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Dry deep drawability of A5052 aluminum alloy sheet with DLC-coating

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ABSTRACT

In the press forming, dry press forming would be required for environmental problem. In this study, a diamond-like-carbon (DLC) for achieving the dry press forming was applied to the surface of blanks. Then, the effect of the deep-drawability of A5052 aluminum alloy sheet with DLC-coating was investigated due to improve the formability in dry press forming. The deep-drawing experiments were carried out at the elevated temperature improve the formability of A5052 aluminum alloy sheet. The deep-drawability with DLC-coating was examined by deep-drawing test and friction test. As the result, dry press forming of the aluminum alloys without metalic adhesion was achieved by DLC-coating. In addition, it is confirmed that the formability of A5052 aluminum alloys sheet due to lower friction coefficient between blank and the die in the case of DLC-coating is improved in comparison with lubricating oil.

1. Introduction

Aluminum alloys have attracted attention as promising materials for various applications because of their characteristics such as a light weight and high specific strength. In the press forming of aluminum alloys, lubricating oil is used to prevent the adhesion of aluminum alloys to the forming tools. However, the disposal of a large amount of lubricant waste is a serious environmental issue. Therefore, new lubricating techniques that have less impact on the environment are an urgent necessity.

In recent years, various studies on dry press forming, which does not involve the use of a lubricant during plastic processing, have been performed [1]. Dry press forming is also attractive as a forming technique with zero CO_2 emissions. However, it is difficult to apply this method to the forming of metal sheets.

The feasibility of deep-drawing has been studied using ceramic dies [2]. Ceramic dies have been successfully applied to the deep-drawing of mild steel and pure copper sheets. In the deep-drawing of metal alloy sheets, a pretreatment, in which an adhesive tribological coating is formed, is effective for improving workability when using alumina and zirconia dies. Adapting the design of the ceramic die to each material is necessary for realizing dry forming. However, the workability of ceramic tools is poor for complicated shapes, and the use of ceramic tools significantly increases the cost of forming simple shapes. Thus, the use of electroconductive ceramic tools has been proposed [3]. Electroconductive ceramic tools can be formed by electrical discharge machining methods. Using an electroconductive ceramic as a plastic-forming tool, high drawability was confirmed and the dry deep-drawing of an aluminum alloy specimen was successfully performed 10,000 times.

Moreover, the use of a die coated with diamond-like carbon (DLC) has been proposed owing to the excellent tribological properties of DLC [4]. The use of a DLC-coating has been found to eliminate the need for any lubricants while preventing the adhesion of aluminum to the die material. Also, the DLC-coating prolongs the die lifetime to up to 10,000 deep-drawing operations.

The use of a die coated with a diamond film deposited by chemical vapor deposition (CVD) has also been proposed, because the film has superior tribological properties to a DLC film [5]. It was confirmed that CVD-diamond-coated dies could perform 100,000 deep-drawing operations on a stainless-steel sheet (SUS304) without the use of lubricants.

The surface of tools is easily damaged upon coming into contact with hard materials and by repeated scratching. A thin hard film coating such as a DLC-coating can be used to improve the lifetime and dimensional accuracy of tools [6]. For instance, thin physical vapor deposition (PVD) layers can be coated on a mold to increase the lifetime of tools [7,8]. It was confirmed that tool lifetimes were increased as the friction coefficient between the tools and hard materials was reduced by the PVD layer. Many studies on coating techniques for tools used in press forming have been carried out.

However, it is impossible to apply dies with complex shapes in these techniques. Therefore, the use of blanks with a DLC-coating was proposed to achieve the dry press forming of magnesium alloy sheets [9]. A deep-drawing test was conducted to evaluate the formability of DLC-coated blanks. It was concluded that the use of

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Table 1
Material properties of A5052-O.

Temperature	*F* value [MPa][a]	*n* value[a]	*m* value[a]
Room temperature	515.8	0.33	−0.0083
200 [°C]	308	0.18	0.0072

[a] $\sigma = F\varepsilon^n\dot{\varepsilon}^m$.

DLC-coated blanks improves the formability of magnesium alloys in comparison with the use of conventional lubrication techniques.

In this paper, the methodology of coating the surface of aluminum alloys with a DLC-coating to increase the surface lubrication and for achieving dry deep-drawing is discussed. Furthermore, the tribological properties and the effect of the DLC-coating on the deep-drawability of A5052 aluminum alloy sheets were investigated.

2. Experimental condition

2.1. Workpiece and DLC coating

2.1.1. Workpiece

An aluminum alloy sheet (A5052-O) of 0.5 mm thickness (t0) and 18.05 mm diameter (d0) was used in this study. Table 1 shows the material properties of A5052-O at room temperature and 200 °C. The following three lubrication conditions were applied to blanks: a DLC-coating, lubrication with GM100 (Nihon Kohsakuyu Co., ν = 38.38 mm^2/s at 40 °C) which is a lubricant for the plastic processing of aluminum alloy sheets and no lubricant. The DLC-coating was compared with the other lubrication conditions in terms of lubricating performance (friction coefficient) and deep-drawability.

2.1.2. DLC coating

Radio-frequency (RF) plasma polymerization CVD, which have high precision, and provide a high adhesion force and a good surface finish (small roughness) after DLC-coating, were applied to form the DLC-coating. In the case of directly depositing a DLC-coating on an aluminum alloy by CH_4 and H_2 plasma treatment, the abrasion of the DLC film occurs easily. Thus, a silicon interlayer was deposited using tetra-ethoxy-silane (TEOS) to improve the adhesion of the DLC-coating. Table 2 shows the conditions of the plasma treatment used to deposit the DLC-coating. DLC1, DLC2 and DLC3, correspond to three different DLC films formed under three different conditions with different proportions of CH_4 and H_2, whereas the flow rare of TEOS was fixed. During the coating process, the plasma treatment with TEOS was carried out to construct an interlayer, and the plasma treatment with CH_4 and H_2 was conducted to coat the DLC film. The silicon interlayer and DLC-coating were generated using a plasma treatment machine at a power of 150 W for a duration of 10 min using a mixture of CH_4 and H_2 with a total flow rate of 25 cm^3/min.

2.2. Surface analysis

Surface chemical composition of DLC were analyzed with X-ray photoelectron spectroscopy (XPS, JEOL, JPS-9200). Sp^3/sp^2 ratio was calculated by the area of deconvoluted C1s peaks.

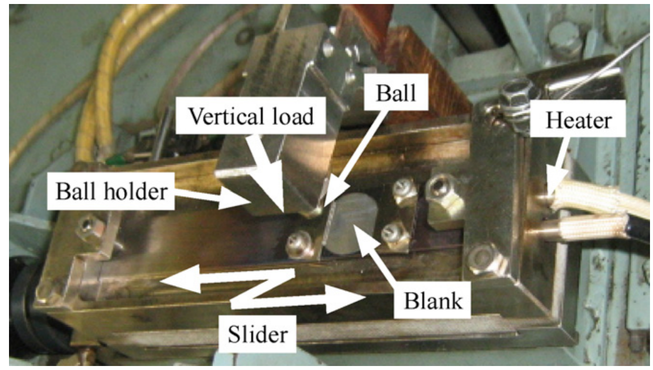

Fig. 1. The photograph of friction test machine.

Table 3
Experimental conditions in friction test.

Vertical load [N]	1.0
Sliding length [mm]	10
Reciprocation speed [mm/s]	10
Material type of ball in friction test	JIS SUJ2

In complement to the data of XPS, glow discharge spectroscopy (GDS, Rigaku GDA750) was used for the analysis of surface concentration of hydrogen.

Raman spectra of DLC films were obtained with laser Raman spectrometry (JEOL NRS-2100) with solid semiconductor laser source (532 nm) for another characterization of DLC structure.

2.3. Friction conditions

2.3.1. Friction test

A friction test was carried out using a friction testing machine (Shinko Engineering Co., Ltd.). Fig. 1 shows a photograph of the friction testing machine. In this test, a ball was placed in contact with an aluminum alloy sheet on a slider and a perpendicular load was applied. The aluminum sheet was heated to the target temperature by a heater, which was set under the slider. The friction test was carried out using the slider, which moves with reciprocating linear motion at intervals of 10 mm sliding length. Then, DLC-coating are used without any other lubricants.

Table 3 shows the experimental conditions in the friction test. The vertical load was 1.0 N, and the test temperatures were room temperature and 200 °C.

The following three lubrication conditions were used with the test piece a DLC-coating (with three different conditions of film formation), lubrication with GM100 and no lubrication. The friction coefficient was measured under these conditions.

2.3.2. Scratch test

To evaluate the adhesion of the three different DLC films (DLC1, DLC2 and DLC3), a microscratch test (CSM Instruments) was carried out. Table 4 shows the experimental conditions in the microscratch test. The initial vertical load was 0 N and the final load was 15 N. The load was increased at a rate of 15 N/min. The bramk with DLC coating was peeled off by the diamond indenter to evaluate the exfoliation load and select the film type of DLC-coating.

Table 2
Conditions of plasma treatment.

DLC type	TEOS [cm^3/min]	CH_4 [cm^3/min]	H_2 [cm^3/min]	CH_4 concentration [%]
DLC1	4.60	10.1	14.6	40
DLC2	4.50	12.5	12.5	50
DLC3	4.59	14.8	10.1	60