, cushion layer thickness and geometry of the 3D substrates. Gao et al. (2014) used a laser shock to compress metallic sheets into a silicon nanomold and realized the fabrication of smooth ultrafine metallic nanopatterns in the laser shock imprinting process (LSI). To understand the underlying mechanisms of LSI, they investigated the microstructure of Al nanobars from the perspective of grain refinement, dislocation density and recrystallization. They also fabricated periodic aluminum nanotrenches with 10, 20 and 30 nm gaps and realized the formation of graphene–metal hybrid nanostructures by directly imprinting a single layer of grapheme grown on Cu foil. Liu et al. (2010) combined the conventional micro-punching process with laser shock forming and put forward a novel and highly efficient process that not only made full use of the ultrahigh strain rate of laser dynamic forming but also solved the technical problem of alignment between the micro punch and the mold. Using the same technology, Liu et al. (2013) successfully punched a high-quality array of square holes in the 20 μm aluminum using this technology, and validated its feasibility in micro-part manufacturing via finite element mesh (FEM) and smooth particle hydrodynamic (SPH) methods. However, they mainly focused on simple contours, such as round holes and plum blossom holes but did not involve the punching of parts with complex contours, such as micro-gears. Moreover, the study of the size effect (foil thickness and grain size) inherent in the laser dynamic flexible punching process is very limited. The specific purposes of the present work are to punch micro internal gears via the laser dynamic flexible punching process and investigated the influence of laser intensity, foil thickness and grain size on the punching quality.

2. Experiments

2.1. Laser dynamic flexible punching process

2.1.1. Punching mechanism

Fig. 1 depicts the schematic setup of the laser dynamic flexible punching process. The experimental device mainly comprises a blank-holder, confinement layer, ablative layer, soft punch, workpiece and punching die. As the diagram shows, the short-pulse laser irradiates horizontally through the shutter and focuses on a point by the focal lens. The spot diameter on the confinement depends on the distance between the focal point and the 3D mobile platform,