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Development of Non-Lubricated Die for Magnesium Sheet Forming of Car Body Part

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According to current development trends for automotive body parts, light weight is a key issue in improving fuel efficiency and CO_2 reduction. Compared to steel and aluminum, magnesium has a relatively low specific gravity. However, it is challenging to use magnesium to produce a product at room temperature because magnesium has a Hexagonal Close-Packed (HCP) crystal structure. Therefore, the structure is not suitable for plastic deformation without using a heating system. As a result, a magnesium sheet and die need to be heated from 250 to 300°C. Unfortunately, this procedure has positive and negative effects. It increases not only the material's elongation, but also the friction between the material and die during warm forming. Furthermore, lubricant cannot be used due to corrosion occurring on the surface of a part after manufacturing. To overcome these challenges, we developed a "Partition panel," which is a warm-formed part with a non-lubricated die with a Diamond-Like Carbon (DLC) coating. A one-quarter sized prototype was successfully produced with the DLC-coated non-lubricated die, and its characteristics were verified through an evaluation of the friction coefficient and mechanical properties.

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1. Introduction

Magnesium alloys have been widely used in the automotive and aviation industries.[1] Magnesium alloys has many advantages such as lower density, high specific strength, specific stiffness, excellent electromagnetic wave shielding and so on. Most of magnesium alloys are used in casting processes such as die-casting, because magnesium alloy has a Hexagonal Close-Packed (HCP) structure. Magnesium crystal lattices make plastic deformation difficult at room temperature.

Many studies to improve formability of magnesium sheet have been conducted at warm forming.[2] This method can enhance the formability of a magnesium sheet. However, it increases not only the material's elongation but also the friction between the material and die during warm forming. If the coefficient of friction is high, the material does not flow well between the material and die. To reduce the coefficient of friction, high temperature lubricant is usually used on the die and material. A residual by high temperature lubricant can eat away at the surface. In addition, residue created by the high temperature degrades the work environment significantly. Oxidized magnesium sheets are easily discolored on the air by lubricant. Surfaces corroded by lubricant also affected the electro-painting processing of an automobile production line.

To date, many studies have only considered optimization of the process and the heating method of magnesium. Ambrogio et al. improved formability by hot incremental sheet forming.[3] Zhang et al. introduced Repeated Unidirectional Bending (RUP) of magnesium sheet forming.[4] Quan et al. improved formability for Multi-point bending process using elastic cushion.[5] These studies considered temperature control and the development of new processes by using high-temperature-lubricant. There was no previous research to improve coefficient of friction with die coating method between dies and blank. Also, research without any high-temperature-lubricant was not presented.

We suggest the use of a Diamond-Like Carbon (DLC) coating when developing a magnesium sheet forming process at warm form process. This coating can improve formability and the work environment by increasing the surface roughness. The DLC coating condition was optimized to have uniform distribution on the dies, and the DLC coating was applied under optimum conditions. This study compared dies and product before and after DLC coating at same tryout conditions. The formability, coefficient of friction, and a scratch were evaluated.

A partition panel that divides the automobile interior and trunk is

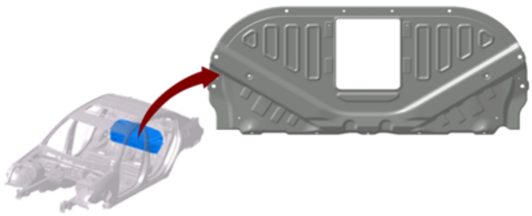


Fig. 1 Position of partition panel in Body-In-White

Table 1 Chemical compositions of X40CrMoV5-1 (STD61) (wt%)

	C	Si	Mn	P	S	Cr	Mo	V
Min.	0.35	0.8	0.25	-	-	4.8	1.0	0.8
Max.	0.42	1.2	0.5	0.03	0.02	5.5	1.5	1.15

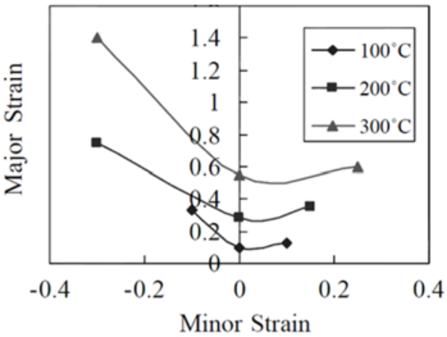


Fig. 2 Forming limit diagram of AZ31B at 100, 200, and 300°C

located in the rear body, as shown in Fig. 1. This body part also reduces noise from the exterior.

2. Experimental Method

2.1 Materials

To make a non-lubricant die for magnesium sheet forming, X40CrMoV5-1(KS:STD61) in ISO which mainly used of hot-work tool steel, was selected. The tool steel's chemical compositions are shown in Table 1.

AZ31B magnesium sheet were used made by POSCO(Korea). Thickness is 1.3 mm. The Forming Limit Diagram (FLD), dependence on the temperature, is shown in Fig. 2.[6] As shown in Fig. 2, the formability of magnesium increases as the blank's temperature increases. Formability increases dramatically between 200°C and 300°C. So, this FLD data was applied when the prototyping is produced.

2.2 Experimental condition

We used the Autoform R2 hot form simulation tool, and the simulation result is shown in Fig. 3. The analysis shows that the decreasing rate of thickness is locally the Max 24%. The decreasing rate of thickness area is expected to high fracture possibility. Therefore, the lubricant is needed to flow well between dies and materials. But, fracture area was not found at 300°C FLD data.

In order to heat the material and prototype, the draw type die, which

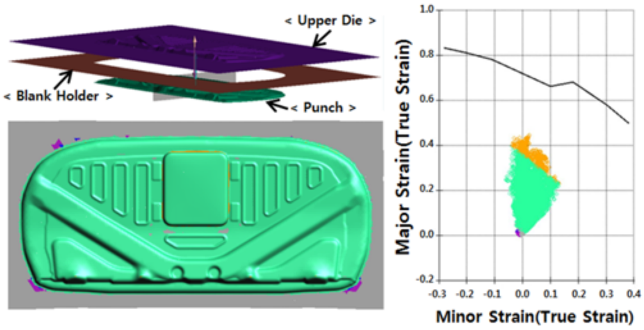


Fig. 3 Simulation results and Forming Limit Diagram

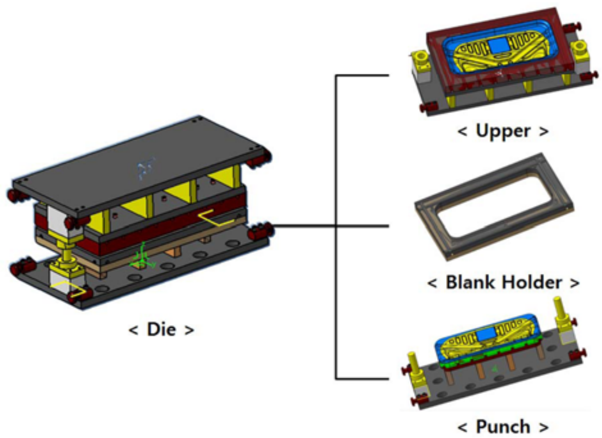


Fig. 4 Partition panel die structure

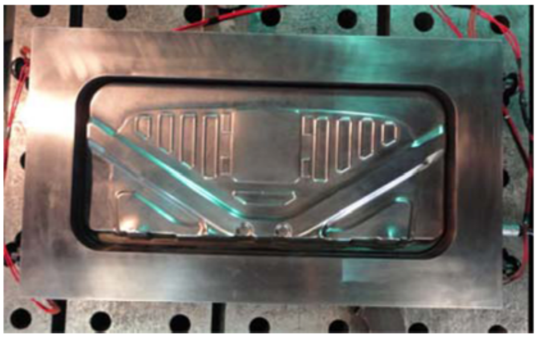
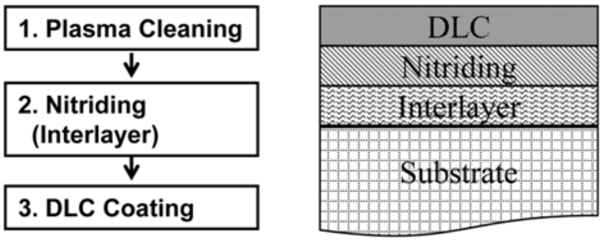


Fig. 5 Partition panel die before DLC coating

is composed of an upper die, blank holder and punch, was designed as based on the simulation results (Fig. 4). The materials were heated using a cartridge heater between the blank holder and upper die. The cartridge heater was inserted in the dies. A temperature control device was installed to control the temperature up to 350 °C in the dies. After die design, magnesium partition panel die was made as shown in Fig. 5.

Using DLC coating, the partition panel die was coated in order to reduce the coefficient of friction. DLC is coated different condition to improve adhesion and hardness, as shown in Fig. 6, followed by plasma cleaning, nitriding (interlayer) and DLC coating. Plasma cleaning process is to improve the adhesion of the thin film and removing the oxide film on the surface of dies. Nitriding treatment is the process for increasing the hardness by diffusing nitrogen on the surface of the dies.



(a) Coating process (b) Coating layer

Fig. 6 DLC Coating process and layer

Table 2 Nitriding treatment process conditions

Sample number	1-1	1-2	1-3	1-4
$N_2:H_2$ (sccm*)	4,500 : 900			
Bias Voltage (V)	650			
Temperature (℃)	400			
Vacuum (mbar)	1.33		0.67	
On-Off Pulse (μs)	3/15	10/100	3/15	3/15
Coating Time (min.)	180	180	270	180

sccm*: standard cubic centimeter per minute.

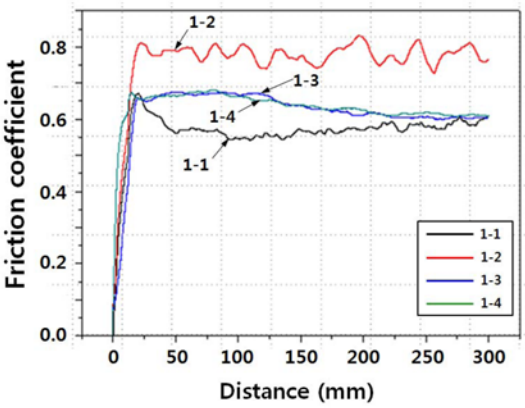


Fig. 7 Partition panel friction coefficient before DLC coating

Interlayer is to improve the adhesion between substrate and DLC coating layer. Finally, DLC coating layer facilitate non-lubricant at warm forming process.

To measure the coefficient of friction, we used a specimen with same condition as tool steel. Because it is difficult to obtain a specimen directly at dies. The coefficient of friction was measured using the ASTM G99 standard ("Standard Test Method for Wear Testing with a Pin-on-Disk Apparatus"). The pin was measured using a ball-on-disk by ball. Nitriding treatment condition is shown in Table 2. The coefficient of friction, as shown in Fig. 7, is the high value between 0.6 and 0.8 before DLC coating. '1-3' and '1-4' conditions have a constant friction coefficient at each condition. So, short time coating conditions of nitriding treatment '1-4' was determined.

We used four specimens. Each specimen have different DLC coating conditions. DLC coating variable is type of gas, vacuum, coating temperature and coating time. DLC coating process condition is shown in Table 3. As a result, two (#2, #3) of the four specimens were measured between 0.1 and 0.2. The others (#1, #4) are higher than

Table 3 DLC coating process conditions

Sample number	1	2	3	4
Ar : CH_4 (sccm)	300 : 300			
Bias Voltage (V)	700			
Temperature (℃)	100			
Vacuum (mbar)	0.13	0.13	0.067	0.067
On-Off Pulse (μs)	10/50	30/50	10/50	10/50
Coating Time (min.)	180	180	180	360

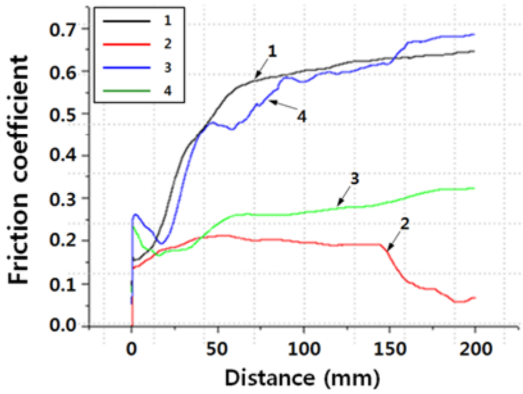


Fig. 8 Friction coefficient according to DLC coating condition

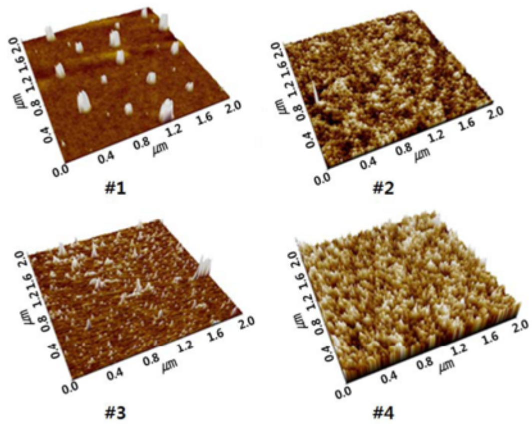


Fig. 9 DLC surface by AFM Images

#2, #3 as shown in Fig. 8. DLC coating layer was detached during the test at #1, #4 conditions due to low adhesion between the base metal and coating layer. Thus, the #2 and #3 DLC conditions are better.

Fig. 9 shows Atomic Force Microscopy (AFM) images on the die surface. Uniform coating film was obtained at low gas pressure in high-vacuum condition by decreasing coating speed. In result, #3 images is the lowest surface roughness.

Magnesium sheet forming conditions (heating temperature, blank size, and the material's heating time) were optimized through tryout and simulation. Constant values were obtained by tryout, as shown in Table 4. The blank size is one of the biggest variables when warm forming. The best blank size for partition panel is 590×275 (mm). For a larger blank size, material did not flow well into the dies due to holding force between the upper die and blank holder. The magnesium sheet was heated for 180 (s) between the upper die and blank holder,

Table 4 Blank size, die heating time, and die type for tryout

Blank size (mm)	590×275
Die heating time (s)	180
Die type	Draw type

Table 5 Tryout conditions

Tryout condition	ⓐ	ⓑ	ⓒ
Upper die temperature (°C)	300		
Blank holder temperature (°C)	300		
Punch temperature (°C)	300		100
DLC coating	Not applied	Applied	

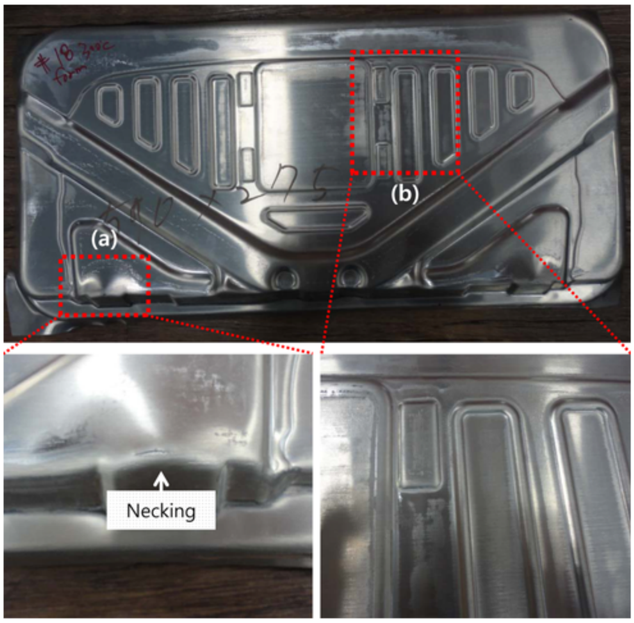


Fig. 10 Partition panel tryout results at tryout condition ⓐ [(a) Necking, (b) Scratch]

just before forming. The die is the draw type.

Table 5 shows variable tryout factors. The variable factors are the DLC coating and punch heating temperature. The main focus of this study is to determine if a DLC coating should be used. The other issue is the formability of local heating and cooling dies when warm forming. M.H. Lee et al. applied this method to improve formability.[7-9]

3. Results and Discussion

Fig. 10 shows the draw panel using different tryout conditions with constant values. Fig. 10 shows the draw panel in 'ⓐ' condition (Before DLC coating). 'ⓐ' panel did not have a crack at the draw panel. However, necking occurred at the deepest forming area. The draw panel was scratched by friction between the dies and blank at the surface. [Fig. 10(b)] Many scratches make a defective product. The draw panel was stuck at the upper die after forming. Fig. 11 shows the draw panel in 'ⓑ' condition (After DLC coating). The formability is similar to the 'ⓐ' condition. Scratching decreased significantly in comparison with the non-DLC coating condition. That is the reason why the DLC coating reduces the coefficient of friction between the material and the dies.

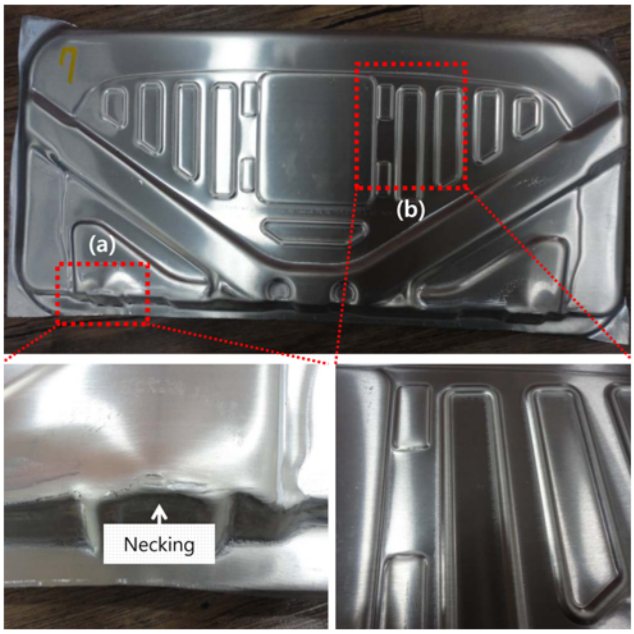


Fig. 11 Partition panel tryout results at tryout condition ⓑ [(a) Necking, (b) Scratch]

Fig. 12 Partition panel tryout results at tryout condition ⓒ [(a) Necking, (b) Scratch]

As previously mentioned, if the punch temperature is relatively lower than other temperatures, formability is improved (such as local necking and stuck). The punch temperature was set at 100°C. Fig. 12 shows the draw panel in 'ⓒ' (Punch temperature 100°C) condition. This is the best condition of the partition panel. As shown in Fig. 12, there was no defect anywhere.

In the future, a variety of research is needed such as considering different types of car body parts, method to reduce a cycle time and so on.

4. Conclusions

In this study, we considered the development of magnesium sheet forming to improve the lubrication of a partition panel that was manufactured by DLC coated dies. The following conclusions can be drawn.

1) It's confirmed that the coefficient of friction was reduced by up to 0.2, before and after the DLC coating.

2) There are many scratches at the surface, which occurred due to a high coefficient of friction without lubricant. Therefore, DLC coating was used to prevent defects such as surface scratches and necking.

3) In the tryout results, the condition that the temperature of punch was 100°C, showed better formability than that the temperature of all dies were 300°C.

4) Depending on a product's shape and working condition, the use of a DLC coating can improve formability and protect the environment by using non-lubricant dies.

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