Design Notes...

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Ball Milling Theory

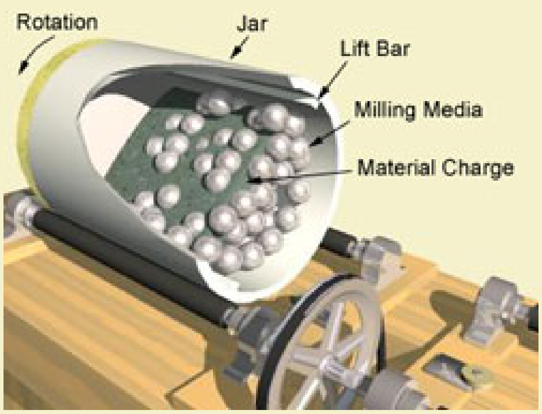


Figure 1: Ball milling terminology.

Introduction:
I was first given the formula for gunpowder by my Uncle at age 14, after he had observed my apparent obsession with class C fireworks. Being a scientist who had experimented with the ancient recipe himself during his youth, he thought I should try making my own fireworks. When I found out that these three simple ingredients could be purchased at the local drug store, I was ecstatic! It wasn't long before I had a box of Swan brand "flowers of sulfur", a pound of saltpeter and some charcoal briquettes I had ground up with a sledge hammer. Imagine my disappointment when the resulting greenish powder slowly burned with pools of bubbling white slag!

It wasn't until 14 years later with the publication of Lloyd Sponenburg's dissertation on ball milling in American Fireworks News (December 1995) that I was finally able to make commercial quality meal powder. Even though I had discovered the importance of using good charcoal through experimentation, my grinding efforts were previously limited to tediously grinding small batches in a marble mortar and pestle! I had read about the large wooden barrel filled with lead balls described by George Weingart in his book Pyrotechnics, but such a milling contraption seemed to be excessive for a small scale hobbyist.

With the better understanding of ball milling brought to the hobby pyro community by Lloyd's research in the mid 90s, many pyro hobbyists can now experience the joy of making high quality gunpowder without ever experiencing the frustrations of grinding by hand or the "CIA" manufacturing method (an alternative method of making BP that doesn't involve grinding). With Lloyd's ball milling book having sold over 2000 copies, there are probably over 1000 home built ball mills operating in just America alone.

This article borrows from Lloyd's research, which was obtained from the commercial ball milling industry, and explains some of the key design criteria for making your own ball mill. This is a good starting point for anyone interested in making their own black powder, which is the foundation upon which all other pyrotechnics have been built.

Grinding Theory:
There are a lot of misconceptions about what goes on in a ball mill. We know that a drum filled with heavy metal objects will grind powder when it is rotated, but how exactly does this happen? Some people think that the powder is pulverized against the sides of the drum as the media roll over top of it. Others believe the grinding media should drop down onto the powder grains from above, thus crushing it by impact. While there are "drop" mills that operate in this fashion, the use of high-impact methods are not recommended nor even necessary for effectively milling live batches of black powder.

The ideal milling method for optimized black powder milling involves what is called "cascading" action. This is a continuous flow of media

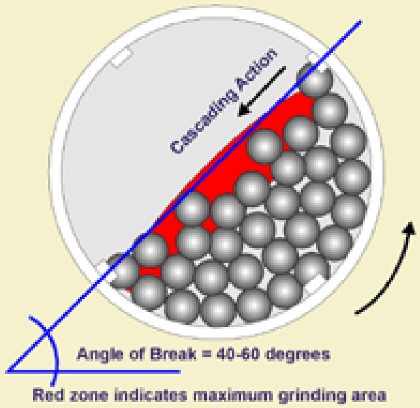


Figure 2: Optimal angle of break for cascading action.

Optimal Speed Calculator:

Enter the diameter of your milling media and jar I.D. below to get the optimum speed of rotation for grinding efficiency. You may also enter the media size and a rotation speed to determine the jar size for that combination. Calculations are performed as you type.

Jar I.D. (inches)	
Media O.D. (inches)	.75
Critical Speed (RPM)	
Optimal Speed (RPM)	

Drive Train Calculator:

Enter values for five of the six parameters below in order to solve for the missing parameter. You can use this to calculate the required motor speed by entering all drive train diameters plus the optimal speed calculated above.

Motor Speed:

RPM

Pulley #1 Dia.:

Pulley #2 Dia.:

Drive Roller Dia.

Jar Outside Dia.:

rolling over itself with the powder being sheared between them. Figure 2 shows the active grinding area for an optimally charged ball mill. As the drum rotates, the media should ideally form a sloping pile that maintains a 45 degree angle so that there is a constant cascading of media at the surface. Because the media is falling the fastest and for the longest distance at the top of the pile, the majority of grinding action takes place at the surface and diminishes the closer you get to the jar wall.

Optimized Rotation Speed:

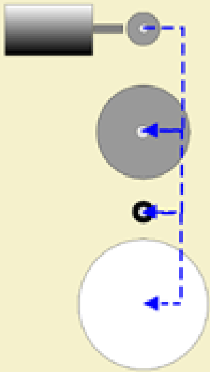
The speed at which the ball mill jar rotates is responsible for maintaining the slope of the cascading media pile, which is known in the industry as the "angle of break." This angle can be between 40 to 65 degrees as measured from the horizontal. If the angle is too shallow, the media will not cascade much from one end to the other. If the angle is too steep, the media will actually break free and fall from top to bottom while striking nothing in between. Still faster speeds can cause the media to centrifuge away from the pile and not cascade at all. The speed at which this begins to occur is known as the "critical speed."

Steep angles are caused from overly high rotation speeds, while shallow angles are caused from low RPMs or slippage of the media inside the jar. The slippage problem can be counteracted with the use of lift bars, as seen in Figure 2. These are traction bars that run the full length of the jar and act to support the media as it climbs the wall. At least two lift bars should be used in smaller jars, with four being used in larger jars. Jars that are multi-sided like hexagons or octagons usually do not have the slippage problem and do not need lift bars. rubber jars such as those used in rock tumblers also do not have the slippage problem.

The rotation speed of the jar required to obtain the optimal angle of break is dependent on both the diameter of the jar and the diameter of the media being used. The following formula can be used for determining the critical speed based on these two dimensions (diameter measurements must be specified in inches):

$$\text{Critical Speed} = \frac{265.45}{\sqrt{\text{Jar I.D.} - \text{Media O.D.}}}$$

The critical speed must be known in order to calculate the optimum speed, which is the speed that you actually want your jar to rotate at. The optimum speed varies as a percentage of the critical speed depending on the viscosity of the material being ground. For the dry powders used in pyrotechnics, the optimum speed will be 65% of the critical speed. Using the interactive calculator on this page will help you determine the optimal speed for your mill without having to reach for a calculator.



Jar Speed:

RPM

Calculate

Once you know the ideal speed of rotation for your mill jars, you will need to design your mill around this critical parameter. With most ball mill designs, you have two areas of speed reduction to tweak: from the motor drive shaft to the drive pulley and from the roller bar to the milling jar. The drive train calculator featured on this page gives you a simple way to play with these numbers and find the dimensions you need. The numbers you enter are not tied to specific units (inches vs centimeters) but you must be consistent in the units you choose to use. Do not enter some numbers as measured in CM and other measured in inches. All numbers are assumed to be using the same units otherwise the calculations will be wrong. Start by entering the dimensions that are the most difficult to change, such as the jar diameter and the roller bar diameter. You can only solve for one number in the table, so five out of the six fields must contain a value before hitting the "calculate" button. Filling all four diameter fields and leaving the motor RPM blank will help you determine the ideal motor for your mill. If you already have a motor and you know the RPMs, you can enter it and then play with the other fields to find the best combination of pulleys, jar and roller diameters you need to get close to the optimal jar RPM.

More...

Ball Milling Theory

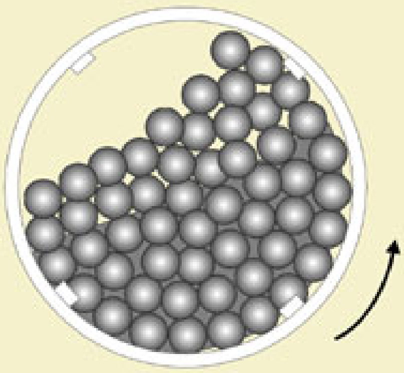


Figure 3: An overcharged mill.

Optimized Jar Loading:
One key to efficient milling is a properly charged milling jar. "Charge" refers to the amount of media and powder loaded into the jar, which is specified as a percentage of the overall jar volume. In order to maximize the cascading distance at the surface of the media pile, the jar should be filled 50% by volume with the milling media alone. This gives a cascading surface that is equal to the diameter of the jar, which is the maximum possible surface length. Too much media or too little will decrease the length of this cascading zone and increase your milling times.

There is a tendency by those using larger milling drums (such as 5 gallon buckets and other large diameter jars) to under charge the media to save money or time spent casting media, as well as to lighten the weight of the drum. Undercharging your mill in this manner will increase the milling times relative to a properly charged mill.

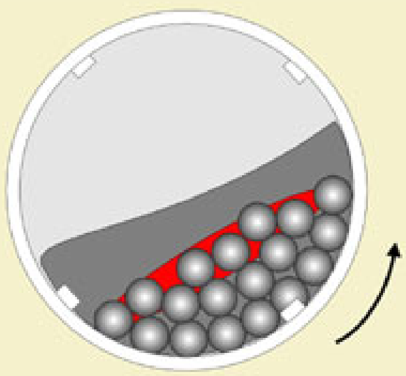


Figure 4: Undercharged media with overcharged load.

The material charge is equally important in running an efficient milling operation. If too little material is loaded with the media, it will mostly stay in the voids between the media and the media will just grind against each other. Too little material will cause excessive wear on the media while grinding very inefficiently. Too much material will also interfere with efficient grinding by creating a shock-absorbing cushion between the media. An overly high material charge is the most common mistake, since it is tempting to try and grind more powder at once. A jar with undercharged media will usually be overcharged with material, thus compounding the inefficiency with a combination of the reduced cascading zone in addition to the cushioning effect.

For most materials you will be grinding, a 25% material charge (relative to jar volume) is the ideal load. There are some exceptions to this, such as when milling fluffy mixtures containing a lot of air. The volume of a high charcoal mix tends to be inflated before grinding due to a large quantity of air trapped in among the light charcoal particles. As milling progresses, this air is forced out and the material volume decreases. To account for this fact, a higher material charge is necessary when milling mixtures containing charcoal and other compounds that seem overly fluffy.

Some experimentation is inevitable in determining the exact amounts of material charge to use. While the media charge should always be 50%, material charge will vary from 25% to 40% or more in some cases such as when grinding 100% homemade airfloat charcoal. The best way to tell if your mill is properly charge is to listen to it after about 15 minutes of grinding. You should hear a continuous cascading sound that is fairly loud. If the mill seems quiet or muffled, you are probably grinding too much material.

"24 Hour Meal" in 5 Hours:
Some BP makers prefer to grind larger batches less efficiently by running over-charged mills that typically involve open ended buckets or drums that spin at an angle to keep the material from falling out. The argument is that while less efficient mills are required to run much longer than a fine tuned closed-jar mill, they can mill a lot more powder at

once and thus reduce the frequency of emptying out the contents. While this argument has merit, I prefer to minimize the amount of time spent tumbling live batches of powder, which also extends the life of the mill and keeps the motor from overheating.

A fine tuned ball mill designed and operated as described in this article will allow you to produce what some people refer to as "24 hour meal" in about 5 hours of milling time. I prefer to mill the nitrate while also milling a parallel jar of the charcoal and sulfur mixed together in the 3:2 ratio for 2 hours. The two are then mixed together in a 3:1 ratio and milled for only one hour. This will give you a very fast burning powder in 5 hours (3 hours total run time with only 1 hour of milling the live mix) that is as fine if not finer than what the bulk-milling crowd had to run their inefficient mills for 24 hours to produce!

Further Reading:
Build A Ball Mill
Making Milling Jars
Casting Milling Media

REFERENCES:

"Ball Milling Theory and Practice for the Amateur Pyrotechnician,"
Lloyd Sponenburgh

Mail Passfire.com