Springer

KSME

Journal of Mechanical Science and Technology 29 (12) (2015) 5325~5333
www.springerlink.com/content/1738-494x(Print)/1976-3824(Online)
DOI 10.1007/s12206-015-1134-6

Effect of carbon nano tube (CNT) particles in magnetic abrasive finishing of Mg alloy bars †

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(Manuscript Received March 6, 2015; Revised June 8, 2015; Accepted July 28, 2015)

Abstract

The Magnetic abrasive finishing (MAF) process is a surface finishing technique in which a magnetic field is used to control abrasive particles during surface finishing of a material. Because smooth surfaces are required for general use, the magnetic abrasive finishing process was developed for finishing surfaces. We studied the effect of CNT particles on the surface roughness of a workpiece. Magnesium alloy bars were used as the cylindrical workpiece and were finished using an MAF process at high workpiece revolution speeds of 1000, 5000, 10000 and 25000 rpm; diamond pastes with diameters of 0.5, 1, and 3 μm were used for comparison. The best value for surface roughness was equivalent to treatment at 0.02 μm when 0.01 g of CNT particles was mixed together with the unbonded magnetic abrasive at 25000 rpm for 20 seconds. CNT particles were applied to the finishing process to improve the surface roughness of the material, because they have many advantageous properties such as very high strength, light weight, elasticity, and high thermal and air stability. CNT particles are particularly effective for the improvement of Mg alloy bar surface roughness in the MAF process.

Keywords: Magnetic abrasive finishing; Magnesium alloy bars; Un-bonded magnetic abrasive; CNT particles; Surface roughness; Change of diameter; Removal weight

1. Introduction

Mg alloy is one of the useful metals which has the low density and on the planet; it is the most light-weight metal, with good mechanical and electrical properties, high specific strength, shielding against electromagnetic waves and vibration damping, and therefore has been widely used in the automobile, aircraft, IT and defense industry [1, 2]. Even though the use of Mg alloy has seen a dramatic increase in industrial applications, it has a high failure rate of surface treatment. It requires high technique and good equipment to treat the surfaces. A Magnetic abrasive finishing (MAF) process is a surface finishing technique in which a magnetic field is used to control abrasive particles to remove the unevenness from the surface of materials. In the previous study, the unbonded magnetic abrasive consisted of iron particles, abrasive particles and lubricant were used to finish the soft and hard alloys [3]. In magnetic abrasive finishing process the abrasive particles are the most critical parameter because they are widely used for cutting or polishing the surface of materials. Chang et al. [4] used SiC abrasive mixed with steel grit to finish the surface of SKD11 materials. Their results showed that the best surface roughness of 0.042 μm Ra was obtained. Im et al. [3] improved the surface of STS 304 bars by using diamond abrasive particles and iron particles. They showed that when diamond abrasive particles were used, a surface roughness as fine as 0.06 μm (Ry) was achieved. Yin et al. [5] finished the surface of magnesium alloy by WA magnetic abrasive particles, and showed that the surface roughness of magnesium alloy could improve from 2.5 μm to 0.7 μm (Ry) by WA magnetic abrasive particles. Even though these kinds of abrasive particles can produce a fine surface finish, they also can produce unwanted side effects and the results are not good enough for surface quality. After finishing, the SiC abrasive particles can be seen on the surface of the material when electron probe micro-analysis, energy dispersive X-ray analysis or related Auger laboratory analyses are used [4]. When SiC is the abrasive, MAF can impart a mirror finish, but it will be a darker color than when SiC is not used [4].

To overcome the problems, CNTs were used as the abrasive particles with the aim to produce fine surface of materials. Carbon nanotubes (CNTs) have excellent electrical and me-

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† Recommended by Associate Editor Taesung Kim

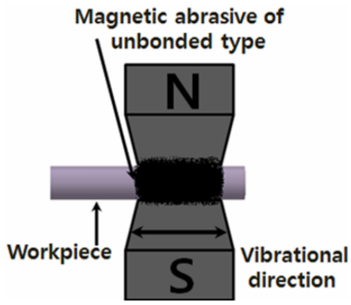


Fig. 1. Schematic of Magnetic abrasive finishing (MAF) process.

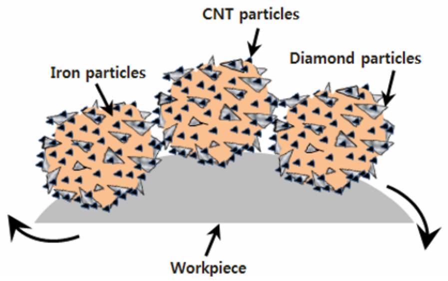


Fig. 2. Machining principles of magnetic abrasive finishing process.

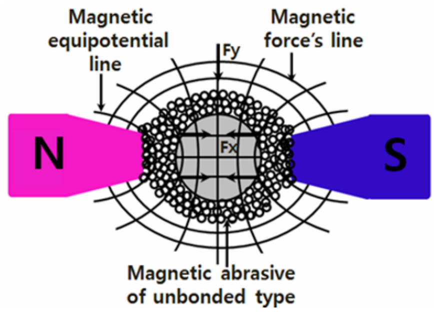


Fig. 3. Schematic of magnetic forces working on the workpiece.

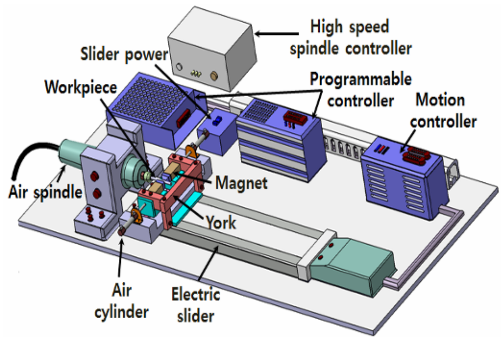


Fig. 4. Schematic of the magnetic abrasive finishing equipment.

chanical properties, high strength, good thermal conductivity, and they have light weight and very small particles [6]. Bakshi et al.'s [7] experiments showed that CNTs have extraordinary mechanical properties over carbon fibers, with stiffness up to 1000 GPa, strength of the order of 100 GPa and thermal conductivity up to 6000 Wmk. Due to their excellent mechanical properties, CNT particles are potentially useful materials in many applications and are very important in order to achieve a high quality of material surface finish. In this paper, a new unbouned magnetic abrasive was introduced by preparing CNT particles and diamond abrasive particles mixed with iron particles with the aim to finish the surface of Mg alloy, and then surface accuracy and dimensional accuracy in ultra-precision machining characteristics were mainly investigated.

2. Principle of MAF process

Fig. 1 shows a schematic of an MAF process; the workpiece is inserted into the gap between the magnetic poles and an unbonded magnetic abrasive used for finishing the workpiece surface is supplied between the magnet poles [2]. The unbonded magnetic abrasive consists of diamond paste with abrasive (0.5 µm, 1 µm, 3 µm), iron particles (mesh size 200), CNT particles and 2 ml of lubricant (light oil). They are mechanically mixed together in a specific ratio to form the abrasive mixture and the machining principles of magnetic abrasive finishing process was shown in Fig. 2. The finishing gap between the workpiece and the magnet is 1 mm and 12 Hz of vibrational frequency is applied during the finishing process.

Fig. 3 shows the dimensional magnetic forces applied to the workpiece during the finishing process. There are two types of forces: (Fx) and (Fy). Force (Fx), called magnetic abrasive finishing force, flows from pole to pole and when the two magnets are attracted to each other. Force (Fy) is generated when the workpiece pushes against the bridges formed in the direction of the magnetic equipotential line. Because two-dimensional forces are generated, the magnetic abrasive particles can finish the surface of a cylindrical bar [3]. Fig. 4. shows the schematic of the magnetic abrasive finishing equipment, which consists of a high speed spindle controller, slider power, programmable controller, motion controller, air cylinder, york, air spindle, workpiece, magnet, and electric slider.

3. Experimental apparatus and method

3.1 Carbon nanotube (CNT) particles

Carbon nanotubes (CNTs) are fullerene related structures which consist of rolled grapheme sheets and their diameter is about 0.01 µm ~ 0.04 µm. There are two main types of carbon nanotubes that can have high structural perfection. Single walled nanotubes (SWNT) consist of a single graphite sheet seamlessly wrapped into a cylindrical tube. Multiwalled nanotubes (MWNT) comprise an array of such nanotubes that are concentrically nested like rings of a tree trunk [8]. Carbon nanotubes have a higher tensile strength than steel and Kevlar. Their strength comes from the sp^2 bonds between the individual carbon atoms. This bond is even stronger than the sp^3 bond found in diamond. Under high pressure, individual nanotubes can bond together, trading some sp^2 bonds for sp^3 bonds. Their

Table 1. Properties of abrasive used in magnetic abrasive finishing process.

	Strength (GPa)	Elastic modulus (GPa)	Thermal conductivity (W/mK)	Density (g/cm^3)
Boron	3.3~4.0	370~400	100~200	2.4
SiC	2.9~4.0	210~400	70~110	3.1
Al_2O_3	1.5	380	30	3.9
PCD	4.0	1050	350	3.42
CNT	20~50	600~1200	1800~6600	1.6

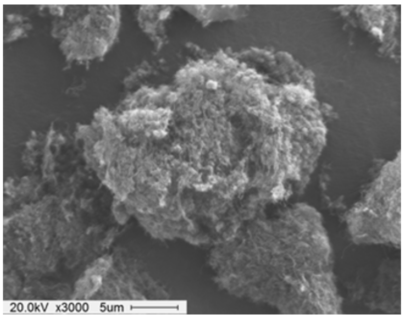


Fig. 5. SEM micro image of multi-walled CNT particles.

electrical properties are better than that of other materials. When the structure of atoms in a carbon nanotube minimizes the collisions between conduction electrons and atoms, a carbon nanotube is highly conductive. The strong bonds between carbon atoms also allow carbon nanotubes to withstand higher electric currents than copper. Carbon nanotubes have been shown to be very good thermal conductors. When compared to copper wires, which are commonly used as thermal conductors, the carbon nanotubes can transmit over 15 times the amount of watts per meter per Kelvin. Table 1 shows the comparison between the properties of CNTs abrasive and other properties of abrasive used in the magnetic abrasive finishing process [9-10]. As shown, the properties of CNTs abrasive are the best when compared to others, and Fig. 5 shows SEM micro image of Multi-walled CNT particles. The particles of CNT are very light and small with a high hardness and high strength, and their diameter is about 0.01 μm ~ 0.04 μm.

3.2 Unbonded magnetic abrasive with CNT particles

The unbonded magnetic abrasive is a mechanical mixture of diamond paste, light oil, iron particles and CNT particles. To obtain a high quality of surface finish, the abrasive grain sizes are significantly important in magnetic abrasive finishing process. When the surface of material was finished by the small grain size of abrasive particles, the value of surface roughness is greater than when the big grain size was used [11]. Im et al. [3] applied three different grain sizes of abrasive particles to the unbonded magnetic abrasive. They showed that the small grain size had better performance than big grain size. If comparing properties of CNT abrasive particles to others, their properties are significantly greater than others. That's why they are the most suitable for applying in the magnetic abrasive finishing process.

Fig. 6. Mixture of unbonded magnetic abrasives with CNT particles.

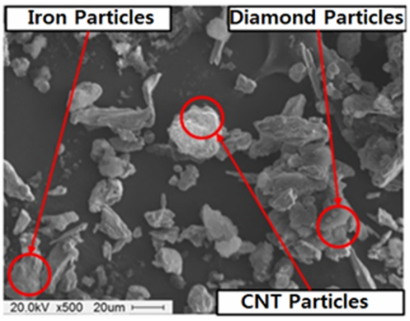


Fig. 7. SEM micro image of unbonded magnetic abrasives with CNT particles.

Fig. 8. Mixture of unbonded magnetic abrasives.

Fig. 6 shows the mechanical mixture of unbonded magnetic abrasives with CNT particles, and Fig. 7 shows the SEM micro image of unbonded magnetic abrasives with CNT particles.

3.3 Unbonded magnetic abrasive without CNT particles

Fig. 8 shows the mechanical mixture of unbonded magnetic abrasives without CNT particles. The unbonded magnetc abrasive was prepared, which is the mechanical mixture of diamond paste, light oil and iron particles. After finishing process was completed, their results were compared to evaluate the possibility of CNT abrasives particles and diamond paste particles in the magnetic abrasive finishing process. Fig. 9 shows the SEM micro image of the abrasive mixture.

Table 2. Experimental conditions.

Workpiece (mm)	Magnesium alloy bar (l: 50, d: 30)
Workpiece revolution (rpm)	1,000; 5,000; 10000; 25000
Mixed type magnetic abrasive	Iron particles: 0.85 g (#200) Diamond paste: 0.2 g (0.5, 1, 3 μm) CNT particles: 0.01 g Lubricant: 0.2 ml (light oil)
Magnetic flux density (T)	0.52
Pole vibration (Hz)	Amplitude: 2 mm; frequency: 12
Magnet	Nd-Fe-B permanent magnet
Clearance (mm)	1
Times (s)	0; 20; 40; 60; 80

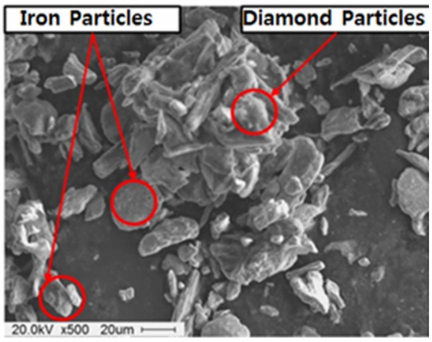


Fig. 9. SEM micro image of unbonded magnetic abrasives.

4. Experimental conditions

Table 2 shows the experimental conditions. As shown previously, a magnesium alloy bar 50 mm in length and 3 mm in diameter was used as the workpiece. The workpiece was rotated at 1000, 5000, 10000 and 25000 rpm, and the mixture of magnetic abrasive consisted of 0.85 g iron particles (Fe, #200), 0.2 g of three diamond pastes (0.5 μm, 1 μm, 3 μm), 0.01 g CNT particles, and 0.2 ml lubricant (light oil). A magnetic flux density of 0.52 T and pole vibration of 12 Hz with a 2 mm amplitude were used. The workpiece was finished with an unbonded type magnetic abrasive from 0 to 80 seconds, and the working gap between magnet and workpiece is 1 mm.

5. Results and discussion

5.1 Effects of diamond particles and workpiece revolution

5.1.1 Effects of diamond particles

To fix the diamond particle grain size, the workpiece was rotated at 10000 rpm, and diamond pastes of 0.5, 1, and 3 μm abrasive were used, respectively. Fig. 10 shows the relationship between surface roughness and processing time. In this paper, when 1-μm diamond paste abrasive was used, the best Ra value was achieved, because 1-μm diamond paste abrasive and Mg alloy have the same characteristics, and 1-μm grain size has good cutting ability for soft material surfaces such as Mg alloy.

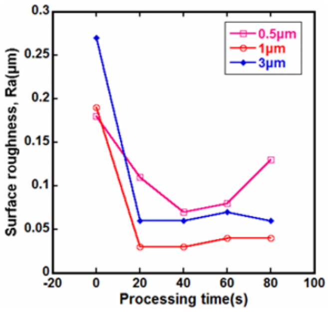
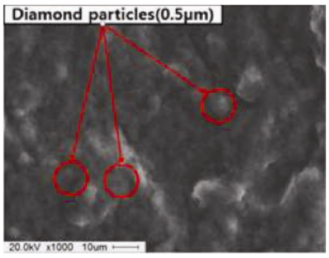
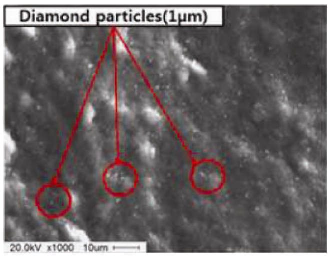


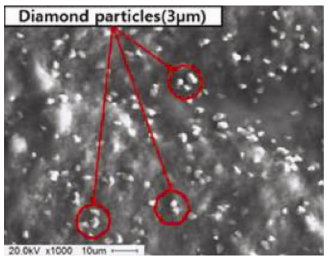
Fig. 10. Surface roughness (Ra) vs. processing time (10000 rpm).



(a) Diamond partcles (0.5 μm)



(b) Diamond partcles (1 μm)



(c) Diamond particles (3 μm)

Fig. 11. SEM micro images of diamond particles.

The SEM micro image of the 1-μm diamond particles is shown in Fig. 11(b). The largest grain size among three diamond pastes was the 3-μm diamond paste, which was the second best for finishing the surface roughness. Meanwhile, 0.5 μm had the worst performance among the three grain sizes, because the grain size was too small. SEM micro image of 0.5 μm diamond particles is shown in Fig. 11(a).

Fig. 12 shows the relationship between the removal weight of the workpiece and processing time. The slopes of 0.5, 1, and 3 μm pastes are similar and not significantly different, but

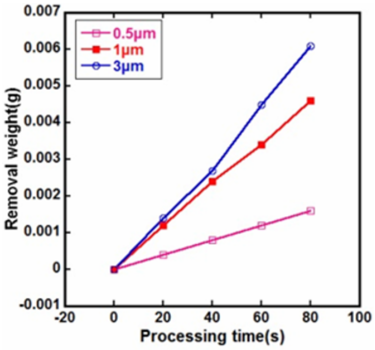


Fig. 12. Removal weight vs. processing time (10000 rpm).

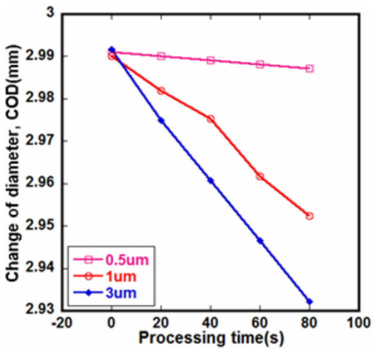


Fig. 13. Relationship between COD vs. processing time.

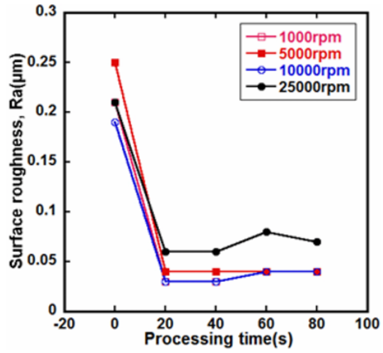


Fig. 14. Surface roughness (Ra) vs. processing time (1μm).

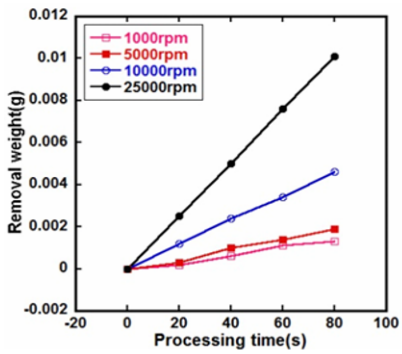


Fig. 15. Removal weight vs. processing time (1 μm).

the slope of the 3-μm paste demonstrated the best improvement in workpiece weight due to the large grain size.

Fig. 13 shows the relationship between Change of diameter (COD) and processing time. When the workpiece was rotated at 10,000 rpm and 0.5 μm, 1 μm and 3 μm pastes were used, the largest slope was achieved for 3 μm, which had the best performance for reducing the COD of the workpiece due to large grain size, while 0.5 μm showed the smallest slope. The slope of 0.5 μm did not indicate significant improvement because the grain size of the diamond paste was too small. These results indicate that to obtain the best COD value or removal weight of the workpiece, a large-grain-size diamond paste is suitable. The SEM micro image of the 3-μm diamond particles is shown in Fig. 11(c).

5.1.2 Effects of workpiece revolution

To fix the workpiece revolution, itkpiece was rotated at 1000, 5000, 10000 and 25000 rpm and a 1-μm abrasive of diamond paste was used for finishing. Fig. 14 shows the relationship between surface roughness and processing time. The figure indicates that the slopes of 1000, 5000, 10000 and 25000 rpm were rapidly improved for up to 20 seconds, because the high speed of the workpiece could remove the unevenness effectively, but after 40 seconds the slopes of surface roughness did not improve further. In the case of 5000 rpm the Ra value was 0.04 μm and remained constant for all finishing times. In the case of 25000 rpm the surface roughness only improved significantly at 20s and 40s, and the slope decreased at processing times of 20 seconds and 40 seconds, because the high speed of the workpiece could effectively remove only the uneven surface. However, when the workpiece was rotated at 1000 rpm and 10000 rpm, the Ra slopes were identical, requiring only 20 seconds to enhance the Ra from 0.20 μm to 0.03 μm. After 40 seconds, the Ra value was 0.04 μm, which was worse than the result at 20 seconds and 40 seconds, because the uneven surface was already removed after 20 seconds, and thus magnetic abrasive finishing could not improve Ra.

Fig. 15 shows the relationship between the removal weight of the workpiece and processing time. There are four slopes in the figure; the largest slope was observed for 25000 rpm and the smallest slope was noted at 1000 rpm. In the case of 25000 rpm, the removal weight rapidly changed from 0.6281 to 0.6180 g in only 80 s due to the high speed of the workpiece, but at 1000 rpm the weight of workpiece was decreased from 0.62433 to 0.62185 g. The total weight removed by abrasive at 1000 rpm was 0.00248 g, which is less than that removed at 25000 rpm (0.0101 g). Moreover, the figure indicates that the slope of 5,000 rpm is less than the slope of 10000 rpm, but greater than the slope of 1000 rpm. These results indicate that revolution of the workpiece is particularly effective in this regard.

Fig. 16 shows the relationship between change of diameter and processing time. When 1-μm diamond paste abrasive was used and the workpiece was rotated at 1000 rpm, 5000 rpm, 10000 rpm and 25000 rpm, respectively, For 25000 rpm, the COD slope was the greatest, the slope of 10000 rpm was sec-

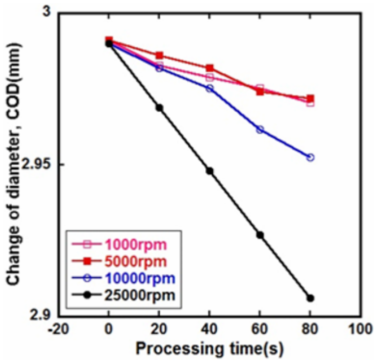


Fig. 16. Relationship between COD vs. processing time (1 μm).

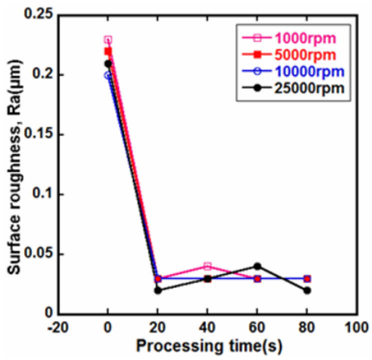
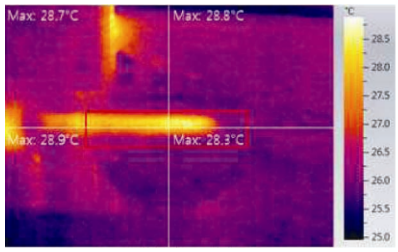


Fig. 17. Surface roughness (Ra) vs. processing time (1 μm).

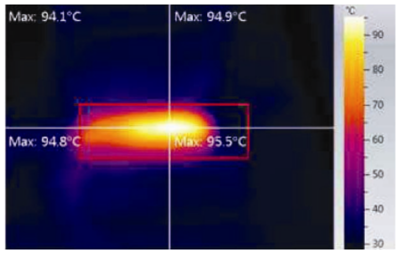
ond greatest, the slope of 5000 rpm was third greatest and the slope of 1000 rpm was the smallest. The COD of the workpiece can be evaluated through the results; when the highest revolution speed was applied, the best COD value was obtained.

5.2 Effects of CNT particles on finishing characteristics

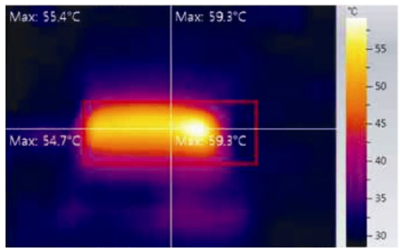
The finishing characteristics of CNT particles and the effects of CNT particles on the surface of Mg alloys were studied. Fig. 17 shows the relationship between surface roughness and processing time; 0.01 g of CNT particles were added to the mixture of unbonded magnetic abrasive with 1-μm abrasive of diamond paste. The workpiece was rotated at different speeds (1000, 5000, 10000 and 25000 rpm). As shown in the figure, all slopes were rapidly improved from the initial value during the first 20 seconds because the uneven surface of the workpiece. After 20 seconds, the slopes could not improve anymore because the uneven surface of the workpiece was already finished. In the case of 5000 and 10000 rpm the observed slopes are the same; the Ra slopes showed improvement until 20 seconds and then remained constant after 20 seconds. For 25000 rpm, the best Ra value results were achieved at 20 seconds was 0.02 μm and then declined after 20 seconds. The results indicate that when CNT particles were used to smooth the surface of material via the magnetic abrasive finishing process, 25000 rpm was the most effective speed. The best value Ra (0.02 μm) was obtained because of



(a) Before finishing



(b) After finishing with CNT particles in 80 sec



(c) After finishing with CNT particles in 80 sec

Fig. 18. Surface finishes temperatures by an infrared camera.

the relationship between high speed finishing and very small grain size with high strength cutting edge of CNT particles. When the workpiece was finished with high revolution speed, the surface of workpiece was strongly against with the cutting force of abrasive particles. If the workpiece is finished by small abrasive particles with high revolution speed, the surface finish will be significantly smoother than before finishing. On the contrary, if the workpiece is finished by big grain size abrasive particles, the deep scratches and irregular asperities will occur on the surface finish due to the high speed revolution. Because CNT particles have very small grain size with high strength cutting edges, their particles can produce a smooth surface finish. Furthermore, CNT particles can protect the high temperature, which impacts on the surface of Mg alloy due to their high thermal conductivity. The high temperature occurred on the surface of material when surface finished with high speed revolution. The temperature of the surface finishes measured by an infrared camera before finishing in 0 second and after finishing with 20000 rpm in 80 seconds. As shown in Fig. 18(a) the temperature was about 28°C, but after finishing with abrasive without CNT particles, the surface finish temperature reached to 95.5°C in (Fig. 18(b)). When the workpiece was finished with abrasive with CNT particles, the temperature reached to

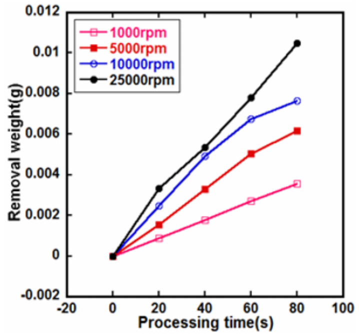


Fig. 19. Removal weight vs. processing time (1 μm).

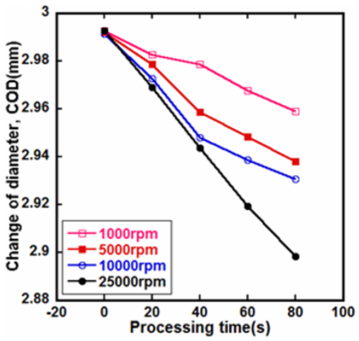


Fig. 20. Relationship between COD vs. processing time (1 μm).

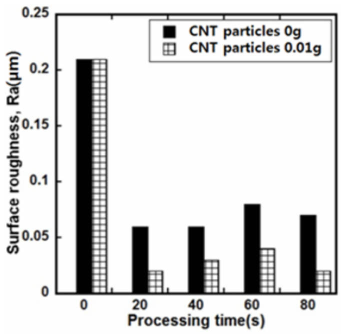


Fig. 21. Surface roughness (Ra) vs. processing time.

59.3°C as shown in Fig. 18(c). According the results in Fig. 18, CNT particles could reduce the temperature during the process.

Fig. 19 shows the relationship between removal weight and processing time and Fig. 20 shows the relationship between COD and processing time. The COD and removal weight of the workpiece were investigated; when high speed was applied, the weight and COD of the workpiece changed significantly. These results indicate that for removing weight or improving the COD of the workpiece, a high revolution speed is the best choice for applying a magnetic abrasive finishing process.

Fig. 21 shows the relationship between surface roughness and processing time. To compare the effects of abrasive with CNT abrasive particles and the abrasive without CNT particles in unbonded magnetic abrasive, the workpiece was finished with 25000 rpm. The results indicate that when CNT

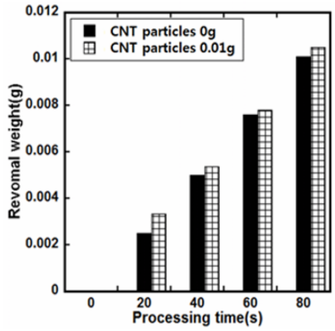


Fig. 22. Removal weight vs. processing time.

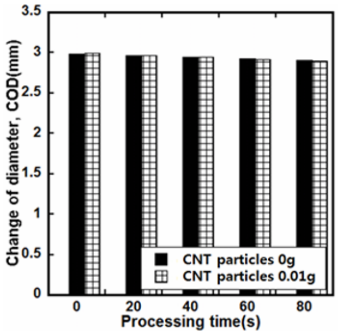
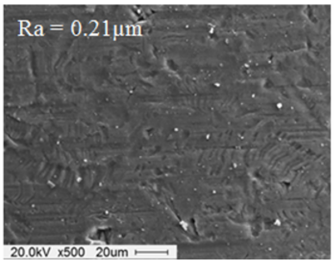
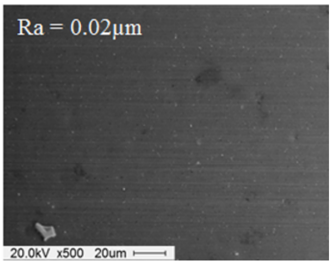


Fig. 23. Relationship between COD vs. processing time.

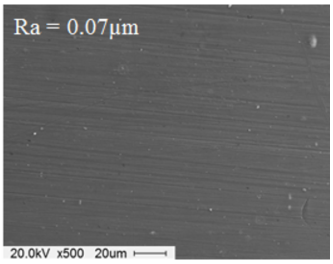
particles were used in MAF process the Ra result was much better than the abrasive without CNT particles. As shown in Fig. 21, the abrasive with CNT particles rapidly removed the rough surface within 20 seconds and the best Ra value achieved was 0.02 μm, but when they were not used, the best Ra value achieved was 0.07 μm. The grain size of CNT particles is very small and strong when compared to the grain size of diamond particles and when the workpiece was finished with CNT particles, the temperature of the surface finish was lower than when finished with abrasive without CNT particles. They have very small grain size with high strength cutting edge abrasives and can produce a smooth surface. In the cast of unbonded magnetic abrasive without CNT particles, only diamond particles can finish the surface because their grain size is not small and strong enough for finishing and small scratches still remain on the surface. Fig. 22 shows the relationship between removal weight of the workpiece and processing time. As shown, the weight of the workpiece continuously improved from the initial processing to processing completion. When 0.01g of CNT particles were applied the total removal weight by abrasive was 0.0105g, and when CNT particles were not applied, the total removal weight by abrasive was 0.0101g. These results indicate that CNT particles are effective at weight removal. Fig. 23 shows the relationship between COD of workpiece and processing time. The diameter of the workpiece improved continuously until the end of the processing time when the samples were largely the same. These results show that CNT particles are very effective for the magnetic abrasive finishing process; while they are neces-



(a) Before finishing



(b) After finishing with CNT particles



(c) After finishing without CNT particles

Fig. 24. SEM micro images of Mg alloy bars before and after finishing.

sary for removing unevenness from the workpiece surface, they are unable to improve the weight or diameter of the workpiece.

Fig. 24 shows the SEM micro images of the material surface roughness. Before finishing, the Ra value of Fig. 24(a) was 0.21 µm and the rough surface had many grooves. Fig. 24(b) shows the surface roughness of the workpiece after finishing with the abrasive with CNT particles at a workpiece revolution of 25000 rpm, (Fig. 24(b)) has a roughness of 0.02 µm (Ra), the surface of the workpiece was significantly smoother than before finishing as shown in Fig. 24(b). In Fig. 24(c), the workpiece was finished with the abrasive without CNT particles at the same workpiece revolution speed (25000 rpm), the value of surface roughness Ra was 0.07 and the micro cracks still remained on the finishing surface.

6. Conclusions

This study showed the possibility of using CNT particles mixed with an unbounded magnetic abrasive in the MAF process for finishing the surface of Mg alloy bars.

(1) When Mg alloy bar was finished by unbonded magnetic abrasive with CNT particles, the best value of Ra (0.02 µm) was obtained at 25000 rpm due to very small grain size with high strength cutting edge abrasives and high thermal conductivity of CNT particles.

(2) When Mg alloy bar was finished by different grain sizes of diamond particle abrasives (0.5, 1 and 3 µm) without CNT particles, 1 µm was the most effective grain size on the surface finish at 10000 rpm; the corresponding Ra value was 0.03 µm and 3 µm was the most effective grain size for improving weight and COD of Mg alloy due to the big grain size and characteristics of Mg alloy.

(3) When the Mg alloy bar was finished by CNT particles mixed with 1 µm diamond abrasive in different rotational speeds (1000, 5000, 10000 and 25000 rpm), 25000 rpm was the most abrasive speed for improving weight and COD of Mg alloy due to the high rotational speed.

Acknowledgment

This work was supported by research program of national research foundation (NRF) of Korea researchers in 2014 (Research Project No. 2014R1A1A2059389).

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