Study of Ultra-Precision Cutting of Amorphous Alloy

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論文内容要約

Functional microstructured surfaces have attracted attention from scientists and engineers in recent years. Surfaces with tailored periodic, random, hierarchical, or hybrid textures at micro- or nanometer scale (hereafter referred to as nano/micro) can indu novel functional performances such as antireflective / retroreflective / diffractive effects, optimal friction coefficient, self-cleani action and so on. These functional performances strongly depend on the features of structures on surfaces. Especially, the fo precision of the structures seriously affects the optical performances of optical functional surfaces. For example, a hybrid diffracti refractive lens composing surface microstructures with their pitch at several tens of micrometers can realize an achromatic singl while several optical components are required with the conventional achromatic optical systems. The hybrid structures can help reduce the weight and the size of optical systems, but structural defects on the lens seriously deteriorate the performance of the le Moreover, various microstructures such as V-shaped groove, square grooves, holes, lens arrays and pyramid arrays are required optical components depending on a design of optical functions. Therefore, the development of manufacturing methods capable of precisely fabricating various microstructures on polymer or glass is a primary task.

There have been many manufacturing methods to fabricate microstructures developed in different industrial fields, in which the process consists of ultra-precision cutting with diamond tools and molding is suitable for fabricating optical components with microstructures for mass production. Microstructures are fabricated on the mold surface by the ultra-precision cutting and then the mold surface profile is replicated on a preform of optical component at the molding. Burr and chipping generated at the cutting process will deteriorate the form precision and the durability of the mold. The mold material should have good machinability for microfabrication in addition to good mechanical properties. Electroless nickel phosphorus (hereinafter, Ni-P) plating is suitable material since it has excellent mechanical properties including high hardness, good wear resistance and heat resistance. However, Ni-P is an amorphous alloy and there are only few researches on cutting of amorphous alloys. Namely, the effects of material properties and cutting parameters on burr and chipping generations when fabricating microstructures are not well understood. Thus, the machinability of Ni-P is not well understood and thus cutting parameters are difficult to be optimized. To reveal the machinability of Ni-P, the chip formation process has to be revealed and compared with other conventional mold materials. To achieve high precision of microstructures, the design process has to be developed.

The main objectives of this dissertation are the following:(1) to reveal the burr and chipping formation mechanism of Ni-P and compare it with those of other crystalline metals; (2) to define the effect of cutting parameters on the burr and chipping generation; (3) to establish the design method for cutting a tailored microstructure, and finally to establish the process for cutting tailored microstructure on Ni-P.

Firstly, the chip formation processes, which represent the whole deformation during the materials removal, at Ni-P and other conventional mold metals were revealed and compared. In Chapter 2, experiments of parallel microgrooving and orthogonally crossed microgrooving were conducted on three metals: Ni-P, oxygen-free copper C1020 and aluminum alloy A7075. Three tools with different tool nose shapes were used in the experiments: two triangle tools with nose angle of 90°and 60°, and a tapered square tool with nose width of 10 µm. The burrs and chippings were generated on the groove edges and the exit part. The formed chips and the chip origins were observed to estimate the chip formation processes of the three materials. The conventional continuous chip is generated in C1020 cutting. The slippages were observed on the chip of A7075, which was little serrated. The slippages were also observed on the chip surface of Ni-P and their slippages were smaller, more stable and more frequent than those of A7075. Under the conditions where obvious burrs were generated, the area of the plastic deformation on the chip origin partially protrudes from the cutting locus. The plastic deformation that emerges outside of the cutting locus remains on the structure edge after the cut and form the burr. Under the conditions where the chippings are generated on C1020, material was torn off and partly left on the exit part. Under the conditions where chippings were generated on A7075 and Ni-P, large slippages arose and they propagate passing the outside of the cutting locus, which caused the chipping.

The results verified that the slippage plays an important role in the burr and chipping generation. As the large strain emerges instantaneously at the slippage occurrence, an accumulation of plastic strain and the subsequent plastic deformation expansion are prevented. Therefore, the generations of large burrs and chippings are prevented under the conditions where the small and frequent slippages occur. Moreover, the results verified that the stability of slippage occurrence directly affects the stability of the burr and chipping generation. The slippages on Ni-P were the smallest, the most frequent and the most stable in the three materials. These results came from what induced the slippages: shear fracture induces them on crystalline metals; meanwhile the inhomogeneous deformation (IHD) does on amorphous alloys. The yield stress and propagation path of IHD are much more stable than those of crystalline metals. All the results in Chapter 2 indicate that Ni-P has excellent machinability compared with C1020 and A7075.

Chapter 3 investigates the effect of cutting parameters on the burr and chipping generation, so the following three conditions were varied one by one: (1) tool geometries and depths of cut, (2) tilting angle of the tool, and (3) finish cut. Experiments of varying tool geometries and depths of cut verified that the higher the geometry of tool aspect ratio became, the larger burrs and chippings got. Experiments with a tilted tool verified that the angle between the tool edge and the material flow direction, hereinafter referred to as the chip-edge angle, is an important factor in the burr and chipping generation; burrs and chippings decrease with the increase in the chip-edge angle. Experiments of finish cut verified that designing its geometry can control the forms of burr and chipping. However, the actual burr and chipping cannot be predicted from cutting conditions since the emergence of the homogeneous deformation and the slippage, which cannot be predicted by existing theories, seriously affects the burr and chipping generation.

In Chapter 4, numerical simulations of the cut were performed to reveal the mechanism of the emergence of the homogeneous deformation and the slippage. The distributions of maximum shear stress (MSS) and compressive stress at the moment immediately before a major slippage occurrence were evaluated by the simulations of elastic deformation. The simulation results showed that the high MSS is distributed at which the small and frequent slippages occur and high compressive stress is distributed at which the homogeneous deformation occurs, and they agree well with the slippage behavior in the experimental results. They also showed that the different stress distributions are observed at the finish cut and the cut with the tilted tool, which verified that the burrs and chippings can be controlled by designing the cutting procedure which consists of multiple cuts. However, the definitive criteria for the emergence of the homogeneous deformation and the slippage could not be founded in the simulation results. Thus, the burrs and chippings cannot be predicted precisely from cutting conditions. It indicates that the experimental validation is necessary for each process to design an optimal cutting procedure.

In Chapter 5, the design of the cutting procedure for fabricating the objective structure without large burr or chipping, which is a cross tapered square groove with the bottom width of 20 µm and the depth of 30 µm. The structure has high aspect ratio of almost 1.0 and very steep groove surface, which are the factors making the machining process difficult. Therefore, if the design method is validated as capable of designing the optimal cutting condition at the cutting of the objective structure, it also verifies the design method can be applied for fabricating various microstructures precisely. The slide cut method was proposed for fabricating the trapezoid groove with high chip-edge angles and the sharp groove edges. The burr and chipping formation at the slide cut were experimentally confirmed as it was designed. To sum up the whole preceding discussions of this dissertation, the optimized cutting procedure consists of eleven steps including the slide cut was designed and conducted. The result verified that the burr and chipping generations at each step are as designed, and the objective structure was successfully fabricated with only small chippings on one side of the exit parts. The results also verified that the design process developed in this dissertation is effective to optimize a cutting procedure for fabricating various microstructures precisely.

Chapter 6 gives out general conclusions. The present dissertation revealed the chip formation mechanisms during ultra-precision cutting of C1020, A7075 and Ni-P in relation to the material properties. The comparison of chip formation mechanisms revealed that Ni-P has an excellent machinability. The effects of cutting parameters on the burr and chipping generations, and their mechanisms were clarified. The optimal cutting procedure for fabricating the microstructure was designed and conducted. The results proved that the designed ultra-precision cutting process can fabricate various microstructures precisely.