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Optimization of Die Material and Its Surface Coating for Press Forming Magnesium Alloy

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Grain sizes of die material and die surface coatings were examined with the achieving mass-production of magnesium alloys by advanced continuous press forming. The results showed that there is an optimum tungsten carbide grain size of 1 to 2 μm for press-forming AZ31 magnesium alloy in terms of surface roughness fluctuation. It was also shown that the adherence of the DLC coating was improved by implanting C ions into the tungsten carbide surface. 10,000 times square-cup drawings were successfully achieved at 543 K using C-ion implantation and a DLC coated die together with a newly developed heat-resistant lubricant.

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1. Introduction

Magnesium alloy is expected to be the next-generation lightweight, high-tech material,[1)] and many studies have been carried out on it in recent years.[2,3)] The main method of processing magnesium alloy is casting (thixomolding and die casting),[4)] but it has serious problems including low yield and low production efficiency. Continuous press-forming, which is an alternative to casting, is very promising because it is an advanced production technology which makes it possible to mass-produce low cost quality products without surface defects. Such products are better than those produced in other countries. However, magnesium is a material which is fundamentally difficult to work, and is unworkable at room temperature.[5–7)] Therefore, the magnesium alloy AZ31 is pressed between 523 K and 573 K for easier pyramidal slip. Since magnesium is active at high temperatures, surface scorches and flaws are likely to occur during high-speed press-forming.[8–10)] There are various problems to be solved, including the occurrence of surface flaws due to the adhesion of magnesium to the die,[11)] the control of the die temperature during press-forming and the layout of the progressive die.[12)]

The authors are developing high-quality high-speed hot-working transfer press processing of magnesium alloy for laptop PC casing, digital camera and various multimedia device casings as part of a 3-years government-funded R&D project. Both the development and method of using the dies are important in order to achieve the target lifetime of 100,000 times drawing of AZ31B magnesium alloy plate.

In this study, we examined various die material grain sizes and die surface coatings with a view to achieving mass-production of magnesium alloy products through advanced continuous press forming.

2. Experimental Procedure

Magnesium alloy (AZ31B) is used for press-forming of deep-drawing square-cup in this study. Table 1 shows chemical compositions of magnesium alloy (AZ31B) used in this study. The press forming conditions of our experiments for magnesium alloy (AZ31B) is shown in Table 2.

Table 1 Chemical compositions of Magnesium alloy (mass%).

Sample	Al	Zn	Mn	Mg
AZ31B	3.5	1.3	0.37	Bal.

Table 2 Press forming conditions for deep-drawing square-cup.

Stroke		23 mm/s-30 mm/s
BHF		10 t
Pre-heating temperature		423 K
Press forming temperature	Punch temperature	390 K
	Die temperature	533 K

Table 3 Mean grain sizes of tungsten carbides used.

Material	Mean grain size (μm) for WC
F20	Less than 1.0
D50	1.0 ~ 2.0
G70	2.0 ~ 3.0
C70	3.0 ~ 5.0

We examined the die material and die surface coatings. The base material of the die is WC-Co (Fuji Dies). We examined WC-Co with four kinds of grain sizes. The base materials used in this analysis are summarized in Table 3. For improving the lubricity and workability, diamond-like carbon (DLC) coating was conducted. Detailed condition of DLC coating has been reported elsewhere.[13)] Before the DLC coating, C ion implantation was conducted on some die materials. C ions were implanted into the carbide at a pulse voltage of 20 kV.

Microstructural analyses were conducted with scanning electron microscopy (SEM) and transmission electron microscopy (TEM). The analyses of the chemical bonding state and the depth profile of implanted carbon were conducted with X-ray photoemission spectroscopy (XPS). Scratch tests were used to examine the adhesion of the DLC coating.

3. Results and Discussion

3.1 Optimization of die surface coating

Initially, we examined die surface coatings. We found that DLC coating exhibited the best lubricity and workability.[14] However, it was found that the DLC coating adhered poorly to the metal die and came off immediately after the press-forming procedure. Thus, DLC was unsuitable for practical use. Therefore, we turned our attention to the research and development of tungsten carbide hybrid dies (a set of tungsten carbide-inserted progressive dies for use only in the deep-drawing process) in which an inclined C structure is formed by DLC coating after a C-ion implantation to improve the adherence of DLC to the die.[15,16]

The base WC-Co material using in this section is F20 with a grain size of less than 1 μm. C ions were implanted into the carbide at a pulse voltage of 20 kV.

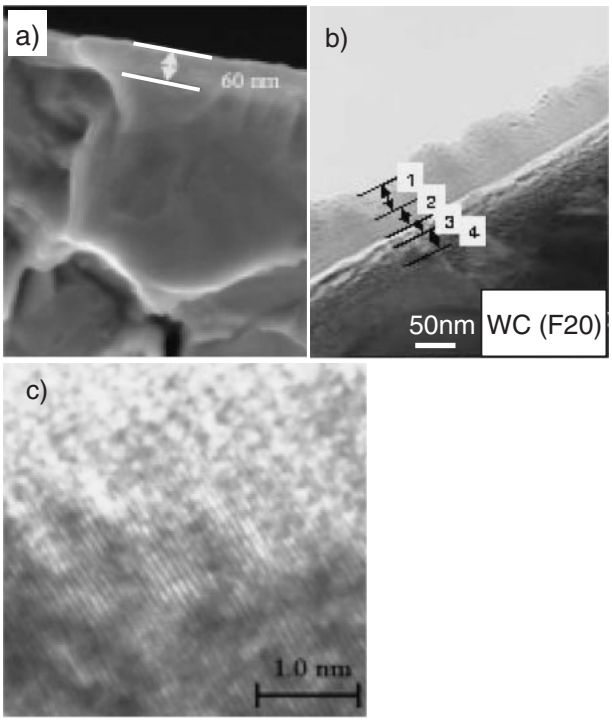

Fig. 1 TEM cross-sectional images of the C-ion-implanted layer: a) C-ion-implanted layer of which thickness is 60 nm b) Magnified view of the C-ion implanted layer, which shows a four-layer structure. 1 a carbon deposition layer 2 an interface layer 3 a mixed layer 4 an implantation layer c) Magnified view of the implantation layer, which shows an ordered structure.

Figure 1 shows the TEM cross-sectional image of the C-ion-implanted layer. It confirms that the C-ion-implanted layer is comprised of 4 layers: a C-deposition layer, a surface layer, a mixed layer and an implantation layer.[17]

XPS was used for analyzing the chemical bonding state of implanted C-ions on the tungsten carbide surface after C-ion implantation. The results revealed a peak at 284.48 eV. Therefore, it is assumed that the C ions implanted into the carbide are present as a C-C or C-H chemical bond.

Figure 2 shows the scratch test results on the DLC coating, (a) with C-ion implantation and (b) without C-ion implantation. Where C ions were not implanted, the DLC coating fractured at 50 N or less, whereas C-ion implantation allowed a critical load of 50 N or greater. This result indicates that the C-ion implantation improves the adherence of DLC coating.

XPS was used for depth profile analysis of the DLC coating for C1s and W4f, (a) with C-ion implantation and (b) without C-ion implantation. The results are shown in Fig. 3. Where C ions were not implanted, the greater the depth, the more rapidly C decreased and W increased, whereas where C ions were implanted, both C and W levels gradually changed with increasing depth. These results suggest that improved adherence is due to reduced stress on the DLC coating resulting from an increase in the C ratio in the carbide surface.

3.2 Optimization of grain size of tungsten carbide

Figure 4 shows the SEM images of four kinds of tungsten carbides. The mean grain size of each material is also summarized in Table 3.

First, the relation between the duration of the C-ion implantation and the adherence of the DLC coating was examined by scratch tests. Figure 5 shows the results of a F20

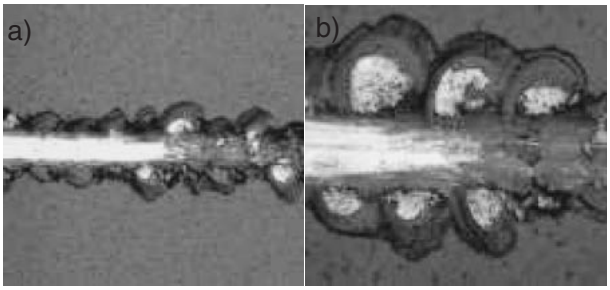

Fig. 2 Results of scratch tests on the DLC coating with a critical load Lc(Ft2) = 57 N: a) with the C-ion implantation, b) without the C-ion implantation.

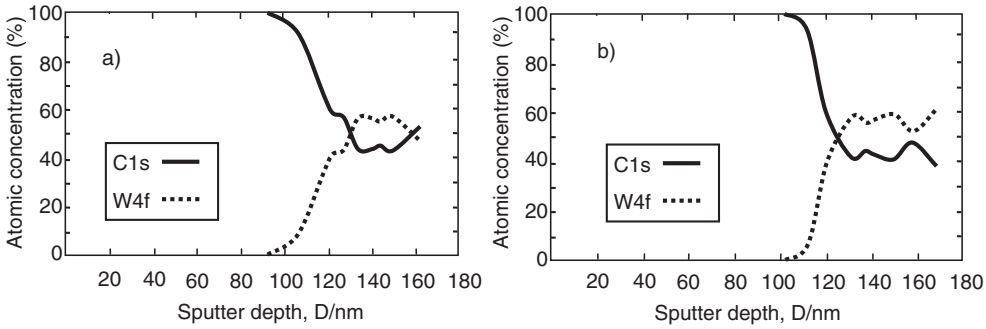

Fig. 3 XPS depth profile analysis of the DLC coating for C1s and W4f basal plate (a) with C-ion injection (b) without C-ion implantation.

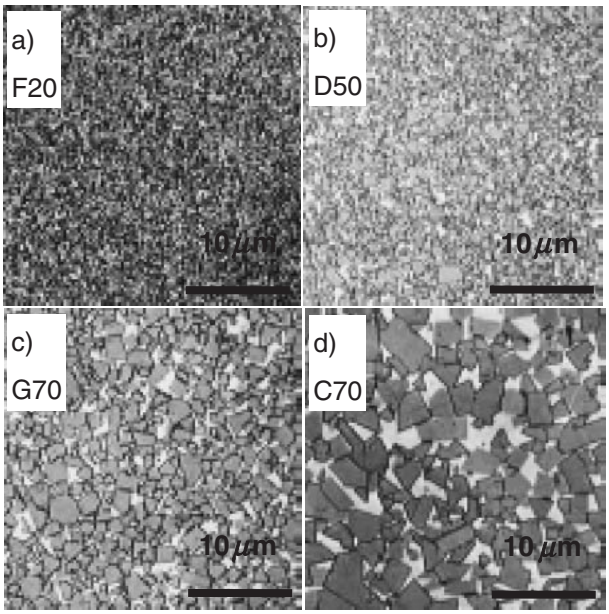

Fig. 4 SEM images of four kinds of tungsten carbides: a) F20 with mean grain size of less than 1.0 μm, b) D50 with mean grain size of 1.0–2.0 μm, c) G70 with mean grain size of 2.0–3.0 μm, d) C70 with mean grain size of 3.0–5.0 μm.

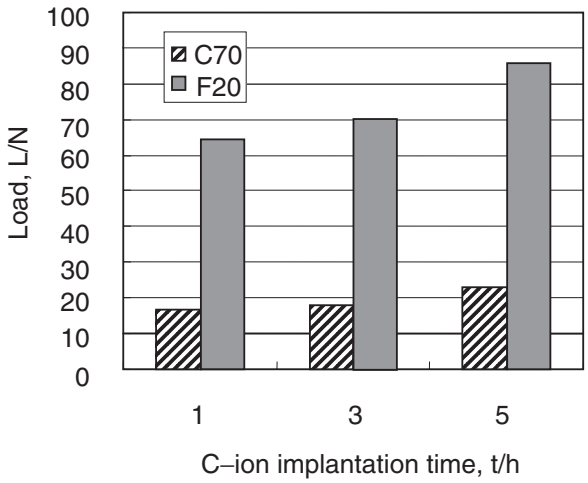

Fig. 5 Effects of the ion implantation time on the adherence of the DLC coating.

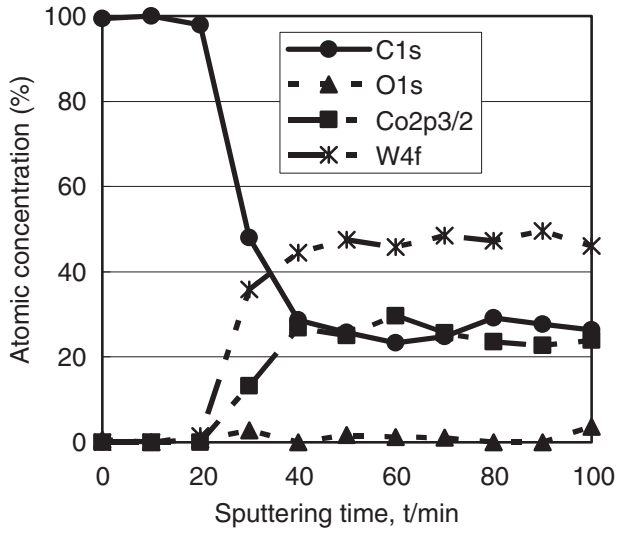

Fig. 6 XPS depth profile analysis of the C-ion implantation for C1s, O1s, Co2p3/2 and W4f (type of tungsten carbide: C70).

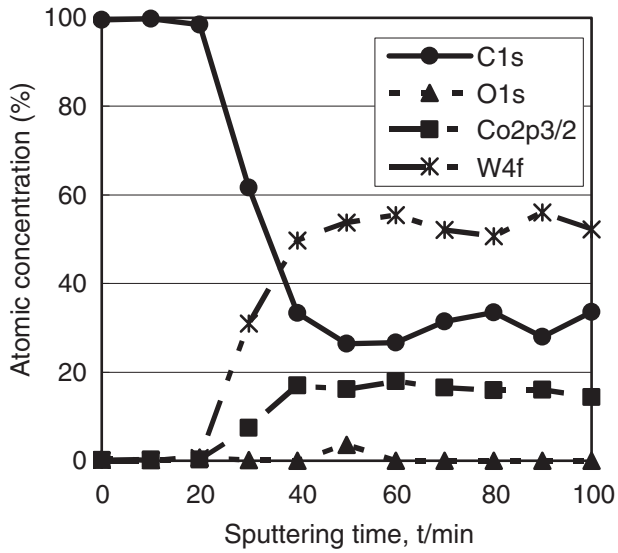

Fig. 7 XPS depth profile analysis of the C-ion implantation for C1s, O1s, Co2p3/2 and W4f (type of tungsten carbide: F20).

tungsten carbide with a fine grain size less than 1 μm and a C70 tungsten carbide with a coarse grain size of about 4 μm. It became clear that the adherence of the DLC coating improved with an increase in the C-ion implantation time irrespective of the grain size of the tungsten carbide.

Second, an XPS depth profile analysis was conducted for C1s, O1s, Co2p3/2 and W4f. The results shown in Figs. 6 and 7 confirmed that the implanted C ions reached about the same depth in all tungsten carbide samples irrespective of the grain size, that is, tungsten carbide grain size had nothing to do with the C-ion implantation depth.

The frictional coefficient was measured on C-ion implanted and DLC coated F20 carbide. It was found that the DLC coating significantly lowered the frictional coefficient, making it possible to keep the frictional coefficient under 0.1. Details of the wear properties of DLC coating have been reported in another paper.[13)]

Next, we examined the effect of the grain size die materials on the surface roughness of the press formed articles. We produced dies using WC-Co with various grain sizes. The shape of the dies was a deep-drawing square-cup with the radii of the two types of corners of 4 mm and 2.3 mm. For each die, 10,000 times square-cup drawings were carried out at 543 K, the degree of damage on the die surface was visually inspected, and the surface flaws of the press formed articles were measured with a surface roughness meter to determine the optimal grain size for tungsten carbides. The measured points for surface roughness are shown in Fig. 8. A newly developed heat-resistant lubricant was used for the drawing. The amount of lubricant used was 3,000 mg/m^2. Details of the lubricant have been reported in another paper.[18)]

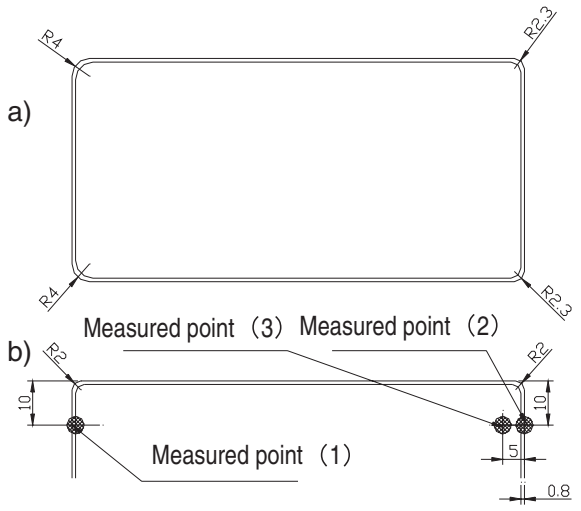

Fig. 8 Measured points for surface roughness on deep-drawing square cups: a) Viewed from the above b) Viewed from the side.

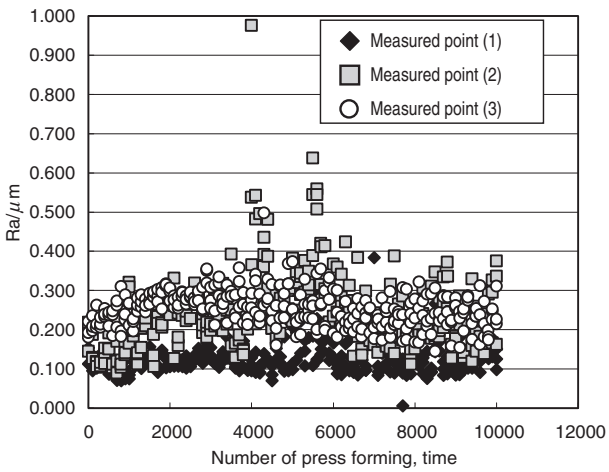

Fig. 9 Measurement analysis of surface roughness on 10,000 times pressing tests (type of tungsten carbide: D50).

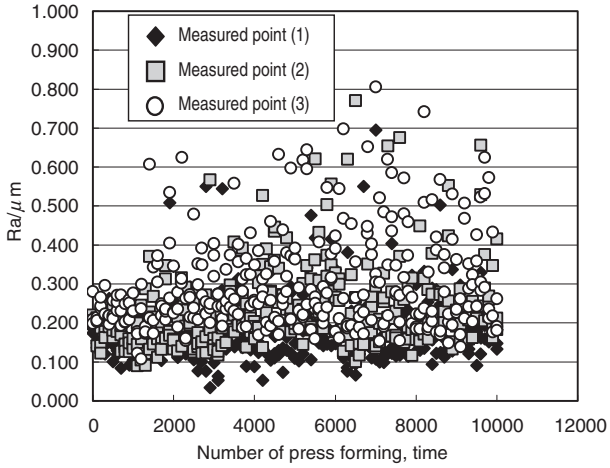

Fig. 10 Measurement analysis of surface roughness on 10,000 times pressing tests (type of tungsten carbide: G70).

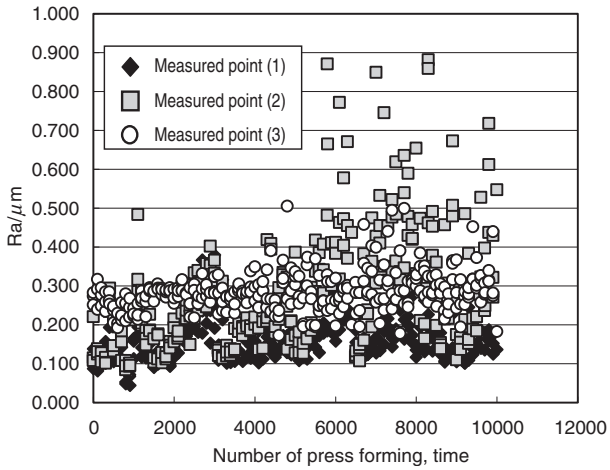

Fig. 11 Measurement analysis of surface roughness on 10,000 times pressing tests (type of tungsten carbide: C70).

For F20 tungsten carbide, the pressing test was interrupted because of the conspicuous wear and tear of the DLC coating after 5,000 times drawings. In the pressing test conducted using tungsten carbide dies with other grain sizes, 10,000 times drawings were achieved in every case. Of the tested materials, D50 had the most stable stamping performance; Figs. 9, 10 and 11 show the results. Determination of the approximate formula confirmed that D50 was the most stable material in terms of surface roughness fluctuation.

From these results, the optimum grain size of tungsten carbide was not less than 1 μm but in the range of 1 to 2 μm. It has been reported that oil film retention is improved by the micro-pool mechanism which brings the oil films closer to the state of fluid lubrication, thereby improving material processability when the die surfaces are rougher.[19–21] Detailed analysis of this phenomenon will be conducted in further research.

4. Conclusions

The results showed that there is an optimum tungsten carbide grain size of 1 to 2 μm for press-forming AZ31 magnesium alloy in terms of surface roughness fluctuation. In addition, it was shown that the adherence of the DLC coating, which was likely to exfoliate using the conventional technique, could be improved by implanting C ions into the carbide surface. 10,000 times square-cup drawings were successfully achieved at 543 K using C-ion implantation and a DLC coated die with a newly developed heat-resistant lubricant.

Now that the optimal progressive die layout has been determined, a 100,000 times continuous press-forming test with a target Ra value of 1.5 μm or less is in progress.

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