Large area micro-texture imprinting onto metallic sheet via CNC stamping

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Abstract

Micro-lens array and micro optical elements require for geometrically accurate registration of micro-patterns onto the oxide glasses. Heat radiation device and heat reservoir units have to equip their own unique micro-patterns with high aspect ratio. Lithography and related processes, or, micro- and nano-imprinting are effective to make these micro-patterns once onto the silicon or silica substrates. Even in those applications, the aspect ratio of micro-patterns is still limited to be shallow. The authors have been developing a new method to fabricate a DLC (Diamond-Like Carbon) coated mother mold-die by plasma oxygen etching and to duplicate the original micro-patterns on the mold-die onto the metallic and plastic sheets. This approach is suitable not only to mass-production of micro-patterned sensors and devices but also to selective nano- and micro-imprinting of various micro-patterns onto the metallic sheets. In the present paper, a micro-cavity pattern with the unit size of 3.5x3.5x4.6 \(\mu m^3\) is imprinted onto an aluminum sheet with the thickness of 0.08 mm by CNC-stamping with use of the micro-textured DLC-die. This CNC-stamping system is revised to make motion control both in loading and unloading processes for improvement of geometric accuracy and increase of aspect ratio in the micro-cavity pattern. Among several motion-control programs, a pulse-wise motion is employed to duplicate the deeper micro-cavity patterns onto the aluminum sheets.

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1. Introduction

High power generated in the mobile phones or in the power semi-conductor, become a heat source. Smart phone customers suffer from low-temperature skin burns in U.S.-FCC, 2011. The present heat transfer capacity of heat sink cannot catch up with high power density generated in the power semi-conductors in EV (Ohnuts, 2014). In past, many efforts have been advanced in the literature: e.g. forced cooling system by heat pipe (Chi, 1976), heat absorption by phase transformation (Watch, 2014), or, heat conductive paints (Moisala, 2006). However, these steps are still insufficient to make a solution to the above engineering issues. Heat radiation device (Yugami, 2010) was proposed to activate the heat radiation process by its micro-textured surface. In an ideal heat radiation device working at the ambient temperature, a high heat flux comes up from the bottom of device and changes to electromagnetic waves with longer wave length. Since the micro-cavity on the conductive device material works as a resonator, these waves radiate from solid substrate to air. Hence, the geometric configuration of each micro-cavity must be precisely formed on the heat conductive substrate. In addition, the density of micro-cavity assembly must be dense to increase the equivalent heat transfer coefficient in radiation. Lithography, LIGA ((Lithographie, Galvanof ormung, Abformung) process or micro- and nano-imprinting (Pang, 1998) are effective to make these micro-patterns once onto the silicon or silica substrates. They have little or no means to make fine micro-patterns onto the metallic sheets. Two technological issues must be solved: how to construct the original mother micro-texture and how to duplicate this micro-pattern onto the metallic sheet.

The authors (Aizawa, 2013-1) have been developing a new method to fabricate a DLC (Diamond-Like Carbon) coated mother mold-die by high density plasma oxygen etching in order to solve the first issue. Owing to the reactive ion etching via the high density oxygen plasmas, micro-grooves and micro-grids were etched into the DLC coating to have higher depth to width ratio. CNC-stamping also became a solution to the second issue where this mother micro-texture on the DLC-die should be duplicated on the metallic sheet by fine stamping (Aizawa, 2013-2). In particular, the DLC coating was utilized as a mold-die material so that friction and wear could be reduced in the stamping processes for duplication of micro-patterns. In order to lower the working stresses in stamping and to attain higher aspect ratio in micro-patterning, a stamping process must be updated to control the macroscopic deformation of work materials as well as microscopic metal flow around each micro-pattern during stamping.

In the present paper, the heat radiation device with the micro-cavity texture is fabricated by CNC-stamping from the aluminum sheet. Two dimensional mask, corresponding to the micro-texturing design, is micro-printed onto the surface of DLC-coated die unit. High density oxygen plasma etching system is used to remove the unmasked DLC coating and to build up the micro-textured die unit. This die unit is fixed into a cassette mold-die for CNC stamping to duplicate the mother micro-texture onto the work material sheet. In particular, the effect of selective motion controls on the micro-texturing into aluminum sheet is experimentally investigated. Two loading sequences are employed to quantitatively control the micro-embossing process: normal and pulsewise loading motions. In each motion control, the relationship between the applied pressure and average micro-cavity depth is measured to describe the micro-frictional behavior during micro-embossing. Incremental loading becomes the first way to reduce the micro-friction by using the stepwise motion; unloading sub-sequence in the pulsewise motion significantly reduces this micro-friction. Reduction of micro-friction results in enlargement of the surface area extension ratio during the micro-embossing of micro-cavity patterns.

2. Experimental procedure

Table-top CNC (Computer-Numerical-Control) cold stamping system with the capacity of 200 kN, was developed in order to establish the micro-embossing line in mass production. This system worked on the table top; temporal variation of processing parameters was directly controlled besides data acquisition. Both stroke and load were digitally monitored by load cell and linear scale, respectively. The maximum working speed was 10 mm/s. The stroke range was designed to be wide for various deformation modes in micro-embossing; e.g., open height between upper and lower bolster plates was 187 mm, and, the maximum stroke, 55 mm. A cassette mold-die unit was placed between upper and lower bolster plates; actually working mold-die pair was set-up in this cassette mold-die unit. In parallel with precise positioning control, both the loading and displacement rates were also controllable; then, loading and stroke sequences were both programmed to be run for optimum sequential control to each experimental set-up. To be noticed, the CNC feeding system of metallic sheets was attached to the above
mold-stamping system, not only to control the movement of work material in backward and forward but also to make tension control of thin sheet material for suppression of wrinkling. Dimensional accuracy in CNC-feeding was 2 μm. When using the CNC stamper, various kinds of motion control were performed by a customized program. In the following experiments, two motion-controls were employed to investigate their effect on the micro-imprinting behavior of micro-textures onto the aluminum sheet: i.e., the normal loading and the pulsewise loading. In the former, the applied load was controlled to monotonically increase up to the specified holding load before unloading. In the latter, the unloading sub-sequence was included in each incremental loading in case of the pulse-wise loading.

Thick DLC (Diamond-Like Carbon) film was formed on the AISI420 stainless steel die by CVD coating; the thickness of DLC coating was 10 μm. This DLC coating was used as a die material for micro-embossing, as shown in Fig. 1 a). The two dimensional masking pattern was first formed on this DLC film as a mother micro-texture by photo-lithographic etching procedure. Thin mask was designed to have a negative pattern; e.g. in case of micro-cavity formation onto the aluminum sheet, the original mask must have a square dot pattern. High density oxygen plasma etching system was employed to remove the un-masked DLC film. Through this process, the original square dot pattern on the mask changed itself to be a square prism pattern. Figure 1 b) shows an SEM image of formed micro-texture by this high density oxygen plasma etching process. The square-head DLC micro-punches with 3.5x 3.5 x 4.6 μm³ were formed in regular alignment into the DLC-coated AISI420 stainless steel die. The pitch between the adjacent square prism DLC micro-punches was 1.5 μm. Then, the density of DLC-punches aligned on the mold die-pair in Fig. 1 was 40,000 punches mm⁻².

An aluminum sheet with the purity of 99.94 %, the average grain size of 8 μm, and the thickness of 80 μm was prepared as a work material. PTFE (Poly-Tetra-Fluoro-Ethylene) sheet with the thickness of 100 μm was also used as an elastic foundation material. Optical microscope and SEM (Scanning electron microscope) were utilized for observation and measurement of formed micro-textures. Laser microscope was also employed to measure the micro-cavity depth profile.

Fig. 1. Micro-textured DLC die for precisely fine stamping. a) DLC-coated AISI-420 dies and b) SEM image of microtexture imprinted onto the DLC coatings.

3. Experimental results

CNC mold stamping system was utilized to make micro-embossing onto a pure aluminum sheet by using the cassette mold-die at the room temperature. As the first motion controlling procedure, the stroke sequence was programmed to be loaded with the constant velocity up to the maximum stroke corresponding to the specified load and to be also unloaded with the constant velocity. In the following experiments, one shot requires for 10 seconds. No lubrication was performed during this micro-embossing experiment. In every one shot of micro-embossing by CNC-stamping, the original microtexture on the DLC-punches is progressively duplicated onto the aluminum sheet. Aluminum sheet outside of the contact with the DLC-punches has metallic shining without wrinkling since it is fixed by upper and lower die striper during stamping. The micro-embossed area in the aluminum sheet has a rainbow color because of surface plasmon effect by duplicated micro-cavities. In the above normal loading motion,
a shallow micro-cavity was first formed on the contact area between the DLC-punch and the aluminum sheet up to \( p_c = 90 \) MPa. This bulging deformation changes to the shearing deformation at this critical applied stress. When the applied stress \( (p) \) is higher than 90 MPa, a deeper micro-cavity is formed on the aluminum sheet together with formation of its fresh side surface by shearing deformation. As depicted in Fig. 2, the applied stress still increases monotonically with deepening the average micro-cavity depth \( (d) \). To be discussed in later, this \( d \) is determined by the laser microscopic measurement in the line scanning.

![Fig. 2. Variation of the micro-cavity depth with increasing the applied pressure by the normal loading and the pulsewise loading motions.](image)

In the normal motion, the SEM image of formed micro-cavities at \( p = 200 \) MPa, is shown in Fig. 3. A micro-cavity pattern is formed onto the aluminum sheet; a square head shape of DLC micro-punch with \( 3.5 \times 3.5 \) \( \mu \)m\(^2\) is imprinted onto the bottom of cavity. A micro-cavity depth profile, measured by the laser microscope, was inserted in Fig. 3. Rectangular prism micro-cavity is formed and aligned to have four side walls to neighboring micro-cavities. The clearance of \( 1.5 \) \( \mu \)m between neighboring DLC-punches turns to be an aluminum wall between the neighboring micro-cavities. However, significant irregularities or defects are observed in its depth or on its side walls; e.g. the maximum depth in Fig. 3 is attained at the micro-cavity “A” by \( d_{\text{max}} = 3.4 \) \( \mu \)m but the depth of micro-cavity “B” is only \( 2.3 \) \( \mu \)m. This occurrence of defects as well as un-filling metal flow into a DLC mold-die, might be caused by the micro-friction between the work material and the DLC-punch during formation of fresh side walls of micro-cavity.

![Fig. 3. SEM image of micro-cavity texture imprinted onto pure aluminum sheet by normal loading motion.](image)
The pulsewise loading motion is employed to improve this micro-embossing behavior. In this motion, a loading sequence is composed of a set of sub-sequences like a pulse. In a single sub-sequence, loading and unloading steps are included. In addition of the incremental loading by this sub-sequential loading and unloading steps, the unloading to loading ratio in one step plays a role in improvement of total micro-embossing process. As compared to the normal loading motion, the average micro-cavity depth reaches to 3.8 to 3.9 \( \mu \text{m} \) even when applying the stress up to 140 MPa. Considering that this depth is limited by 3.4 \( \mu \text{m} \) by \( p = 200 \) MPa in normal loading, much deeper micro-cavities are formed by this pulsewise motion. This high formability seen in the significant reduction of applied stress reflects on the quality of micro-cavity pattern duplicated onto the aluminum sheet. Figure 4 depicts an SEM image of imprinted micro-cavity pattern by this pulsewise motion control.

![Fig. 4. SEM image of micro-cavity texture imprinted onto pure aluminum sheet by the pulsewise loading motion for \( p = 200 \) MPa.](image)

The maximum depth of micro-cavity reaches to 4.3 \( \mu \text{m} \). No defects or irregularities in the micro-cavity pattern as seen in Fig. 2 are detected in this imprinting; homogeneous micro-cavity pattern is precisely duplicated on to the aluminum sheet. This high quality in micro-embossing process might be attributed to significant reduction of micro-friction. During micro-embossing, a micro-cavity is gradually formed by piercing the DLC-punch into aluminum sheet for \( p > P_c \). Since four side surfaces of this micro-cavity are newly formed as a fresh surface, the adhesive force between DLC-punch and these fresh surfaces works as a frictional stress. The surface area extension ratio \( (r) \) has a significant effect on the frictional process in forging or in press-forging of automotive parts. Even in the micro-texturing into the aluminum sheet, this \( r \) is expected to affect the micro-frictional behavior. The original surface area \( (A_0) \) in contact with the DLC-punch is defined by \( A_0 = b^2 \). Since fresh side surfaces of micro-cavities are formed by micro-embossing, this \( A_0 \) changes to \( A_0 + 4 \times b \times d \), for the current micro-cavity depth \( (d) \). Then, the surface area extension ratio \( (r) \) in micro-embossing is calculated by

\[
r = \frac{(A_0 + 4 \times b \times d)}{A_0} = 1 + 4 \times \frac{(d/b)}{b^2}. \tag{1}
\]

For an example, this \( r \) is estimated to be 6.0 for the deepest micro-cavity when \( d = 4.3 \mu \text{m} \) when the maximum micro-cavity depth is attained. Considering that the filling process into a micro-cavity by metal flow is terminated when the average depth approaches to the DLC-punch height or \( d = 4.6 \mu \text{m} \), this surface area extension ratio is mainly governed by the micro-friction when \( r < 6.0 \). The friction coefficient is expected to increase with significant increase of surface area extension ratio in micro-embossing.

Assuming that increase of applied pressure is mainly balanced with the frictional stress, the average micro-frictional stress \( (P_f) \) in forming the fresh side surfaces of micro-cavity is represented by \( P_f = p - P_c \). From the measured relations between the applied pressure and the average micro-cavity depth in Fig. 2, the relationship
between \( P_f \) and \( r \) is calculated to describe the micro-frictional behavior in micro-embossing. Figure 5 shows the variation of frictional stress with increasing the surface area extension ratio for three loading motion controls. In the normal loading motion, \( r \) is limited by \( r = 4.0 \) by significant micro-friction. Incremental loading in the stepwise motion reduces this micro-friction to extend \( r \) up to \( r = 5.0 \). Unloading sub-sequence in the pulsewise motion lowers the frictional stress; \( P_f = 50 \text{ MPa} \) even for \( r > 5.0 \). The surface area extension ratio becomes nearly constant even for \( P_f > 50 \text{ MPa} \) in the pulsewise motion. This is because the microscopic metal flow turns to be in un-filled state when \( d \) comes up to the DLC-punch height. In other word, \( r \) is expected to monotonically increase without significant increase of \( P_f \) if the average micro-cavity depth is less than the DLC-punch height.

Fig. 5. Relationship between the frictional stress (\( P_f \)) and the surface area extension ratio (\( r \)) for \( p > 90 \text{ MPa} \).

4. Conclusion

Micro-cavity textures with \( 3.5 \times 3.5 \times 4.3 \mu m^3 \) were successfully duplicated into the aluminum sheet with use of DLC-die by selection of adequate loading motion. Both the macroscopic formability and the microscopic plastic flow were significantly affected by the CNC-motion control. In case of normal motion, the micro-cavity depth was strictly suppressed by local friction during the surface area extension in forming its fresh side surfaces. The incremental loading in the stepwise motion can afford to lower the micro-frictions. Unloading sub-sequence in the pulsewise motion control has a significant role to attain higher surface area extension ratio without much increase of the applied pressure.

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