Improvement of humidity resistance of magnesium powder using dry particle coating

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Abstract

Dry particle coating is used to enhance the moisture resistance of ground magnesium powder (primary size 75 µm) by coating its surface with carnuba wax (primary size 15 µm). Coating was done using magnetically assisted impact coating (MAIC), and two high-speed impaction-coating devices, the hybridizer and mechanofusion. The uncoated and coated samples are characterized by scanning electron microscopy (SEM), humidity tests, and X-ray diffraction. SEM images indicate that in MAIC the coated wax is mainly observed in and around the cracks, whereas in the hybridizer and mechanofusion the wax was softened and spread more evenly over the magnesium surface. The results of 150-h humidity tests as well as extended 400-h tests show a significant improvement in the moisture resistance of ground magnesium powder after coating in all three devices. Extended 400-h tests show that in some cases, the wax-coated samples perform similar to atomized magnesium. In particular, the mechanofusion-coated product showed moisture resistance comparable to atomized magnesium, with an amount of wax as little as 2%. These results are also verified by XRD analysis to measure the amount of hydroxide formation. Thus the wax coating increases humidity resistance by delaying hydroxide formation, hence increasing the shelf life of the coated ground magnesium.
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1. Introduction

Powdered magnesium has a wide range of applications in various chemical, pharmaceutical, metallurgical, and agricultural industries. Specific applications include steel desulphurization, pyrotechnics, metal matrix composite fillers and powder metallurgy [1,2]. Magnesium is a highly energetic material, i.e., it has a tendency to catch fire, and it also has a high affinity with oxygen and water. Fig. 1 shows a scanning electron micrograph (SEM) image of commercially available as-received magnesium powder. In its ground form as shown, the particle is irregularly shaped with a large number of cracks where the formation of hydroxide occurs when exposed to moisture. Fig. 2 shows a higher magnification SEM image of as-received ground magnesium after

100 h of exposure to the atmosphere that includes humidity. It clearly shows the very different morphology of magnesium hydroxide, a flake-type structure. The formation of magnesium hydroxide deteriorates many of the desirable properties of ground magnesium, e.g., the reduction or even elimination of its pyrotechnic properties and hence severely limits its applications.

An alternative to ground magnesium powder is atomized magnesium. Atomized magnesium particles are spherically shaped and have a lower tendency to form hydroxide on its surface, i.e., it has a greater shelf life than ground magnesium. Kalyon and Yazici [3] showed that when ground and atomized magnesium powders were exposed to 100% humidity at 65 °C for a short test duration, ground magnesium powder formed hydroxide close to 5% by weight, or about 2.5 times greater than that formed by atomized magnesium powder. The main reason for this difference appears to be the larger surface area to volume ratio in the ground form. However, the manufacturing and handling

cost of atomized magnesium is significantly higher than that of ground magnesium. Hence, it is desirable to develop a method that can cost-effectively improve the moisture resistance property of ground magnesium, which could be an acceptable alternative to atomized magnesium.

Kaneyasu et al. [4] observed that crushing ground magnesium powder into finer particles increases the water absorption properties of magnesium. In order to achieve a better hydration resistance, they used a wet coating technique to add organic silicon compounds on the surface. Surface modification of metal powders such as sodium, magnesium, aluminum and tantalum was also done using a resin binder in a solvent by Mitsui Mining and Smelting [5]. The metal was coated with metal alkoxides, the condensate having non-hydrolysable groups attached to the metal. The hydrophobic nature of the non-hydrolysable groups improves the hydration resistance.

Alternatively, dry particle coating techniques can be used to modify particle surfaces by coating a protection layer to achieve hydration resistance. Several dry particle-coating systems have been developed, such as magnetically assisted impaction coating (MAIC) [6,7], mechanofusion [8–10], theta composer [11,12], hybridizer [13–15] and rotating fluidized bed coater [16]. A comprehensive review of dry particle coating is given in Ref. [17]. In dry particle coating methods, fine particles (guests) are attached or embedded onto the surface of larger particles (hosts) by means of high shear and/or impaction forces. The hybridizer and mechanofusion systems generate higher local temperatures as compared to MAIC and other dry coating methods. The coating strength also differs to a great extent depending on the properties of the hosts and guests and the particular dry coating process that is used. Dry particle coating methods are becoming more important in powder processing industries because of their ability to modify particle surface properties to suit the requirements of the particular applications [17]. A distinct advantage of dry coating techniques over conventional wet coating methods is that they do not require any liquids or binders that may
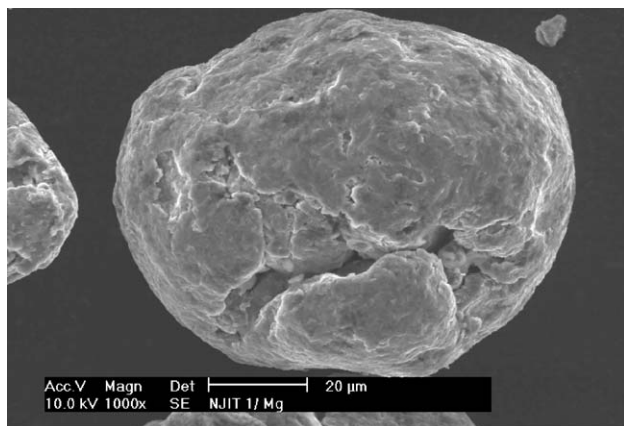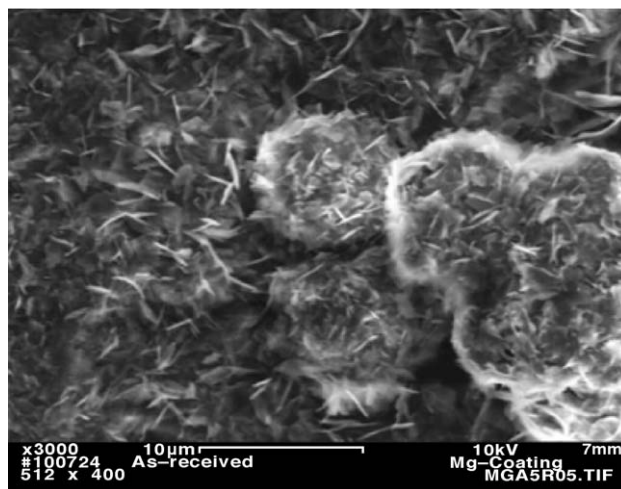

Fig. 2. Hydroxide formation on the surface of as-received magnesium after 100 h of exposure to the atmosphere.

result in waste products. Additionally, no complex chemistry is involved to achieve the coating. Moreover, they do not require drying of the product and are therefore cost-effective and save energy as compared to certain wet coating methods.

The objective of this study is to develop a simple, potentially cost-effective technique to preserve the pyrotechnic properties of ground magnesium by dry coating wax or silica onto the surface of ground magnesium particles. The main idea is that the coating with materials that are hydrophobic will delay the formation of magnesium hydroxide, hence increasing the shelf-life of the ground magnesium. Various dry coating systems are used to accomplish this goal. The products are characterized by their morphology, speciation and moisture absorption. The performance of the various coating systems is also compared.

2. Experimental

Three dry particle coating systems, MAIC, hybridizer and mechanofusion, are used in this study to coat the particles. The coating mechanism and operating variables of these processes are described in detail in Pfeffer et al. [17] and will not be repeated here. Only some of the main features are briefly reviewed here. The experimental procedure is as follows. A weighed amount of host particles (magnesium powder) and guest particles (wax or silica) is

Fig. 1. SEM image of ground magnesium particles (as received).

Table 1
Physical properties of materials

Host particle mean size: magnesium (μm)	75
Guest particle mean size: Carnuba wax (μm)	15
Guest particle mean size: hydrophobic fumed silica (μm)	0.7
Magnetic particle size: barium ferrite (mm)	0.8 to 1.4
Melting point of wax (°C)	65

Table 2
Experimental conditions of the coating processes

Set No.	Guest material	Mass ratio of guest to host	Coating device	Operating conditions	Processing time (min)
I	(1) Carnuba wax (2) Hydrophobic fumed silica	2%	Hybridizer	10,000 rpm	2
II	Carnuba wax	1%, 2%, 4% 5%, 10%, 20%	MAIC	average magnetic field strength: 1.4 mT weight of magnets to sample: 3:1	10
		1%, 2%, 5%, 10%, 20%	Hybridizer	5000, 10,000 rpm	2
		1%, 2%, 5% 10%, 20%	Mechanofusion	1000, 3000 rpm	5, 10, 20

placed into a processing chamber. Batch sizes of magnesium powder and guest particles are varied depending on the type of instrument and time of operation.

In MAIC, a pre-weighed mass of magnetic particles is also placed in the chamber, followed by the application of an oscillating external magnetic field around the processing device to agitate the magnetic particles. The magnetic particles spin and translate which results in collisions with host and guest particles, allowing coating to be achieved by means of impaction of the guest particles onto the surface of the host particles. In the hybridizer system, guest and host particles are mixed and due to the ultra-high speed rotating blades in the mixing chamber, they collide with each other as well as with the walls of the unit. Coating is accomplished through the impaction between hosts and guests resulting from the high-speed rotation of the blades. The temperature inside the chamber is varied from 22 °C to 60 °C by controlling the temperature of inlet water into the cooling jacket of the mixing chamber. The mixing chamber is flushed with nitrogen gas to prevent ignition of the

magnesium powder. In the mechanofusion system, a mixture of guest and host particles is forced to pass through a very narrow clearance in a rotating chamber where high shear and compression forces are responsible for the coating. A scraper is used to remove the powder layer attached on the chamber wall.

The physical properties of the materials used in the experiments are given in Table 1. Two sets of experiments were carried out and the experimental conditions are listed in Table 2. In the first set of experiments, the choice of which guest particles (hydrophobic fumed silica or Carnuba wax) should be used to coat the host particles (ground magnesium) was determined by comparing the performance of the coated products by humidity testing. In the second set of experiments, the effect of guest particle loading and different operating conditions was studied. The coated, as well as the uncoated, samples were then tested under nearly 100% humidity at 65 °C. The morphologies of the coated products were characterized using a Philips XL 30 scanning electron microscope (SEM) as well as a Leo 982 Field
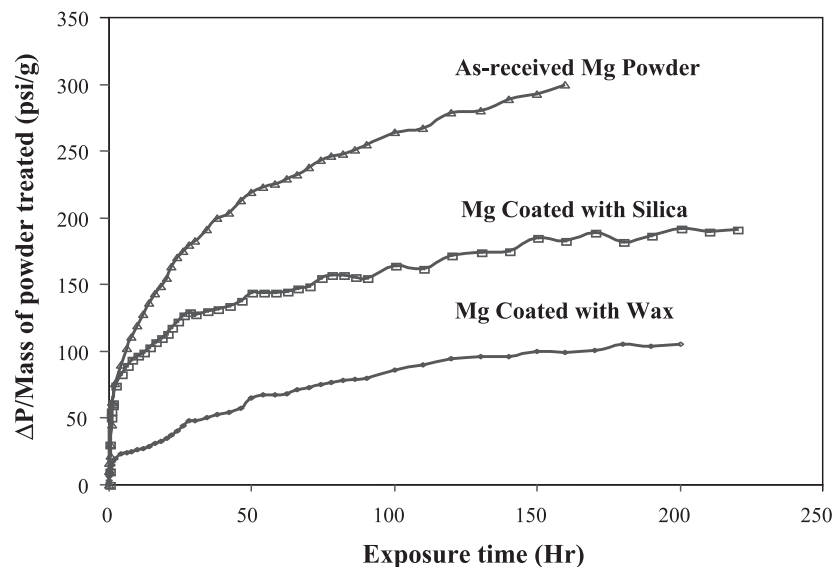

Fig. 3. Comparison of H_2 pressure increase from coated samples with wax or hydrophobic fumed silica (processed in hybridizer) and as-received magnesium powder.

Emission SEM. The products were also characterized using X-ray diffraction (XRD, Philips PW 3040) to determine the level of hydroxide formation on the surface of the coated and uncoated samples.

3. Results and discussion

3.1. Determination of coating material

The first set of experiments was carried out to determine which is the better coating material for dry particle coating, hydrophobic silica or carnuba wax. The hybridizer was used to accomplish the coating, and 2% by weight of the coating material was added. When magnesium comes in contact with water, hydrogen gas is generated through the following reaction:

$$Mg + 2H_2O \rightarrow Mg(OH)_2 + H_2 \qquad (1)$$
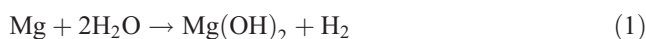
Therefore, the amount of water absorbed can be determined by measuring the amount of hydrogen gas generated. In each test, the magnesium powder batch size was 5 g. The results generated, using the experimental test rig at Picatinny Arsenal, Dover, NJ, are shown in Fig. 3.

The coated samples were also tested (fired) at Picatinny Arsenal and the coating showed no adverse effect on their pyrotechnic properties. One important parameter in characterizing pyrotechnic material is the energy density. Due to coating by lighter material such as wax, there is a risk of decreasing the energy density. While this cannot be avoided, it is expected that one can accept a small decrease in energy density in exchange for a much-improved shelf life. For the purpose of quantifying this potential disadvantage, the tapped-bulk density for the uncoated and coated (2% to 20% wax) materials was measured using the Hosokawa Powder Tester (Model PT-N, Hosokawa Micron Powder Systems, Summit, NJ). The results are shown in Table 3 for four different samples processed in MAIC. These results are encouraging; it appears that mechanical processing in the dry coating machines does not decrease the tapped-bulk density significantly despite the fact that lower density wax was added. This is attributed to the fact that the unprocessed ground magnesium is rough (see discussion of Fig. 4) and the extra wax usually fills some of the surface cracks and does not add any significant bulk to the powder. In addition, some rounding of the powder may also take place. Overall, if the coating is restricted to 2% to 5% wax, then the resulting loss in energy density is insignificant.
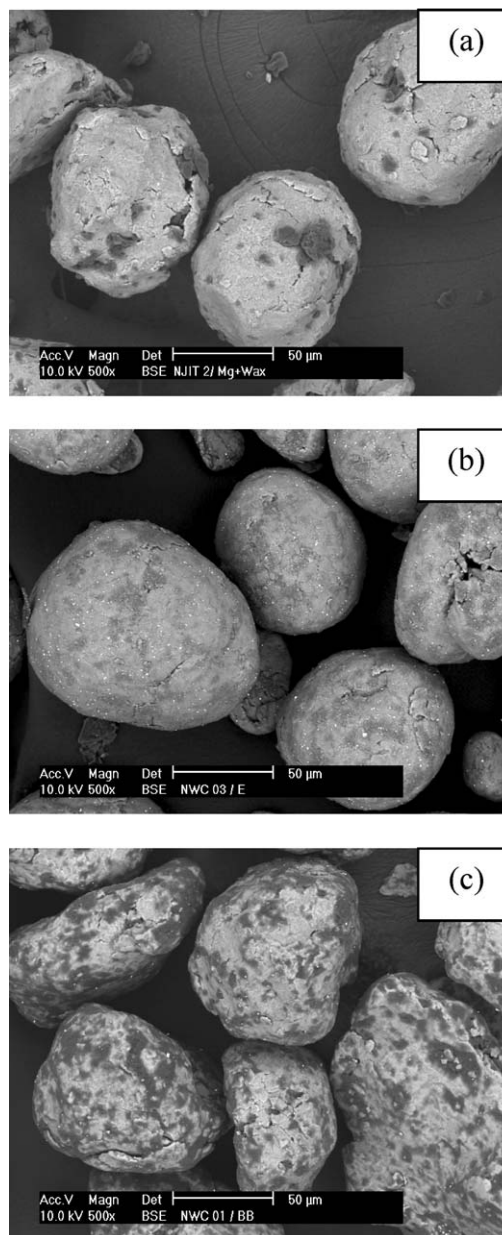

Fig. 4. SEM images of magnesium coated with various loadings of wax in MAIC (a) 1%, (b) 2%, (c) 4%.

Returning to Fig. 3, it is seen that the as-received Mg powder generated the largest amount of H_2. Magnesium coated with hydrophobic fumed silica reduced the amount of hydrogen generated, but the wax-coated product showed the best performance, resulting in about half the H_2 pressure increase as compared to that coated with hydrophobic fumed silica. The large difference can be explained by observing the morphologies of the coating layers. Silica particles were discretely lodged on the surface of the magnesium while wax particles formed a film, which covered a larger fraction of the magnesium surface (as will be shown later). The film provided a greater coverage and hence less water absorption. Due to its superior perfor-

Table 3
Decrease in tapped density for various coating amount of wax (in MAIC)

Percentage of wax	2	5	10	20
Percentage decrease in tapped density	1.5	3.8	6.4	12.6

mance, only wax was used to coat the magnesium in subsequent experiments.

3.2. Surface morphology

In the second set of experiments, the use of different dry coating systems and the effect of varying operating conditions on the coating were assessed. The surface morphology of the coated product from the MAIC process with different wax loadings is shown in Fig. 4. In SEM, lighter elements absorb more electron energy and emit fewer electrons when illuminated with a beam of electrons, whereas denser materials emit more electrons. Consequently, the dark spots correspond to wax coverage on the surface of magnesium, assuming that carbon is the major component of the wax. The SEM image of the as-received ground magnesium has been shown earlier in Fig. 1. The particle in its original form is irregularly shaped with lots of cracks and a rough surface. As shown in Fig. 4, particles processed in MAIC were smoother and rounded off as compared with the uncoated ground magnesium and the wax guest particles were discretely distributed on the surface. Greater wax coverage is observed on the surface of magnesium as the wax percentage is increased from 1% to 4%.

The coatings obtained using the hybridizer and mechanofusion with 2% wax are shown in Fig. 5. Differences in the morphology of the wax coating in the three different coating devices are readily observed. More wax can be seen on the particles when they are processed in the hybridizer or by mechanofusion. Due to the higher forces and higher local temperature in these devices, wax would soften and spread over the surface of the particles, increasing the surface coverage; higher surface coverage is critical to better moisture resistance. Fig. 5(c) is a plot of the EDX spot spectrum, and as can be observed, the carbon peak is much higher as compared to the magnesium peak for a spot where wax is visually observed in the SEM image (as a darker spot), and vice versa in Fig. 5(d). Interestingly, for areas where the wax coating is very thin and highly flattened out, as shown in Fig. 5(e), the carbon peak is high, but the magnesium peak is also significant.

3.3. Water immersion test

Since the wax is hydrophobic, the coating should make the hydrophilic magnesium surface become hydrophobic. To qualitatively test if the coated magnesium becomes hydrophobic (i.e., less hydrophilic), the coated and uncoated
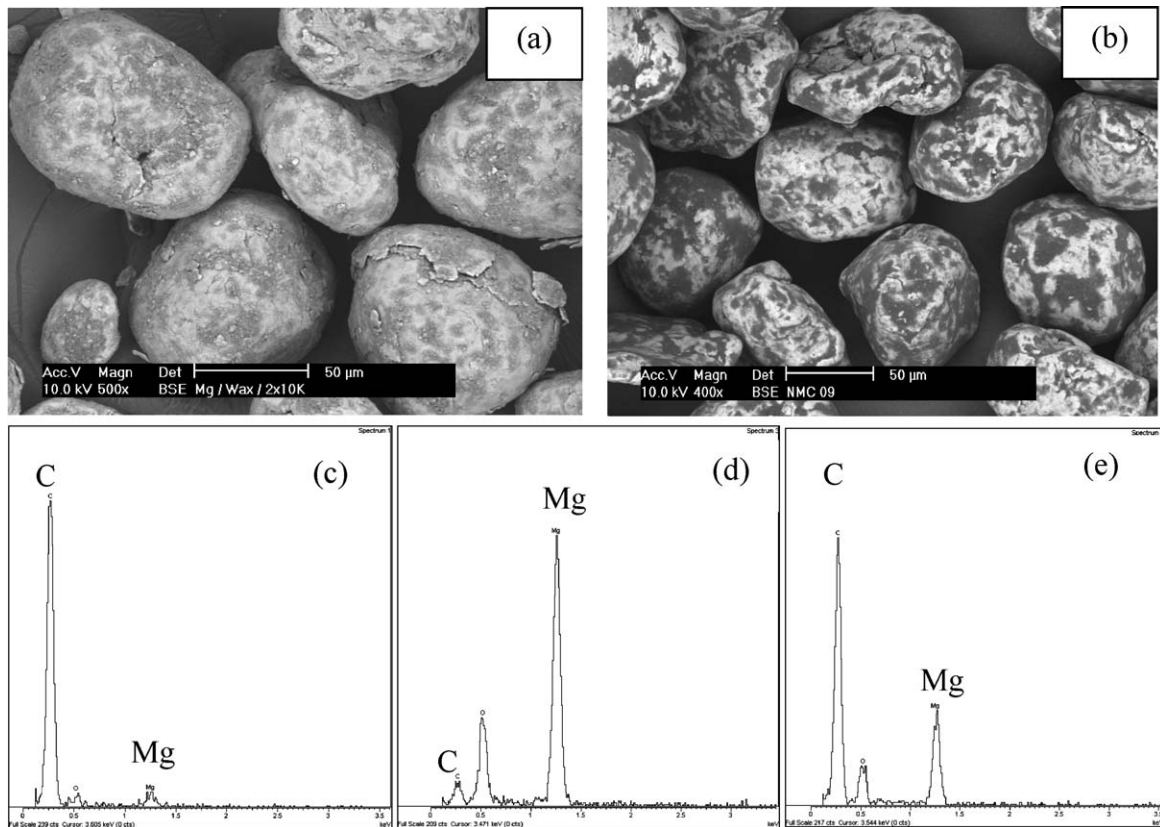

Fig. 5. SEM images of magnesium coated with 2% wax, including EDX elemental spectrum; (a) hybridizer (5000 rpm, 2 min); (b) mechanofusion (1000 rpm, 10 min); (c) spot where coated wax is visually observed, the carbon peak is much higher than the magnesium peak; (d) spot where wax is visually absent on magnesium surface, the carbon peak is much smaller than the magnesium peak; (e) area where wax is highly flattened out and thinly coated, the carbon peak is higher than the magnesium peak, but even the magnesium peak is significant.

samples were immersed in water to observe their hydrophilic or hydrophobic behavior. As expected, the uncoated sample settled in water (Fig. 6). On the other hand, the coated sample (processed in the hybridizer at 10,000 rpm, for 2 min with 2% wax and exposed to the atmosphere) floated on water. The coated product was observed to be still floating on water after 30 days, even though much of the surface was not coated with wax as shown in the SEM micrographs This transformation is due to the high hydrophobicity of the wax coatings. While the coating of wax may not completely isolate the magnesium from the atmosphere, its presence will delay formation of hydroxide by reducing the amount of moisture that will reach the magnesium surface.

While this test does not provide quantitative results, it generally indicates that the layers of wax on the magnesium surface would repel moisture from the atmosphere, making it less hydrophilic. In the next section, humidity resistance tests, which are more quantitative, are described.

3.4. Humidity tests

To evaluate the impact of the coating on the improvement in moisture resistance, preliminary humidity tests were carried out for the various coated products as well as the uncoated samples. The samples were coated by wax (1%, 2% and 5%) using several different processing conditions for each coating device. The test samples were kept in a container at nearly 100% humidity at 60 °C for 100 h to allow the formation of hydroxide on the surface of the magnesium particles. These were accelerated tests to simulate the increase in hydroxide formation after about 6 months of normal shelf life. As the melting point of wax is 65 °C, the temperature inside the chamber was kept at 60 °C in order to avoid complete melting of the wax. Nevertheless, it is high enough to soften the wax so that it would
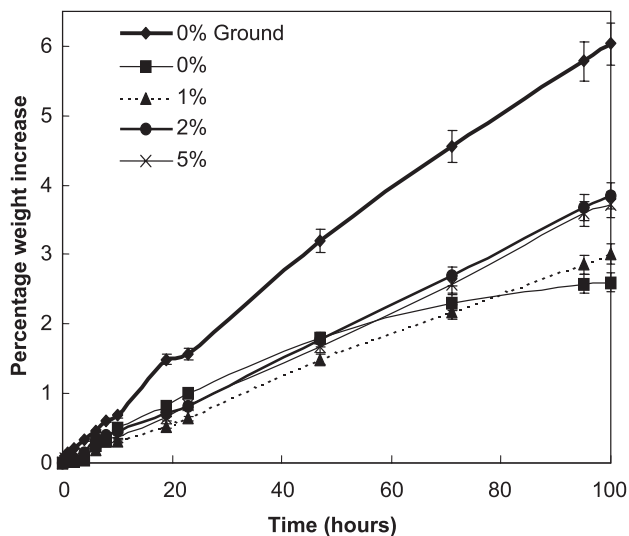

Fig. 7. Humidity test for the hybridizer products, 2 min processing time at 10,000 rpm. Increase in weight (percentage) for various cases (1%, 2% and 5% wax coating) is shown.

cover the small cracks remaining on the surface of magnesium after the coating process. The samples were weighed at regular intervals of time. The weight increase in the samples was compared with the uncoated ground magnesium sample, as well as the atomized magnesium sample tested at the same conditions.

In Figs. 7–9, the results for each dry coating machine at typical operating conditions are presented. The results for samples coated in the hybridizer at 5000 rpm with various wax loadings are shown in Fig. 7. As seen, the moisture absorption rate was highest for the uncoated ground magnesium as expected. Very encouragingly, the coated samples reduced the absorbed amount of moisture to almost the same level as that of the atomized magnesium. However, it is noted that the moisture absorption for the hybridizer-pro-

Fig. 6. Ground magnesium powder settled in water (right) while the coated sample floated on water (left) even after 30 days of exposure to the atmosphere.
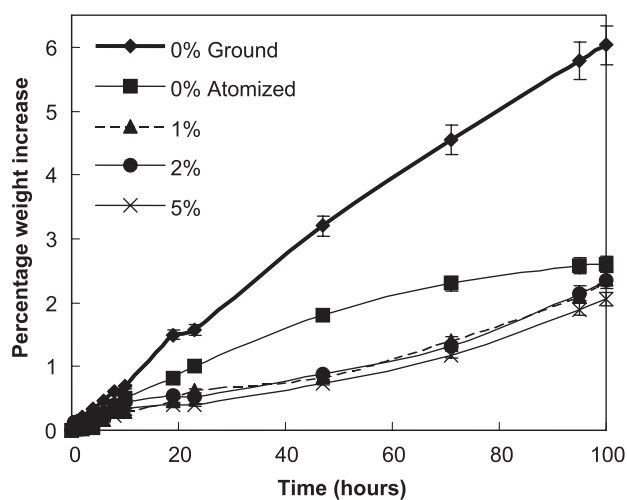

Fig. 8. Humidity test for the mechanofusion system products, 5 min processing time at 1000 rpm. Increase in weight (percentage) for various cases (1%, 2% and 5% wax coating) is shown.
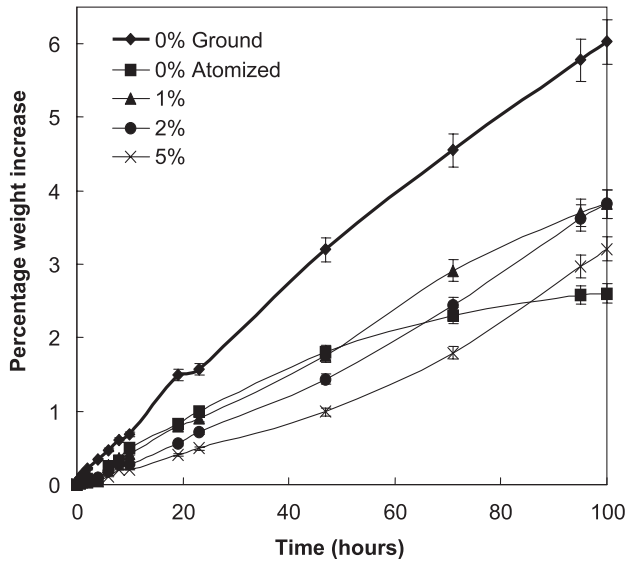
Fig. 9. Humidity test for the MAIC system products, 10 min processing time. Increase in weight (weight) for various cases (1%, 2% and 5% wax coating) is shown.

cessed products continues to rise with time, while for the atomized magnesium, it appears to be leveling off.

Humidity tests were also performed for samples processed in the mechanofusion and MAIC systems. The results are shown in Figs. 8 and 9, respectively. For mechanofusion-processed samples (in contrast to hybridizer-processed samples), moisture absorption of the coated samples is seen to be marginally less than that for the atomized uncoated magnesium. However, looking at the trend of these curves, it appears that as time increases towards 100 h of exposure, the atomized magnesium moisture absorption appears to have become flat whereas the

moisture absorption of the coated samples is still rising. For the MAIC experiments, as shown in Fig. 9, the moisture absorption of the coated product is similar to that of the mechanofusion-processed samples, except that their degradation is more rapid, i.e., their moisture absorption becomes greater after 50–90 h (depending on the percentage of wax) than that of the atomized magnesium.

Overall, as seen from these results, while there were some differences in the trend, all of the coated products processed in the different coating machines showed a reduction in moisture absorption. These tests were run for 100 h because that amount of time is supposed to represent about 6 months of shelf life. However, since the atomized magnesium results were somewhat better than those obtained using the coated particles, it was decided that longer tests were needed to examine how well the coated products fare as compared to the atomized magnesium at longer exposure times. Once again, our goal was to use atomized magnesium as a benchmark for the coated products. The new tests were more comprehensive; the humidity exposure time was increased to 400 h and higher amounts of wax coating (10% and 20%) were also used. For each coating device, one typical set of operating conditions was again selected.

The results for 400 h of testing revealed some very interesting features. While the results showed trends similar to those seen in Figs. 7–9 for the first 100 h, the moisture absorption rate was quite different beyond that. Results for the MAIC processed products are shown in Fig. 10 for all of the different coating levels. The figure also shows the results for the as-received ground magnesium and the atomized magnesium. As can be seen, MAIC-coated products indeed absorb significantly more moisture than atomized magnesium beyond 150 h, particularly for wax coatings of up to
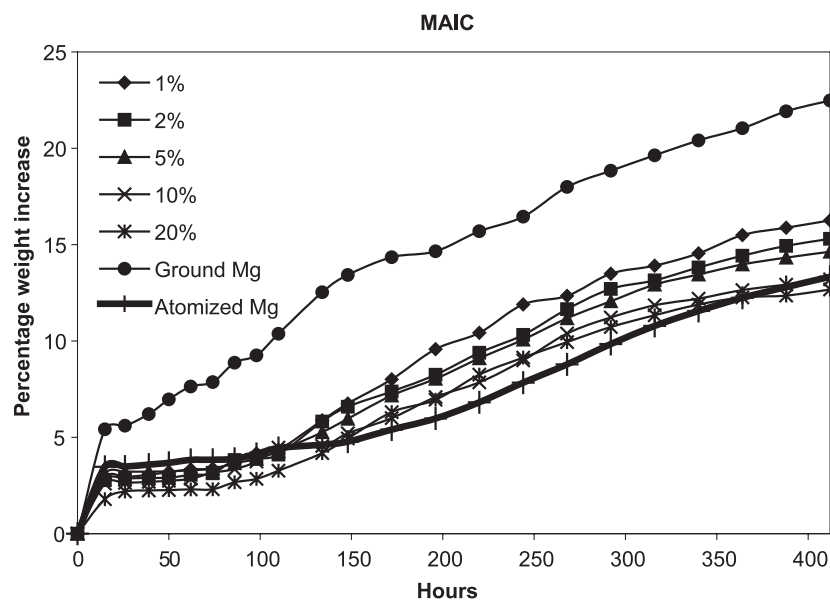

Fig. 10. Humidity test for the MAIC system products, 10 min processing time, extended 400-h testing. Increase in weight (percentage) for various cases is shown.
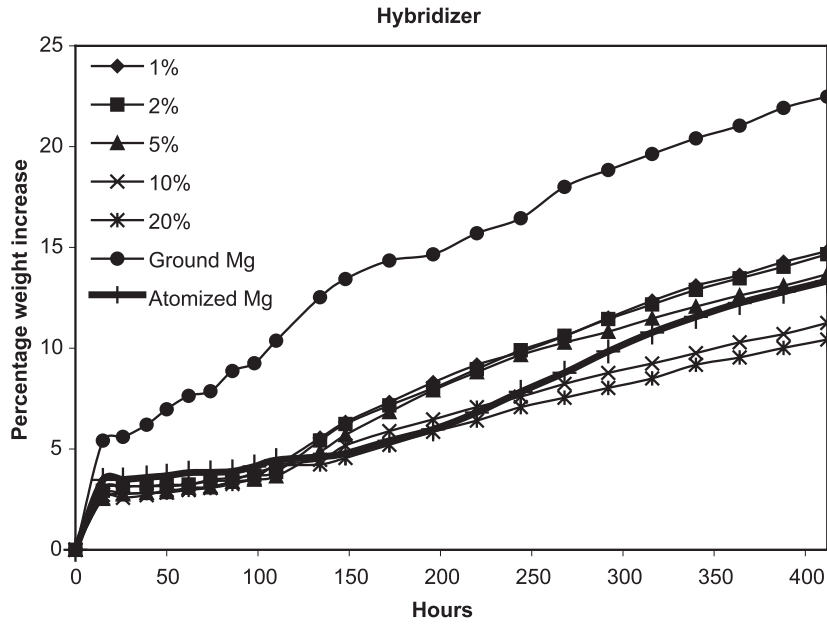
Fig. 11. Humidity test for the hybridizer system products, 2 min processing time at 10,000 rpm, extended 400-h testing. Increase in weight (percentage) for various cases is shown.

5%. Even for larger amounts of coated wax, the water absorption is higher than the atomized magnesium between 150 and 350 h of testing. Only towards the end of the test period is the water absorbed by the 10% and 20% wax coating comparable to that of the atomized magnesium. Nonetheless, the uncoated ground magnesium absorbs about the same amount of moisture in 200 h as the 1% and 2% wax-coated samples do in 400 h, suggesting that these low-percentage coatings double the shelf life.

The hybridizer processed results are shown in Fig. 11. It is clear from these and results from Fig. 10 that the hybridizer outperforms the MAIC, resulting in lower mois-

ture absorption by the coated particles from 150 to 400 h. Moreover, the 10% and 20% wax-coated products seem to absorb about the same or less moisture as the atomized magnesium. The mechanofusion-coated products performed even better than the hybridizer as seen in Fig. 12. It appears that beyond 300 h, all of the coated products absorb somewhat less moisture than the atomized magnesium.

The results of the extended tests reveal that different coating devices can yield quite different results in the long run. It is noted that the reader should not conclude from these results that one device would always outperform the other devices. We have observed in our laboratory for a
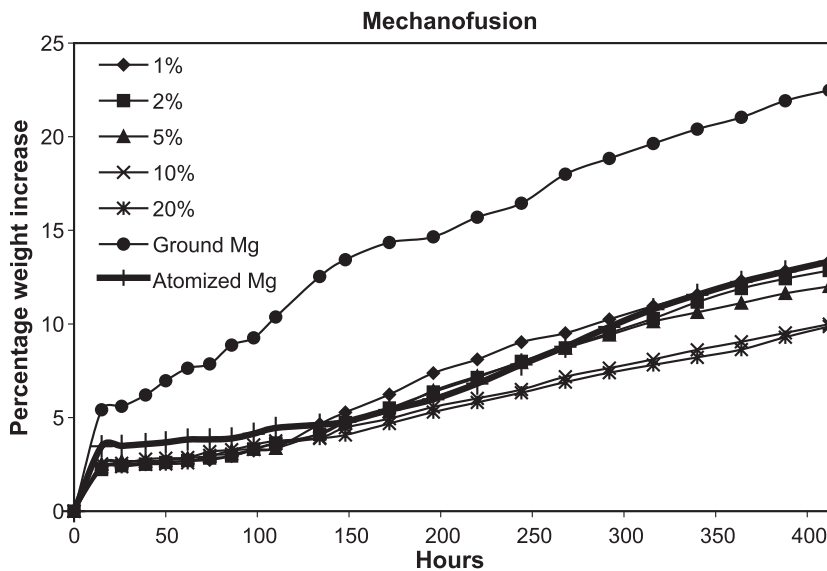

Fig. 12. Humidity test for the mechanofusion system products, 5 min processing time, extended 400-h testing. Increases in weight (percentage) for various cases is shown.
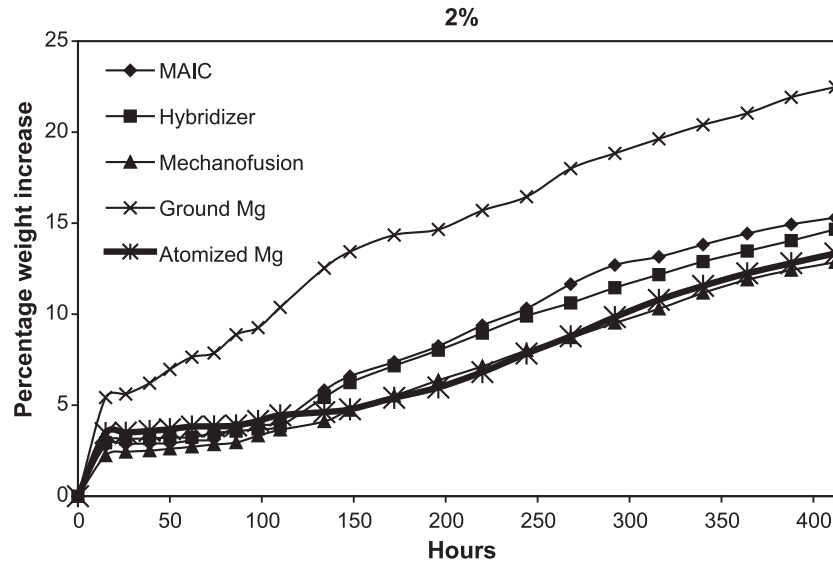
Fig. 13. Humidity test for products with 2% wax coating, extended 400-h testing. Increase in weight (percentage) for various cases is shown.

variety of different dry coating applications that the particular dry coating device, which performs the best, is very application specific [17]. For this particular case, mechanofusion provides very good moisture resistance for coated ground magnesium with as little as 2% wax.

    While these results are still not very quantitative in terms of delayed hydroxide formation, they show that our objective of developing a simple method to reduce the moisture absorption of ground magnesium powder has been successfully achieved. To get a better picture of the effect of different amounts of wax coating as a function of the processing device, the results from Figs. 10 to Figs. 12 are re-plotted for 2% and 5% wax coatings, in Figs. 13 and

14, respectively. Fig. 13 shows that while all of the dry coating devices are comparable to the atomized magnesium benchmark until about 150 h of testing, only the mechanofusion-processed product shows a performance comparable to the atomized magnesium up to 400 h of testing. As seen in Fig. 14, when the wax is increased to 5%, the mechanofusion-processed product is performing well, but the other coated products are not performing as well as the atomized magnesium, although better than the 2% wax-coated products. While not easy to see from Figs. 11 and 12, when the coating is increased to 10%, both the mechanofusion and hybridizer products perform as well or better than the atomized magnesium.
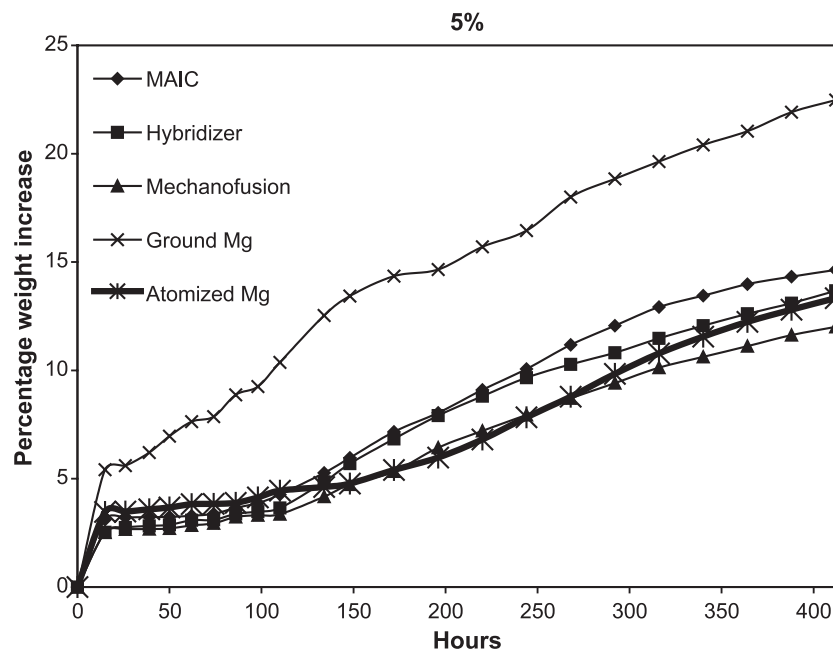

Fig. 14. Humidity test for products with 5% wax coating, extended 400-h testing. Increase in weight (percentage) for various cases is shown.
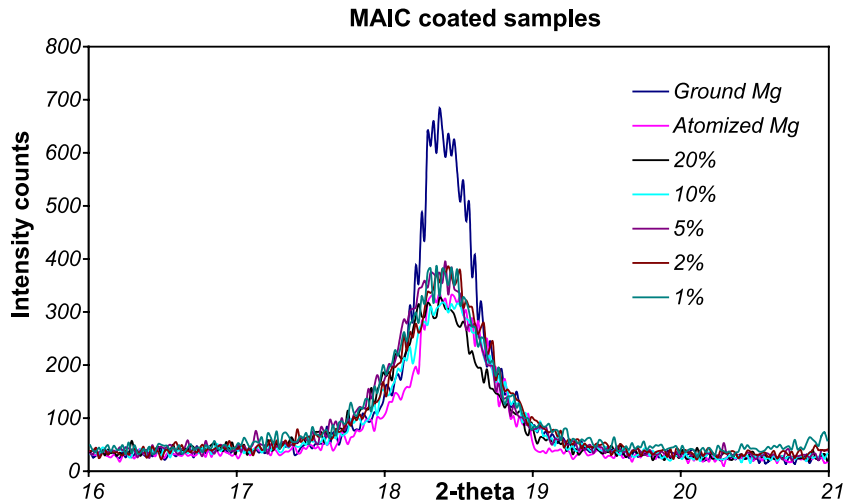
MAIC coated samples

Fig. 15. XRD test results for MAIC-coated products with various amount of wax coating, for extended 400-h testing.

3.5. X-ray diffraction

In addition to the humidity tests, X-ray diffraction (XRD) was used to characterize the hydroxide formation on the surface of the magnesium powder and provide another means to evaluate the moisture resistance of the coatings. The results for samples exposed to moisture for 400 h (the same samples used to obtain the results given in Figs. 10–12) are shown in Figs. 15–17. The samples were scanned from 15° to 75°. The major α-magnesium peak was seen at 34–36°, whereas, the major α-magnesium hydroxide peaks were around 18° and 39°. For clarity, only the region between 16° and 21° is shown in each of the Figs. 15–17.

Fig. 15 shows the XRD scans for various MAIC-coated products, along with the ground and atomized magnesium powders. The peaks indicate that all products fared better than the uncoated ground magnesium, consistent with the results seen in Fig. 10. While there are too many curves too close to each other, it can be seen that only the 10% and 20% coated products have peaks of about the same height as

that of the atomized magnesium. Again these results are consistent with the values at 400 h in Fig. 10.

Fig. 16 shows the XRD scans for the hybridizer-coated products. Once again, the peaks shown are in agreement with the results at 400 h from Fig. 11. It is seen that products coated with 5%, 10% and 20% wax have peaks of about the same height as the atomized magnesium. The mechanofusion-coated products (Fig. 17) show that all of the coated products have peaks comparable to the atomized magnesium benchmark, in agreement with the results of Fig. 12. It is emphasized that the results in Figs. 15–17 are only for the coated products exposed to the full 400 h of testing, corresponding to the 400-h values in Figs. 10–12.

Overall, the results of these figures show that the moisture absorption test and the XRD scans (indicating the hydroxide formation) are in good agreement with each other. Thus we can conclude that all of the dry coating devices are capable of increasing the shelf life of ground magnesium by delaying the formation of hydroxide through the application of a surface coating of wax. It should be
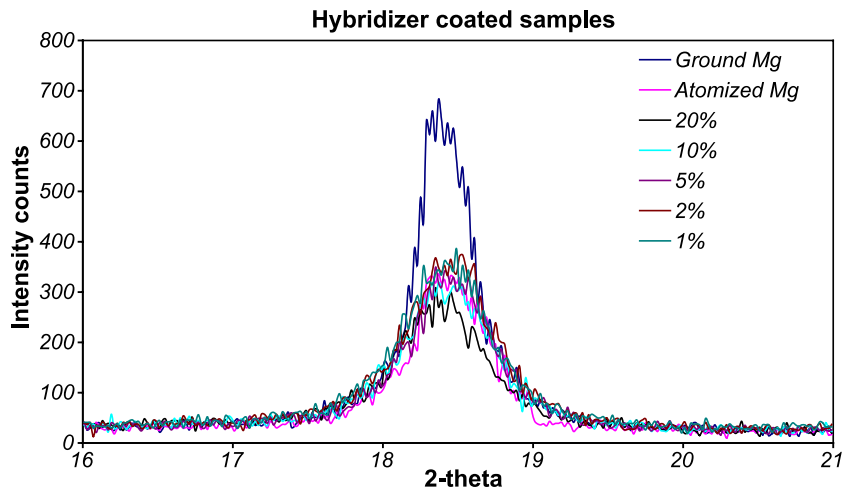
Hybridizer coated samples

Fig. 16. XRD test results for the hybridizer-coated products with various amount of wax coating, for extended 400-h testing.
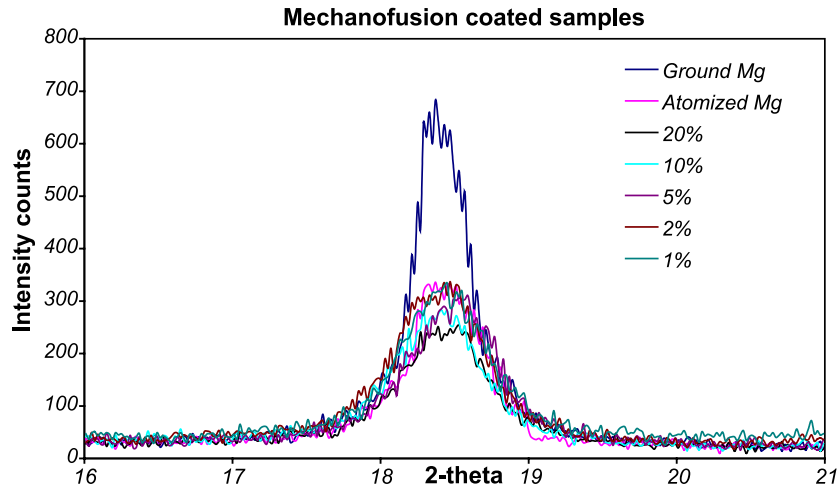
Fig. 17. XRD test results for the mechanofusion-coated products with various amount of wax coating, for extended 400-h testing.

noted that we were more interested in comparing the peaks of the coated products with the peak of the uncoated ground magnesium, than with the peak of the atomized magnesium since all of the peaks (except that of the uncoated ground magnesium) are very close to each other, and without proper calibration and more quantification, a fair comparison cannot be made. These results simply verify that hydroxide formation is delayed for coated samples exposed to moisture for 400 h.

4. Summary

In this study, a cost-effective, environmentally benign method has been developed which improves the moisture resistance of ground magnesium and hence its shelf life by delaying the formation of magnesium hydroxide. This was accomplished using various dry particle-coating devices to coat ground magnesium powder with carnuba wax or fumed silica. The wax-coated magnesium samples were tested (fired) at Picatinny Arsenal and the coating showed no adverse effect on their pyrotechnic properties, other than a slight loss of bulk density that directly relates to the loss of energy density.

Immersing the uncoated and coated samples into water demonstrated that hydrophilic magnesium can be transformed into a much more hydrophobic product by coating a layer of wax onto the magnesium surface. The humidity tests showed that the product's humidity resistance increased significantly even with only 1–2% by weight of wax when devices such as the MAIC, the hybridizer and mechanofusion were used. The improved humidity resistance was further verified through XRD tests, which showed that hydroxide formation on the surface of magnesium was significantly less on the coated samples as compared to uncoated magnesium, and was comparable to that of atomized magnesium in the 400-h runs for certain combinations of the amount of wax used and a particular coating device. It

is noted that for this application, mechanofusion and the hybridizer performed very well, requiring lesser amounts of wax to produce results comparable to MAIC-coated products using larger amounts of wax.

In summary, it has been demonstrated that dry coating techniques can be used to improve the moisture resistance, and hence the shelf life of ground magnesium powders by coating as little as 2% by weight of wax in some of the coating devices. While we have presented results of wax coating as high as 20% by weight, it is recommended that typically, only 2% by weight wax should be used for the purpose of extending the shelf life of ground magnesium.

References

[1] E. Dreizin, Y. Shoshin, R. Mudry, "High Energy Density Powders of the Al–Mg Mechanical Alloys", 50th JANNAF Joint Propulsion Meeting, Salt Lake City, UT, July 11–13, 2001.

[2] Y. Shoshin, R. Mudryy, E. Dreizin, "Preparation and Characterization of Energetic Al-Mg Mechanical Alloy Powders", The Second Joint Meeting of the US Sections of the Combustion Institute, Oakland, California, March 25–28, 2001.

[3] D. Kalyon, R. Yazici, Hydroxide formation in atomized and ground

magnesium powders, A report made for ARDEC (Picatinny Arsenal), 1996.

[4] A. Kaneyasu, S. Yamamoto, T. Watanabe, Taikabutsu (Refractories) 47 (9) (1995) 444–449 (Ube Chemical Industry, Yamaguchi (Japan)).

[5] T. Mitsui Mining and Smelting Organization, Jpn. Pat. Abs., Gp. G 21, 90 (9) (Patent No. JP 02/014258).

[6] R.K. Singh, A. Ata, J. Fitzgerald, Y.I. Rabinovich, Kona 15 (1997) 121–131.

[7] M. Ramlakhan, C.-Y. Wu, S. Watano, R.N. Dave, R. Pfeffer, Powder Technol. 112 (1–2) (2000) 137.

[8] T. Yokoyama, K. Uehara, M. Naito, Kona 5 (1987) 559.

[9] M. Naito, M. Yoshikava, T. Tanaka, A. Kondo, Kona 11 (1983) 229.

[10] M. Alonso, M. Satoh, K. Miyanami, Powder Technol. 59 (1989) 45.

[11] K. Miyanami, M. Satoh, T. Yoshida, Proceedings of First International Particle Technology Forum, AIChE, Part III, 17, Denver, USA, August, 1994.

[12] S. Watano, Y. Imada, K. Miyanami, C.Y. Wu, R.N. Dave, R. Pfeffer, J. Chem. Eng. Jpn. 33 (6) (2000) 848–854.

[13] H. Honda, K. Ono, T. Ishizaka, T. Matsuno, T. Katano, M. Koishi, J. Soc. Powder Technol. Jpn. 24 (1987) 593.

[14] I. Takafumi, K. Yuji, O. Kenji, Sixth International Symposium on Agglomeration, Nov. 15–17, Nagoya, Japan, 1993.

[15] O. Masaru, M. Hironori, U. Tetsuya, S. Kunio, Adv. Powder Technol. 7 (4) (1996) 291.

[16] S. Watano, R.N. Dave, W. Dunphy, R. Pfeffer, Advanced Technologies for Fluid Particle Systems, AIChE Symp. Ser. 95 (1999) 1–4.

[17] R. Pfeffer, R.N. Dave, D. Wei, M. Ramlakhan, Powder Technol. 117 (2001) 40.