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Tribological Behaviors of DLC Films and their Application in Micro-Deep Drawability

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In this study, the surface of micro-punches is coated with a ceramic matrix composite, a graded diamond-like-carbon (DLC) film, in order to improve the micro-deep drawing formability. DLC coatings with Zr/ZrC/NZrC were prepared by magnetron sputtering. The effect of graded DLC films, such as surface textures and wear properties on the ability for the deep drawing of micro-cups based on laser diode copper alloy sheet was explored. In addition, the application of the DLC coated SKD11 substrate to the drawability was demonstrated and its applicability was explored in comparison with that of the other films such as SKD11, CrN and ZrN, and the size effect of friction on the formability of drawn circular cups is discussed according to the DLC films coated punch diameters. Experimental results showed that the graded DLC films significantly improved the surface textures and wear behaviors of the micro-punches. The DLC coated punches which dramatically decreased the stamping force and increased the drawing ratio was better than for other films, whose the drawing ratio yielded an increase of about 24% in the coated micro-punch diameter of 2.5 mm types. The applicability of the DLC films for the drawability of micro-cups was successfully demonstrated through the micro-deep drawing process. Accordingly, the DLC films prepared by magnetron sputtering are promising candidates for enhancing the drawability of micro-cups based on laser diode copper.

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PACS/topics: diamond-like-carbon, micro-deep drawing, magnetron sputtering, drawability, surface texture

1. Introduction

Following the rapid development of electronic products, there is a growing demand for micro-forming in the fields of electronic products, electro-mechanical systems, medical equipment and sensor technology. The miniaturization of various related products has drawn increasing attention and most micro-/meso products are produced by metal castings. For these castings, various metal micro-forming methods have been developed [1–3]. However, micro-sheet metal forming offers potential savings in energy and material — especially with micro-manufacturing technologies for production quantities. In addition, for a given geometry, parts produced by micro-sheet metal forming exhibit better mechanical and metallurgical properties and are more reliable than those manufactured by casting or machining. However, several micro-scale factors such as surface textures and friction that can be overlooked in macro-forming become obvious and significant with the plastic deformation behaviors of thin sheet in micro-deep drawing. The size effect is concerned with the friction and material behaviour, which are significantly relevant for almost all forming processes. Thus, sheet metal drawing for complex-geometry shapes in micro-forming is very difficult due to wrinkling or excessive localized thinning. Many efforts have been put into the design phase of dies and the process such as the perspectives of lubrication, process optimization, and tool coating technologies [4–6]. Due to size effects, several non-intrinsic properties such as surface roughness, frictional coefficient and surface textures are significantly important compared to the minute sizes of micro-products. Several obstacles need to be solved in terms of the dimensions and properties relating to size effects in micro-metal forming, including cup shaped, box-shaped or structural components with complex geometry [7, 8]. However, effects due to the development of micro-scale on the micro-forming process and product quality have not yet been sufficiently researched. This is, at least in part, because the manufacturing of micro-components in micro-deep drawability can be challenging.

To fulfil the superiority of micro-deep metal drawing, the use of surface engineering techniques can enhance surface quality and wear resistance in tool materials, which are significantly important to protect the micro-dies from failure during micro-forming. Due to environmental constraints leading to the demand for green lubricants, solid lubrication films have become a critical issue to improve lubrication in micro-metal forming [9–11]. This is because of the high hardness, low friction coefficient, high wear resisting property and the need for environmental friendliness [12–15]. Thus, low friction and wear resistant surfaces for micro-deep drawing tool materials are required. Recently, the coating of diamond-like carbon (DLC) on the surface of tools has drawn much attention. This coating has excellent intrinsic properties, i.e. high

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hardness, toughness, and high chemical stability, which extend the life of the forming tool. DLC films coated on cylindrical micro-cups as well as blank holders and lower dies showed that DLC films effectively decreased drawing force and increased the limiting drawing ratio [16, 17]. Due to the dependence of formability on surface textures and friction conditions between the tool and blank material, high-performance lubricants are needed. Although several studies on DLC films have reported on macro-forming and even in micro-forming, there has been less consideration for the use of graded DLC films in micro-sheet metal forming.

This paper considers laser diode copper circular cups, and the surface lubrication and textures of the graded DLC film coated SKD11 steel are investigated for micro-deep-drawing. To further investigate the tribological properties and the effect of DLC films on micro-sheet forming, a micro-deep drawing experiment was carried out using different coated films on micro- punches. In addition, a micro-deep drawing that considers graded DLC film in size effects was conducted, and there is also discussion on the influence of graded DLC coated different micro-punch diameters on stroke-drawing force in the micro-deep drawing process.

2. Experimental details

A magnetron system sputtering is used in this experiment, where a sputter magnetic field design supplying rectangle targets ($300\times100\times10$ mm^3) is operated in an unbalanced mode. Table I shows the specific fabrication parameters and their conditions for ZrC, DLC and CrN coatings. The specific fabricating parameters of the interlayered films are listed in Table II. Three different targets, Zr, Cr, and C (99.5%), respectively, were adopted. A mixture of Ar and N_2 gases and CH_4 were used as working gas. The fabrications of CrN, ZrN and DLC films are achieved in the same conditions, except the target, in the sputtering system. On the other hands, when fabricating interlayered Zr\ZrC films, the high-purity chromium and carbon were used as sputtering target and the Ar was used as working gas. The fabrication of CrN, ZrN, and DLC films coated on the SKD11 sample were carried out. The deposited surface morphologies and wear scars of the films were examined with a field emission scanning electron microscope (JEOL JSM-6700F). For surface examination of the films, the digital nanoscope instrument of the atomic force microscope (Nanoscope Dimension 3100 SPM) was used. The tribological properties of the films were determined by a pin-on-disc friction tester, with a test velocity of 286 rev/min, the wear load was 2 N, with a wear diameter of 20 mm, a counterpart is a tungsten carbide ball, with a ball diameter of 12 mm and the sliding length was 1000 m. The wear tracks and scars of the films were measured by a TalyScan 150 (Taylor Hobson, Leicester, UK). A schematic of the micro-deep drawing system is shown in Fig. 1a, which was designed based on a universal precision press machine. A schematic diagram of the micro-deep drawing cylindrical cups is shown in Fig. 1b, where the copper blank (blue) is drawn by the punch together with a DLC film (grey) into the lower die cavity. The drawing force with a range of 500 N was fixed on the drawing punch and the velocity ranged from 0.001 to 500 mm/min. A series of drawing punches were manufactured, and the micro-punches of SKD11 with a hardness of HRC 61 were used for micro-sheet forming, employed for manufactured with diameters of 2.5, 3.3, and 4.1 mm, respectively, length of punch is 4 mm.

TABLE I

Parameters and their conditions for ZrC, DLC, and CrN coatings

Symbol	Material	Substrate bias [V]	C target current [A]	N2/Ar mixture [sccm]	CH4 [sccm]	Sputtering distance [cm]	Sputtering time [min]	Pulse frequency [kHz]
ZrN	Zr	60	1.6	0.15	5	10	60	100
DLC	C	60	1.6	0.15	5	10	60	100
CrN	Cr	60	1.6	0.15	5	10	60	100

TABLE II

Parameters and their conditions for the interlayered coatings on DLC films

Symbol	Argon flow rate	Substrate bias [V]	C/Zr target current [A]	Vacuum based pressure [sccm]	Sputtering time [min]	Pulse frequency [kHz]
interlayer 1	25	100	0/2	3.17×10-3	15	50
interlayer 2	25	60	1.6/0.4	3.17×10-3	15	100

3. Results and discussion

3.1. Surface textures of the films

The macroscopic morphology of the prepared films is shown in Fig. 2a. It can be seen from upper left corner in the figure that the good surface qualities of the films were seen. Figure 2a shows the surface textures of the DLC films on the front part of the punch. The surface films are uniform and compact, and no impurity defects are detected in the films. Figure 2b shows the SEM micrographs of the surface of the DLC films grown, which are characterized by grainy phases, a grain size of 80–100 nm, demonstrating that visible aggregated crystalline structures clearly exist. The surface of the DLC films with

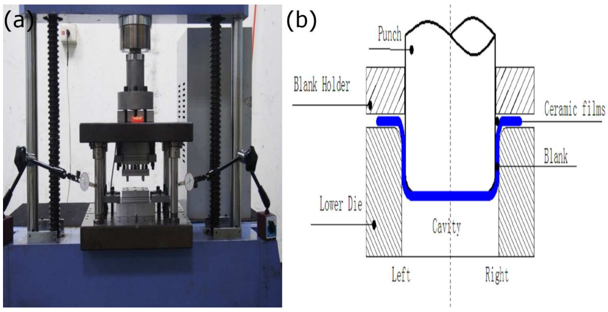

Fig. 1. Schematic diagram of the experimental apparatus: (a) the micro-precision blanking-deep drawing die, (b) DLC-coated punch on micro-drawing of circular cups.

micro-protrusions is much rougher than that of the DLC film, which might be attributed to the heterogeneity of film-forming after Zr doping during the deposition process. Figure 2c shows the cross-sectional micro-structure of the DLC-coated SKD11 alloys, where an even DLC layer about 1.2 μm thick is clearly observed. In addition, no pores are found in the DLC coating, and three graded intervals as Zr, ZrN, and ZrCN can be observed at the interface between the DLC coating and the SKD11 substrate. This shows that there is a very dense coating and good interface bonding. This is very important for improving the adhesion and tribological performance because they efficiently provide better graded interlayers that adhere to the punch. In addition, the surface morphology of the DLC films was characterized by atomic force microscopy. As shown in Fig. 2d, the roughness values (Ra) for the scanning area are 4.386 nm for the DLC films, where the surface features it.

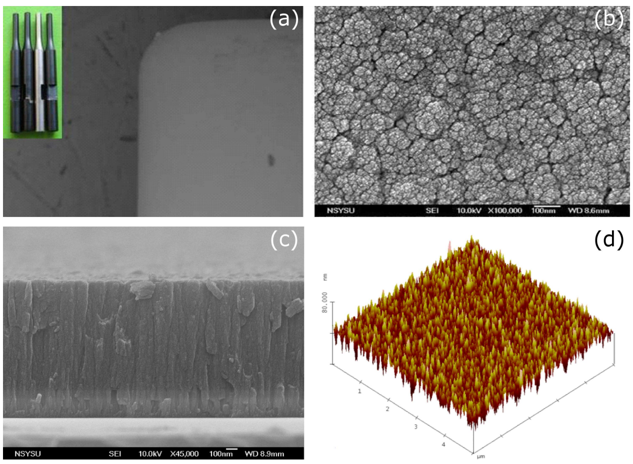

Fig. 2. The surface texture of the graded DLC(Zr\ZrC\ZrCN) films, with: (a) the front micro-graph of a graded DLC punch and a graded DLC coated punch (grey) at upper left corner area, (b) the texture of graded DLC punches, (c) cross-section of graded DLC punches, and (d) AFM images (Ra= 4.74 nm) of graded DLC punches.

3.2. Wear properties of the films

Figure 3 shows the wear tracks of different films by SEM, which display considerably different wear resistance properties. As shown in Fig. 3a, the width of the worn track of the DLC films is relatively small, and the friction profiles with a less undulating film yield a comparatively smooth texture with no signs of wear or delamination. Similar features were also obtained for the ZrC films as shown in Fig. 3b, which had no coating delamination or long narrow furrows on the films of sliding surfaces. The width of worn track profile and wear loss of the ZrN film seemed to be large after sliding 1000 m, while in the case of the CrN coating flaking was observed in Fig. 3c and there was wear extended tearing-off the films in the worn scar features due to extensive increase in stamping force. The further abrasive wear would be promoted for the CrN deposited films. As shown in Fig. 3d, both the worn scar width and wear losses of the SKD11 were very substantial, where the large asperities of worn surface are apparently due to the no film growth with low surface mobility. This may account for the deeper scratches and rough surface of the wear track for the SKD11 substrate. Clearly, the wear trace width of the SKD11 substrate was large, and the wear loss was also large, while the wear trace width and wear loss of the DLC film were small after 1000 m sliding distance. Both the wear trace width and wear loss of CrN films are much more than those of ZrN films. In other words, the morphology of worn surface of the DLC coated film has a relatively smooth surface compared with the others. As demonstrated above, the better result of tribological performance of the DLC films is successfully obtained. The average coefficient of friction of the DLC film gave slightly lower values of 0.21, while the average coefficient of friction of the ZrN film was 0.58. The CrN films had frictional coefficient of about 0.68, which is only marginally lower than frictional coefficient of about 0.71 in the SKD11 sliding. Among the all samples, the DLC films can provide better wear behavior and a lower friction coefficient, indicating that the DLC films are favorable to enhance drawn efficiency. As demonstrated above, the obtained wear resistivity shows the advantageous characteristics in micro-deep drawing compared with the SKD11, CrN, and ZrN films. Based on these results, a DLC film is adapted to be deposited on the punch used in micro-deep drawing.

3.3. Micro-circular drawability of the coatings

To test the friction force in the micro-deep drawing process, the DLC film was fabricated on the drawing punch. Figure 4a shows the drawing punch stroke-drawing force curves for different micro-punch film coatings, such as CZrN, ZrN, CrN, and no SKD11 films, through the micro-deep drawing. It is clear that the punch stroke-load curves for lubrication with both CZrN and ZrN films, whose values are very close, were significantly lower than those of the others, which had a CrN film and a SKD11 film. Thus, both CZrN and SKD11 are

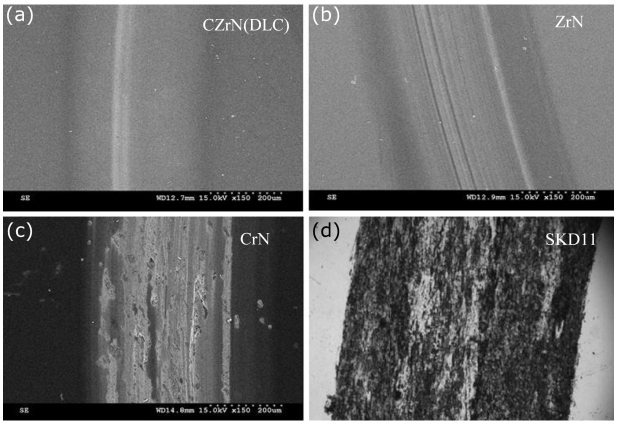

Fig. 3. SEM images of the worn tracks for different coated micro- punch with DLC (CZrN), ZrN, CrN films, and SKD11 substrate.

experimentally compared. For micro-deep drawing, the maximum punch load for CZrN film decreased by about 17% and there was an increase of about 12% for the punch stroke compared to those without the SKD11 films. As demonstrated above, the friction at DLC coated punch deposition has obvious effect on the micro-deep drawing. On the other hand, the increase of the drawing ratio with decreasing friction force is induced in the case of graded DLC films. This is because the punch loads for lubrication with the DLC film for the friction coefficient were much lower and the anti-wear properties were far higher than those of the SKD11. Accordingly, the better tribological performance of the DLC deposited film is clearly demonstrated in the practical forming behavior. Furthermore, the drawing ratios (stroke/diameter) of the micro-punching cups between the DLC films and SKD11 with punch diameters of 2.5, 3.3, and 4.1 mm were compared, as shown in Fig. 4b. The drawing ratios for the drawn cups showed increases of approximately 24%, 7.3%, and 5.8% of the coated punch diameter of 2.5, 3.3, and 4.1 mm, respectively. It can be seen that the drawing ratios of the DLC-coated punch in the laser diode copper sheet was larger than that of the SKD11. Furthermore, in the case of punch diameter of 2.5 mm used in micro-deep drawing experiments, the drawing ratio was 0.58, which is much better than the value of 0.44 with SKD11. Overall, the smaller coated punch diameter type is improved even more than those of the larger diameters. On the other hand, the stroke/diameter ratio of the coated punch diameter increased with decreasing coated punch diameter. This indicates that size effects of friction in the micro-deep drawing cup appeared to have occurred because the stroke/diameter had increased by approximately 24%, and the micro-punch surface films, such as the DLC films, give satisfactory results for friction-reduction in micro-deep drawing. As seen in Fig. 4c, the SEM image of a coated DLC punch was observed through the punch drawn experiment. Few scratch failures on the surface of the DLC film can be detected. This is mainly because the DLC film has strong adhesion and excellent wear resistance to endure the high strain/stress conditions encountered in micro-deep drawing. Figure 4d shows that the images of the drawn cups with a DLC coated punches including diameters of 2.5, 3.3, and 4.1 mm, respectively, were successfully formed in the micro-deep drawing in which drawing ratio was large. Overall, the drawing ratio of the DLC coated punch diameters of 2.5 mm was superior to those of the others in micro-deep drawing.

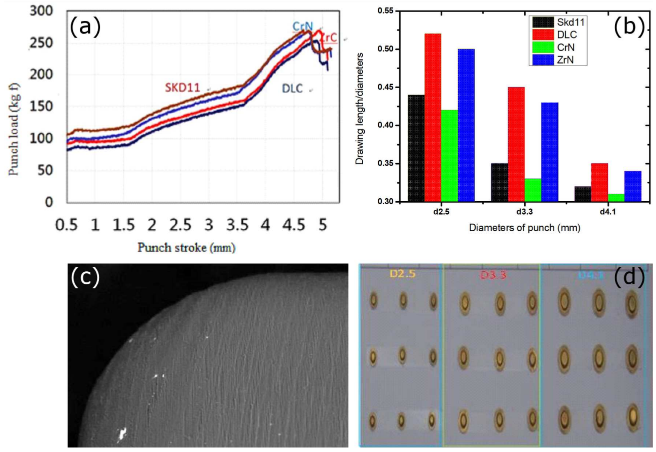

Fig. 4. The micro-deep drawing experiments: (a) punch stroke-load curves with a SKD11, graded DLC, ZrN and CrN films, (b) drawing ratio of three diameters with 2.5, 3.3, and 4.1 mm for the graded DLC coated punch, (c) SEM image of the coated graded DLC punch drawn surface, (d) micro-laser diode cups successfully formed by graded DLC coated micro-punch in laser diode copper.

4. Conclusion

In this study, the application of the DLC coated SKD11 substrate to the drawability of micro-cups based on laser diode copper was demonstrated and its applicability was investigated in comparison with that of the others such as SKD11 substrate, CrN, and ZrN films. The DLC coated micro-punch films were successfully synthesized by magnetron sputtering. Surface textures show that the DLC films exhibit amorphous structures with densely packed nanocrystalline grains with a lower surface roughness value. The tribological behaviors show that the worn track of the DLC films is relatively small, and the friction profiles with a less undulating film make a smoother texture. Similar features were also obtained for the ZrN films, with no coating delamination; but long narrow furrows on the films of sliding surface, as well as the worn track profile and worn loss seemed to be large after sliding 1000 m, while in the case of the CrN film flaking was observed and there was wear-extended tearing-off the films in the worn scar features due to extensive increase in stamping force. Further, the micro-deep drawing experiments show that the maximum punch load for the DLC (ZrCN) film decreased 17% and there was an increase of 12% for the punch stroke over those without SKD11 films. In addition, the drawing (stroke/diameter) ratio of coated punch diameter increased with decrease of the coated punch diameter. This indicates that size effects of friction in the micro-deep drawing cup appeared to occur because the limit drawing ratios had increased by approximately 24%, and the micro-punch surface films, such as the DLC films, can provide significant improvement in micro-deep drawing for reduction of friction. Accordingly, the applicability of the DLC films for the drawability of micro-cups was successfully demonstrated through the micro-deep drawing process.

Acknowledgments

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