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Development of Green CMP by Slurry Reduction through Controlling Platen Coolant Temperature

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Chemical mechanical polishing (CMP) is currently replacing a conventional chemical etching or mechanical polishing to remove overburdened copper deposit in printed circuit board (PCB) manufacturing process owing to its ability to realize a global planarization. In order to stabilize the CMP as one of the PCB manufacturing processes, the CMP machine has been investigated. This paper introduces a newly developed Oscar-type CMP machine and copper CMP process to polish rectangular PCB with a size up to 510 mm by 510 mm, especially focused on the effect of platen coolant temperature on removal rate and removal uniformity during copper CMP to reduce the amount of slurry consumed. The CMP experiments are implemented under the coolant temperatures of 10, 15, 20, 25 and 30°C, and the slurry flow of 600, 800, 1000 and 1200 mL/min. The experimental results show that the removal rate goes up with an increase in the platen coolant temperature during polishing at a fixed slurry flow rate, and the removal rate goes down at any fixed the platen coolant temperature when the slurry flow rate increases. It means that the reduction of thermochemical reaction rate in the chemical mechanical removal, resulting from cooling down of the copper surface when the.

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1. Introduction

Copper chemical mechanical polishing (CMP) is an essential step in the damascene process of integrated circuit fabrication and other types of electronic components.[1,2] The CMP process attains a local and global planarization of interlayer dielectrics, tungsten local vias, and multilevel copper interconnects, etc.[3,4] Semiconductor fabrication still maintains the main application of CMP process; however, its application is now expanding to other related industries.[5,6] The CMP can also be applied to the fabrication of multilevel circuit boards, packages, flat panel displays, flexible printed circuit boards, organic photovoltaics, etc. Recently, these fabrication processes have required a higher degree of planarity to achieve higher integrity and multi-stacking, prompting the application of the CMP process instead of conventional etching or mechanical polishing.

A copper CMP process using Oscar-type CMP machine to polish large rectangular flexible substrates was developed to overcome the limitations of conventional CMP systems. However, no previous in-depth studies have discussed the performance of copper CMP process with an Oscar-type CMP machine. In order to establish a novel green CMP process for reducing slurry consumption and understand the material removal mechanism, it is necessary to study the process parameters. In this study, we investigate the effects of the process parameters (down force, platen and carrier rotational speeds, overarm oscillation speed, slurry flow rate, and platen coolant temperature) on the average MRR (MRR_{avg}) and non-uniformity (NU) in a copper CMP process using an Oscar-type CMP machine to understand the material removal mechanism.

2. Experiments

2.1 Oscar-Type CMP Machine

Experiments were conducted on an Oscar-type CMP machine manufactured by GnP Technology Inc. The CMP machine can accommodate up to 915 mm diameter substrate and the platen can hold up to 1300 mm diameter polishing pad, and ex-situ brush conditioning can be done on the polisher. The substrate mounted to the polishing head under the overarm, the overarm pivot oscillates laterally the polishing head on the spinning platen with an attached polishing pad. The slurry delivered to the polishing pad through holes in the center of the platen. Fig. 1 is a schematic diagram of Oscar-type CMP machine, and Fig. 2 is a photograph of the actual system.

2.2 Consumables and Process Conditions

Cu CMP slurry (MS5000, Nitta Haas Inc.) with 3.2 wt% hydrogen peroxide (H_2O_2) was prepared for polishing of 510×510×0.56 mm sized copper-clad laminate (CCL) which has a 35 μm Cu film on polymer substrate. Polishing pad was a polymer impregnated felt (SUBA 600 XY groove, Nitta Haas Inc.), and was punched with three holes in the center for delivering slurry.

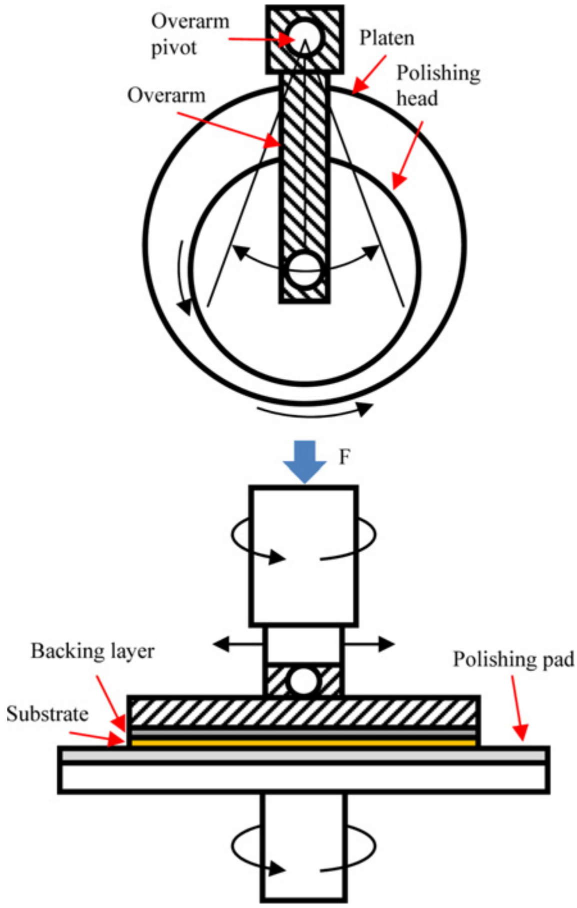

Fig. 1 Schematic diagram of Oscar-Type CMP machine

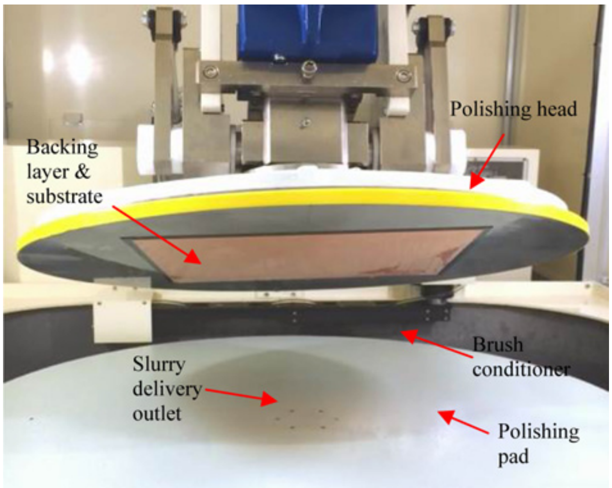

Fig. 2 Photograph of actual Oscar-Type CMP machine

The process parameters for the Oscar-type CMP machine are down force, rotation speeds of the platen and head, overarm oscillation speed, slurry flow rate, and platen coolant temperature. Experimental conditions are listed in Table 1. The thickness of the Cu film was measured with a four-point probe (SR-scope, Fischer Technology, Inc.). The edge exclusion in the x and y directions were 30 mm, respectively. Total of 41 points were measured along with x and y directions. The NU of the MRRs was calculated as

$$NU(\%) = \frac{\sigma}{MRR_{avg}} \times 100 \quad (1)$$

Where σ is the standard deviation of the material removal rates, and MRR_{avg} is the mean value of the material removal rates.

3. Results and Discussion

3.1 Down Force and Rotational Speeds of Platen and Head

Fig. 3 shows the effects of down force and rotational speeds of platen and head on the MRR_{avg} and NU of the MRRs. The down force of the carrier was varied from 3.82 to 7.65 kN, platen and head rotational speeds were changed from 30 to 75 rpm. The highest MRR_{avg} was 4.1 μm/min (7.65 kN down force, 75 rpm platen and head speeds), the lowest MRR_{avg} was 1.2 μm/min (3.82 kn down force, 30 rpm platen and head speeds). The NU varied from 14.4% (5.1 kN down force, 60 rpm platen and head speeds) to 34.2% (3.82 kN down force, 30 rpm platen and carrier speeds) according to process conditions.

From Fig. 3 it can be seen that the MRR_{avg} increases with an increase in the down force and rotational speeds. The NU initially reduces with an increase in rotational speeds up to 60 rpm and then increases with a further increase in rotational speed. Thus it appears likely that the down force should be increased and rotational speeds should be about 60 rpm to obtain high MRR_{avg} and low NU.

According to Preston's equation,[7] the product of the applied pressure and the relative velocity between the substrate and the polishing pad makes a significant contribution to MRR in a CMP process. Fig. 4 shows that the MRR_{avg} of Oscar-type CMP process conforms to Preston's equation. The MRR_{avg} increases linearly with the product of the pressure and the relative velocity between the sliding substrate and the rotating polishing pad.

3.2 Overarm Oscillation Speed

Fig. 5 illustrates the kinematic parameters of the Oscar-type CMP

Table 1 Experimental conditions

Parameters	Conditions
Substrate	CCL, 510 mm × 510 mm × 0.56 mm
Pad	SUBA600 (Nitta Haas)
Slurry	MS5000 (Nitta Haas)
Down force	3.28-8.04 kN
Platen and head rotational speeds	30-75 rpm
Overarm oscillation speed	0-8 rpm
Slurry flow rate	600-1200 mL/min
Platen coolant temperature	10-30 ºC

machine. O and O' represent the origin of the coordinate system located on the platen (or pad) and the polishing head (or substrate), respectively. ω_p, ω_c and ω_o represent the angular velocities of platen, head and overarm, respectively. $\vec{P}(t)$, $\vec{D}(t)$ and $\vec{r}$ are the position vectors from O to A, from O to O', and from O' to A, respectively. The position vector $\vec{P}(t)$ as a function of process time (t) can be written as

$$\vec{P}(t) = \vec{D}(t) + \vec{r}(t) = P_x \cdot \hat{i} + P_y(t) \cdot \hat{j} \tag{2}$$

Where $\hat{i}$ and $\hat{j}$ are the unit vectors of the x and y directions in the coordination system. The relative velocity at the arbitrary position A is the derivative of $\vec{V}(t)$ with respect to process time t as shown below.

$$\vec{V}(t) = \frac{d}{dt}\vec{P}(t) = \frac{dP_x(t)}{dt} \cdot \hat{i} + \frac{dP_y(t)}{dt} \cdot \hat{j} \tag{3}$$

The magnitude of the relative velocity at an arbitrary position (x,y) on the substrate can be calculated as

$$V(x, y, t) = \sqrt{\frac{dP_x(t)^2}{dt} + \frac{dP_y(t)^2}{dt}} \tag{4}$$

The magnitude of relative velocity affects the MRR, but its direction does not Ref. 8. Among the kinematic variables, ω_p is the dominant parameter in the relative velocity magnitude. ω_o also affects the relative velocity magnitude but less than ω_p. ω_c mainly affects the resulting cycle frequency of the relative velocity magnitude.

Fig. 6 shows the effect of the overarm oscillation speed on the average relative velocity and the MRR_{avg}. The lowest MRR_{avg} is 2.6 μm/min at the overarm oscillation speed of 0 rpm. The MRR_{avg} increases with an increase in the overarm oscillation speed. There are no significant changes in MRR_{avg} when the overarm oscillation speeds excesses 2 rpm. Since the overarm oscillation speed is quite small compared with platen and head rotational speeds, its effect on the average relative velocity is not important.

3.3 Slurry Flow Rate

The slurry flow rate affects the material removal characteristics by

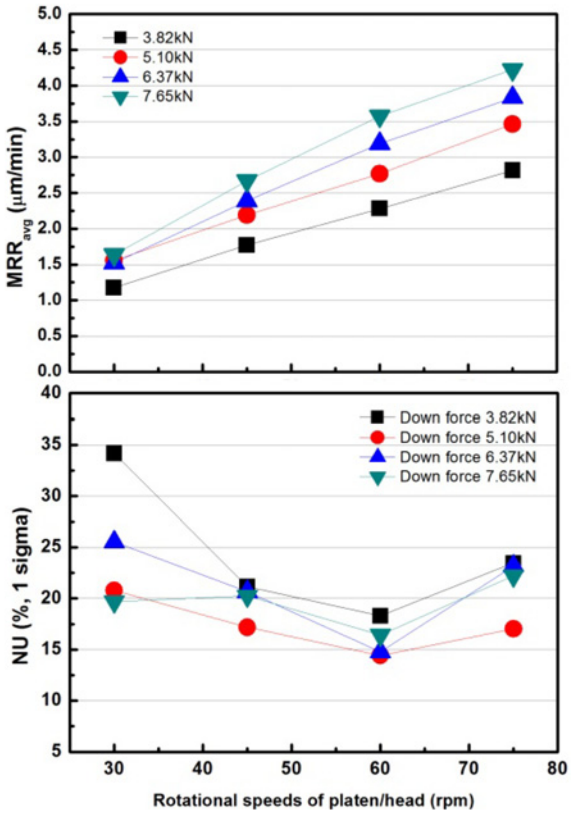

Fig. 3 Variation in MRR_{avg} and NU with down force and rotational speeds of platen and head

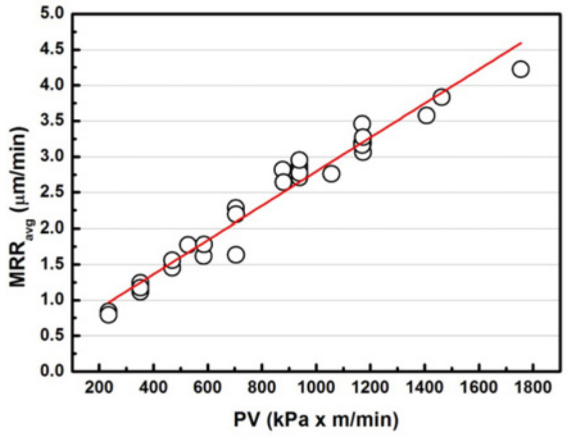

Fig. 4 MRR_{avg} obtained experimentally as a function of the product of the pressure and the relative velocity

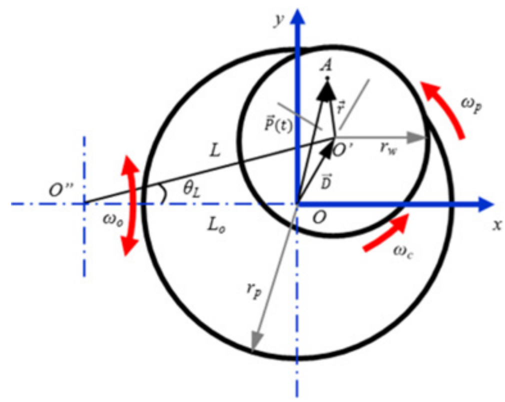

Fig. 5 Kinematic diagram of Oscar-Type CMP machine

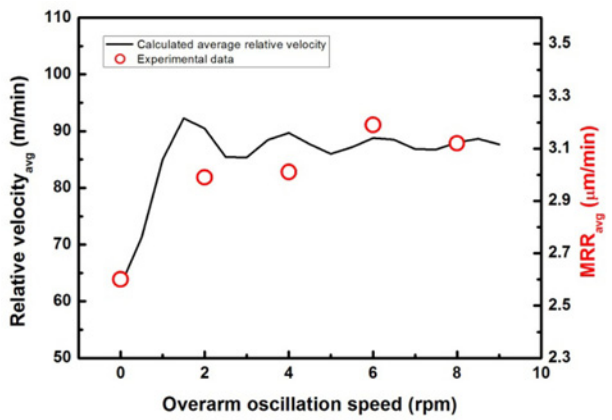

Fig. 6 Calculated average relative velocity and experimental MRR_{avg} as a function of overarm oscillation speed ($\omega_p = \omega_c = 60$ rpm, $L = 868$ mm, $L_o = 768$, down force: 6.37 kN)

changing the interaction between abrasives and chemicals. Fig. 7 shows that the effects of the slurry flow rate on MRR_{avg} and NU. The down force is 8.04 kN, platen and head rotational speeds are 50 rpm and the platen coolant temperature is 20°C. It can be seen that MRR_{avg} increases when the slurry flow rate increases from 600 to 1000 mL/min, and then decreases by further increase in the slurry flow rate. Subrahamanya et al.[9] showed that coefficient of friction decreased and removal rate increased with an increase in slurry flow rate. Li et al.[10] showed that the decrease in material removal rate with increasing slurry flow rate attributed the change to the cooling of the wafer by the slurry in copper polishing. The reasons for the change in MRR_{avg} with increase in slurry flow rate are due to the change in coefficient of friction and substrate surface cooling effect. As the higher slurry flow rate decreases the temperature at the interface between the substrate and the polishing pad, MRR_{avg} decreases at a slurry flow rate of 1200 mL/min.

Increasing the slurry flow rate from 600 to 1200 mL/min reduces NU. Since the slurry supplied to the interface between substrate and pad through holes in the center of the polishing pad in Oscar-type CMP machine, the higher slurry flow rate can transport fresh slurry from center to the edge of the polishing pad. From Fig. 8 it can be seen that the center area of substrate was polished more rapidly than the edge area of substrate at the lower slurry flow rate. The MRR difference between center and edge area was reduced at the higher slurry flow rate. It implies that a sufficiently large slurry flow rate results in a low NU.

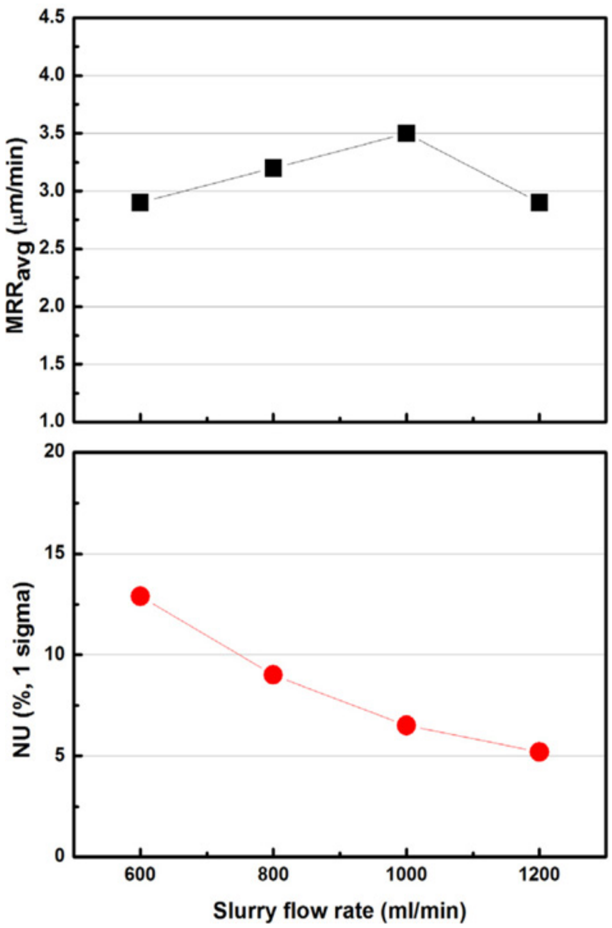

Fig. 7 MRR_{avg} and NU data at different slurry flow rate (down force: 8.04 kN, platen and head speed: 50 rpm, platen coolant temperature: 20°C)

3.4 Platen Coolant Temperature

Pad temperature influences the material removal rate by changing the pad properties and chemical reaction rate. Kakireddy et al.[11] showed that the coefficient of friction and removal rate increased with an increase in temperature during polishing. This change in the coefficient of friction is due to the increased contact area of the pad-substrate surface with an increase in temperature, resulting in a higher shear force at the interface, which can be supported by the change in COF with the change in temperature. Kim et al.[12] showed that the contact area increases with temperature caused by the decrease of asperity hardness due to the temperature elevation. Lee et al.[13] showed that the rise of the pad temperature increases the temperature of the slurry flow in the pad-substrate interface.

In our experiment, the platen coolant temperature is adjusted from 10 to 30°C to verify the effect of elevating pad temperature in the process. The platen coolant flows through circular shaped channels as shown in Fig. 9. The down force is 8.04 kN, rotational speeds of the platen and head are 50 rpm and the slurry flow rates are changed from 600 to 1200 mL/min. From Fig. 10, it can be seen that the MRR_{avg} are increased with an increase in the platen coolant temperature. The observed increase in MRR_{avg} might be due to increase in contact area between the substrate and the pad. This increase in contact area results in reduction of the overall load experienced by the pad. It is the nature of polymer materials that the COF increases with reduction in applied load when in contact with a hard inelastic material. From Fig. 10, it can

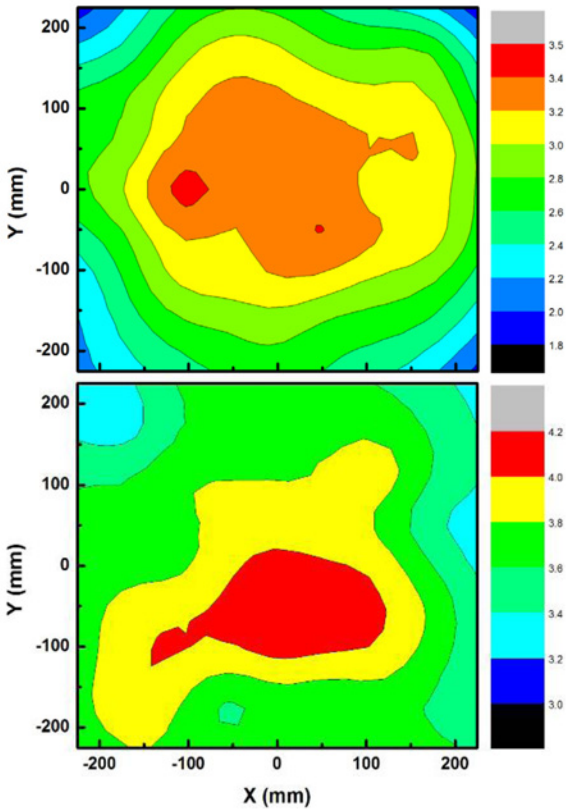

Fig. 8 Examples of MRR contour map of slurry flow rate at (a) 600, (b) 1200 mL/min

be seen that the NU of MRRs reduces with an increase in the platen coolant temperature except at a slurry flow of 600 mL/min. The observed trend of the NU can be attributed to the changes in the slurry viscosity. Viscosity is a very temperature dependent parameter, whereby small variations in temperature can produce large variations in viscosity. As the higher platen coolant temperature decreases the slurry viscosity, fresh slurry can transport to edge of the pad. The higher platen coolant temperature leads to a superfluous chemically reacted area on the substrate without the cooling effect. These results indicate that high MRR and low NU are attained by increasing the platen coolant temperature rather than increasing the slurry flow rate.

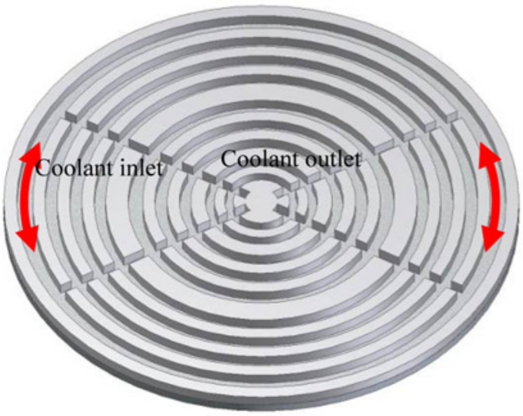

Fig. 9 Circular shaped platen coolant channels

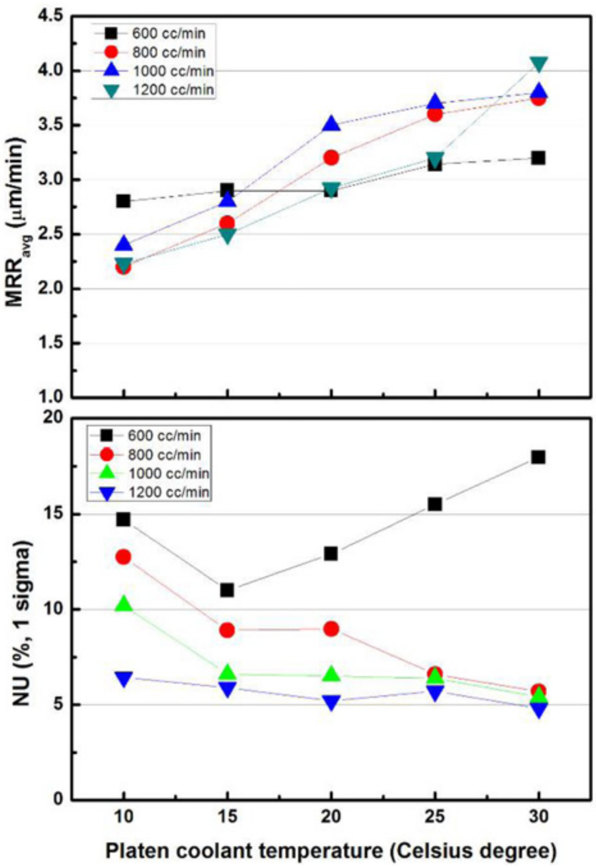

Fig. 10 MRR$_{avg}$ and NU data at different platen coolant temperature (down force: 8.04 kN, platen and head speed: 50 rpm)

4. Conclusions

This paper has described the process parameters for the newly developed Oscar-type CMP machine and copper CMP process for the flexible CCL substrate with a size up to 510 mm by 510 mm. From the viewpoint of average MRR, Oscar-type CMP machine process conforms to the traditional Preston's equation. The overarm oscillation speed is quite small compared with platen speed and head rotational speed, its effect on the average relative velocity is not significant except at 0 rpm. The MRR$_{avg}$ increased and the NU improved with an increase in slurry flow rate up to 1000 mL/min and then decreased with a further increase in slurry flow rate. This could be attributed to the decrease in the temperature at the interface between the substrate and the polishing pad. Finally, the platen coolant temperature directly influences the MRR$_{avg}$ and the NU. The MRR$_{avg}$ increased with an increase in platen coolant temperature without cooling effect at the interface of the substrate and pad. The NU also improved at higher platen coolant temperature. Thus, high MRR and low NU were attained by increasing platen coolant temperature in spite of the reduction of slurry consumption. For the experiment described in this paper, we used a newly developed Oscar-type CMP machine and copper CMP process for PCB rectangular panels. This preliminary study may be helpful for expanding the range of fields to which Oscar-type CMP machine and copper CMP process is applied.

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